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ABSTRACTS  
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## Crustal architecture and tectonic evolution of the northwestern Thomson Orogen

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The ~N-S magnetic trend of the Precambrian Mount Isa inlier is abruptly cut-off by broadly NE-SW geophysical trends, marking the northwestern boundary of the Thomson Orogen. This important boundary, commonly referred to as the Diamantina River Lineament or Cork Fault, is obscured by Phanerozoic sedimentary successions, and therefore, its crustal architecture, kinematics, and tectonic evolution are largely unknown.

Interpretation of gravity and magentic data indicate clear evidence for a broad zone of dextral kinematics along this Thomson-Mount Isa boundary. In cross sections, interpretation of a 2D regional seismic reflection profile (14GA-CF 1) shows an additional component of listric normal faulting with minor inversion, particularly along the ~NE-SW-trending Cork Fault, which seems to penetrate through the whole crust. The 3D fault geometry along the Diamantina River Domain shows a positive flower structure indicating that a major zone of dextral transpression is preserved along this fault Zone. Thick lower reflective crust exists beneath the Mount Isa Province, which becomes slightly thinner along the Diamantina River Domain and very thin farther south. The reflection geometry within the thin reflective lower crust of the northwestern and central Thomson shows some similarities with the reflective lower crust of the Mount Isa. We thus hypothesise that the lower crust of the Thomson orogen represents a hyper-extended continuation of the Mount Isa lower crust.

To the south of the Diamantina River Domain, the central Thomson Orogen is characterized by a ‘smooth’ magnetic signature (long wavelength and low amplitude geophysical anomalies), which indicate deeply buried source bodies in the mid- to lower crust. The eastern part of the central Thomson Orogen is characterized by a prominent NE structural grain where the western part consists of a series of NW-trending structures. These two structural domains are separated by the ~N-S running Canaway Fault. Reinterpretation of the BMR seismic lines suggests that the thin reflective lower crust also continues in the central Thomson Orogen. Structural interpretation of the seismic transects shows that most of the faults are west-dipping inverted reverse faults that extend down to the Moho. Seismic reflection patterns at shallower depth suggest that inversion may took place during or after the Devonian.

The timing of activity along the Cork Fault and other structures within the Diamantina River Domain are not well constrained. We hypothesise that the faults were active during the breakup of Rodinia, and were later reactivated and subjected to transpressional kinematics during the Delamerian Orogeny. Structures within the central Thomson Orogen were possibly developed as normal faults associated with Late Cambrian to Late Ordovician back-arc extension, which were later reactivated and inverted as reverse faults.

## **Towards simulation-based inversions of multiple geoscientific data for the physical state of the Earth's interior**

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The recent development of fast simulation techniques in the engineering community is opening new opportunities to solve large inverse problems in geoscience previously considered impractical. Simulation-based inversions are a more physically realistic way of obtaining models of the Earth's interior than traditional inversion techniques. It also allows for the inclusion of multiple datasets (geochemical, geophysical, geological, etc) into a single inverse problem. In this short presentation I'll explain the main concepts and advantages of working with this scheme.

## Myanmar microplate: A passage to India via the road less travelled

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As oceans to the north and west of Australia have opened, grown and been recycled through subduction various continental fragments that originated as part of Gondwana have departed and, with time, transferred to Asia. Recent field expeditions supported by the Australia-India Strategic Research Fund (AISRF07021) have allowed a collaborative team of Australian and Indian geologists to examine, in detail, regions along the border between Nagaland and Manipur in India and Myanmar that have previously been little explored. The Myanmar microplate terminates along its eastern side at the Sagaing Fault system in Myanmar along which it has been dextrally translated over 480 km northwards during the Miocene. Clearly this microplate did not originate where it presently lies but how far it has travelled remains uncertain. The Indo-Myanmar ranges along the western side of this block are dominated by Cenozoic sediments, which have been thrust westwards (in present-day coordinates) over an Indian passive-margin sequence that includes the Gondwana break-up rift-drift counterpart to parts of the NW Shelf of Australia.

Near the Indo-Myanmar border this giant imbricate thrust stack contains sheets of ophiolitic mélange that are in turn tectonically overlain by high-grade metamorphic rocks known locally as the Naga metamorphics. Well-preserved radiolarian microfossils indicate a Middle to Late Jurassic age for the Nagaland/ Manipur ophiolite (Baxter et al 2011). The ophiolite is heavily disrupted and subsequent to its dismemberment has been overlain by a succession of shallow marine shelf sediments; the Phokphur Formation, that locally contains marine macrofossils of Eocene affinity. Further east a succession of metamorphic units is thrust westwards over the ophiolite.

While superficially it appears that these rocks can be correlated with units known from the Himalaya in fact this is problematic. The area lies to the east of the Namche Barwa syntaxis and tectonic reconstructions indicate it has not directly participated in continent-continent collision. Indeed, stratigraphic and structural architecture differ markedly from that seen in classic Himalayan transects. Our new detrital zircon U/Pb studies reveal a fascinating history that suggests derivation of some units from Sibumasu (Ng et al. 2015; Sevastjanova et al. 2015 in press) rather than the Lhasa or Qiantang terranes. Detailed study of this area sheds important light on the tectonic evolution of the SE Asia region.

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## Origin and tectonic evolution of the NE basement of Oman – a window into the Neoproterozoic accretionary growth of India?

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Jebel Ja'alan contains one of few well exposed inliers of crystalline basement within the Sultanate of Oman, displaying a distinct magmatic and metamorphic history. Unravelling this history is important for understanding the Neoproterozoic tectonic geography of Oman as well as the relationship between the Omani basement and the juvenile arc terranes of the Arabian–Nubian Shield (ANS). To better understand the origin and tectonic history of Jebel Ja'alan we present new U–Pb and Hf isotopic data from magmatic zircons, U–Pb isotopic data from monazite,  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  isotopic data from muscovite, and whole rock Sm–Nd isotopic data from various igneous lithologies that constrain the timing of magmatic and metamorphic events, as well as the origin of igneous intrusions. We present pressure–temperature ( $P$ – $T$ ) forward models to constrain the metamorphic conditions and apparent thermal gradient experienced by the Jebel Ja'alan basement. This thermal gradient is used in conjunction with trace element geochemical data to interpret the tectonic setting in which the Jebel Ja'alan basement formed.

Zircons sourced from the Ja'alan Granite and Kamil Granodiorite provide U–Pb ages of c. 830 Ma that are interpreted as crystallisation ages. The Ali Gneiss protolith is interpreted to have a crystallisation age of  $887 \pm 5$  Ma. Hafnium isotopes from these zircons display  $\text{Hf}(t)$  values ranging from +2.30 to +13.3, demonstrating that these grains originated from a juvenile source. Monazite grains sourced from the metasedimentary Hassan Schist yield a  $^{207}\text{Pb}/^{206}\text{Pb}$  weighted average age of  $838 \pm 12$  Ma, interpreted to represent the timing of near-peak metamorphic conditions.  $^{40}\text{Ar}$ – $^{39}\text{Ar}$  data obtained for muscovite grains from the Ja'alan Granite and Hassan Schist yield plateau ages of  $831 \pm 15$  Ma and  $830 \pm 6$  Ma, respectively, suggesting that cooling of these lithologies occurred rapidly following peak metamorphism. Sm–Nd isotopic data were obtained for igneous lithologies located in Jebel Ja'alan. These data gave positive Nd values ranging between +0.56 and +6.78, indicating a juvenile origin.  $P$ – $T$  modelling shows that the Hassan Schist reached peak conditions of around 4.2–6.2 kbar and 665–695 °C, suggesting a thermal gradient of approximately 112.1–158.3 °C/kbar. This thermal gradient in conjunction with REE spider plots indicate a volcanic arc setting for the Jebel Ja'alan basement.

This study proposes that the basement of Jebel Ja'alan formed in a juvenile volcanic arc environment during the Tonian, similar to basement in Oman and the ANS. Age constraints on basement formation are suggestive of basement in Jebel Ja'alan being c. 20–50 Ma older than that in the relatively well studied region of Mirbat, in the country's southwest. We suggest this age discrepancy represents westward arc accretion and migration in Oman during the Tonian. This is in contrast to progressive eastward arc accretion in the eastern ANS. Our interpretation implies that the Omani basement is not an eastern extension of the ANS, but instead accreted on to an eastern continent (Neoproterozoic India?) before the arc terranes of the eastern Saudi ANS had begun accreting onto the Saharan Craton.

## **An overview of the Petroleum Systems of South Australian basins.**

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South Australia is situated between the ancient Archaean Shield of Western Australia and the mobile orogenic belts of the eastern states. As a result of this tectonic setting, the geological record in South Australia has preserved a unique history of sedimentation from the Neoproterozoic to Ordovician, and from the Early Devonian to Tertiary.

The basins may be subdivided into three groups based on their relative stratigraphic position:  
Basins of Mesozoic age which either overlie older intracratonic basins or are developed on the rifted southern continental margin of Australia. These include the Bight, Duntroon, Eromanga, Otway, Polda and Berri basins.

Permo-Carboniferous to Early Triassic basins which overlie early Palaeozoic basins in northern and southern parts of the state. These include the Arkaroola, Cooper, Pedirka and Nadda basins.

Early Palaeozoic basins of Cambrian to Ordovician age. The last three basins are underlain by extensive Neoproterozoic sediments which are largely unmetamorphosed and thus also prospective for hydrocarbons. The Officer Basin contains a Devonian section preserved in a foreland trough setting. These include the Warburton, Arrowie, Stansbury and Officer basins.

The Cooper and Eromanga basins, which span North East South Australia and South West Queensland, comprise Australia's largest onshore petroleum province. Permian and younger sedimentary basins beyond the main producing region contain similar largely non-marine sequences in intracratonic settings.

Continental margin basins on and offshore have very thick Cretaceous fill and include the Otway Basin, a proven gas province. In several instances there are identified, mature source rocks for petroleum in lacustrine and marginal marine settings associated with reservoir sands. These occur not only in Permian and Cretaceous rocks, but also in basins with thick Neoproterozoic to Ordovician clastics and carbonates with additional source potential in marine settings.

## TOC Estimation of the Goldwyer Formation in the Canning Basin, Barbwire Terrace Case Study

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There is an increasing interest in the Goldwyer Formation of the Canning Basin as a potentially prospective shale play. This Ordovician shaly formation is one of the most prominent source rocks in the Canning Basin. One key property to evaluate the prospectivity of any shale gas is its TOC richness. This study investigates different TOC estimation techniques and validates the reliability of each. The limited well distribution in the large area of the Canning Basin makes a basin wide study not warranted at this stage. A focused look into the Barbwire Terrace was carried out instead. General TOC estimation methods, such as Schmoker and logR were employed for TOC calculation. Both methods tend to overestimate TOC when compared with the available Rock-Eval pyrolysis TOC measurements.

The generalized nature of the Schmoker method, as it provides a global relationship between density and TOC is probably the main reason why this approach does not provide a good fit in the case of the Goldwyer Formation. Furthermore, the uncertainty associated with the logR method factors, such as, level of maturity (LOM), and resistivity and sonic baselines greatly influence the TOC estimation in this method. Apparently, data quality and assumptions made in this method do not merit a reliable TOC estimation for the Ordovician source rock.

Alternatively, implementing local well data to empirically derive TOC relationship has become more warranted. This entails using log and cuttings data to establish a reliable relationship for TOC estimation. With the appropriate data conditioning, simple and multivariate regression analysis have shown great improvements in the TOC estimation from well log data. Sufficient correlation between TOC and other log data was established, and hence, a more reliable TOC calculation has been generated. This approach helps to provide more accurate technical assessment of the Goldwyer Formation and its prospectivity as a potential unconventional hydrocarbon resource.

**A ‘Foxfire Approach’ to teaching integrated Earth and Environmental Science and Mathematics can increase student engagement in science, raise interest in STEM careers and increase the uptake of senior secondary science for the benefit of society.**

**Altman Len**

- (1) *The Geoscience Pathways Project*
- (2) *The Teacher Earth Science Education Program*

In South Australia, senior secondary ‘Geology’ will be replaced by newly developed courses in **Earth and Environmental Science** (EES) from 2017 and 2018. A similar change is occurring (or has occurred) in most states of Australia, in line with the recommendations of the **Australian Science Curriculum**. This session will explain the rationale and potential benefits of the change and provide a brief overview of the new EES subjects in SA. It will also provide a brief history of the ‘Foxfire approach’, a constructivist pedagogy that originated in Georgia in the US in the 1980’s. The workshop will focus on a case study of the application of the Foxfire ‘Core Practices’ to teaching Earth & Environmental Science (EES) and Mathematics, in an effort to attract more students to senior secondary science, and hence towards higher education and Science, Technology, Engineering and Mathematics (STEM) careers, for the benefit of Australian Society.

## Diorite-tonalite in northwest Bangladesh: Constraints on the geodynamic and crustal evolution of the crystalline basement of Bangladesh

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The crystalline basement complex occurs at variable depths of several hundreds to thousands of meters of Gondwana and Cenozoic clastics at the northwestern part of Bangladesh. The present work involves primarily the basement rocks from the drillhole GDH 54 at a depth of ~365 to 486m, in Barapaharpur, northwest Bangladesh. The GDH 54 lies proximal to the eastern margin of the Paleoproterozoic Dinajpur block, and is ~ 40km east from the 1.72 Ga Maddhapara granitoid.

Petrographic and geochemical investigations reveal a diorite basement in Barapaharpur, which is transgressed by minor granite, felsic gneiss and mafic dykes. The diorites are metaluminous, calc-alkaline and have low ASI index and show an I-type character. Both the Maddhapara and Barapaharpur granitoid rocks share similar petrographic and geochemical attributes. However, the dearth of age and geophysical data does not let the two granitoids to be directly correlated with the granitoids from the neighbouring parts of the Indian shield.

In this study, we further investigated the nature of the basement and its extent across Maddhapara, Barapaharpur and surrounding areas, suggested a tentative boundary of the Dinajpur block by processing gravity and magnetic anomaly data, and attempted a geodynamic model for the diorite-tonalite basement in the northwest Bangladesh. The geochemical characteristics of the studied granitoids suggest the geodynamic evolution of the studied portion of the basement were controlled by subduction episode/s which is preserved as deep seismic anomalies. The mapping of lithospheric material of continental slabs based on global seismic tomography of the adjacent area contributed to the delineation of a crustal block with somewhat different boundary from that of the Dinajpur block. Whether the outline suggested in the current study indeed formed a homogeneous Paleoproterozoic microcontinental block as suggested by Ameen and co-workers remains to be seen as new age and isotopic data of the major phases of the basement from these areas would become available in the coming days.

## Petrography and Geochemistry of A-type Granitoid and Associated Charnockite from the Basement Complex of Bangladesh

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The present study incorporates the petrographic and geochemical study of A-type charnockite, monzogranite, and granite from Gaibandha, Northwest Bangladesh. These rocks are identified in the drillhole GDH 31 in Dariapur, Gaibandha, at about 50 km west of the western margin of the Shillong plateau and at about 50 km southeast from 1.72 Ga Maddhapara Granitoid. Charnockite of the studied area are medium- to coarse-grained, shows hypidiomorphic granitic to weakly granoblastic texture and comprises primarily of quartz, K-feldspar, plagioclase, amphibole, biotite and orthopyroxene with minor zircon, garnet, corundum, clinopyroxene, apatite, rutile, and muscovite. Texturally monzogranite is same as charnockite, with the absence of orthopyroxene. Granite is medium- to coarse-grained, holocrystalline and has a hypidiomorphic texture. Monzogranite and granite are primarily composed of quartz, K-feldspar, plagioclase, biotite and amphibole with slightly higher volume of mafic minerals in monzogranite than granite. Accessory minerals are same in these two rocks as in charnockite.

Geochemically charnockite, monzogranite and granite show similar major and trace element abundances. These rocks are mostly high in silica, ranging from ~64 to 73%, and are also enriched in  $\text{Al}_2\text{O}_3$  (13.10 to 16.70%),  $\text{Na}_2\text{O} + \text{K}_2\text{O}$  (6.18 to 9.70%). They have low to moderate  $\text{CaO}$  (1.17 to 3.33%), low Mg# (0.12 to 0.32) and variably high  $\text{Fe}_2\text{O}_{3T}$  (2.34 to 8.70%) contents. They are also characterized by high light rare earth elements (LREE) and large ion lithophile elements (LILE) with Ba, Rb, Sr averaging 1122, 134 and 248 ppm, respectively. They have high Zr (150 to 480 ppm) and moderate Y and Nb (averaging 34 and 17 ppm, respectively) contents. Primitive Mantle-normalized incompatible trace element patterns are also broadly similar for all the rocks with moderate negative Th, Nb and Ti anomalies and weakly negative Eu anomalies ( $\text{Eu/Eu}^* = 0.83 - 0.96$ ). Petrography and geochemical characteristics of the Gaibandha granitic rocks suggest that these rocks belong to a high K calc-alkaline, ferroan,  $\text{A}_2$  subtype of an A-type granitoid suite. The calc-alkaline felsic rocks are considered to have formed from partial melting in a post-collisional setting with mantle wedge influence and by assimilation of minor clastic rocks. As the collision progressed, subsequent crustal thickening and delamination allowed high-temperature mantle upwelling on the bottom of the thickened felsic crust, caused dehydration on the lower part of the A-type granitoid and eventually generated charnockite. No contact between the diorite-tonalite basement (dated at 1.72 Ga in Maddhapra) and these A-type rocks is seen in the drillhole GDH 31, which preclude deducing the relationship between the I-type diorite-tonalite basement and the A-type granitoid in Gaibandha. The discovery of an A-type charnockite-monzogranite suite in Gaibandha added a new location of these high-temperature rocks in Paleocontinent database, the true nature and regional implications of which demand further detail study.

## Detection of buried mineralisation and lithology through transported cover in Australia

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Many prospective areas in Australia are obscured by extensive transported cover which presents a critical challenge for mineral exploration. However, the cover itself presents an opportunity for exploration and we present some results to highlight this opportunity from the gold deposits covered by Permian, Tertiary and Quaternary sediments in Western Australia. The effects of processes related to water-saturated regolith during the Tertiary are preserved in Permian and Tertiary sediments following a transition from wet to arid conditions in the post-Miocene. High palaeo-water tables within the older sediments have allowed upward migration of metals that have been incorporated into secondary minerals and anomalies over mineralisation and can be recognised by a variety of methods. Our research has shown that detailed analysis down to the single mineralogical or textural level within cover materials can provide important signals of metal dispersion not necessarily realised at the larger scale.

Overlying Precambrian crystalline basement in the eastern Yilgarn Craton are scattered remnants of the Gondwanan Permo-Carboniferous glacial sediments. These commonly comprise boulder-rich diamictites set within shallow basins. Ferruginised Permian sediments overlying Tropicana, Agnew and Lancefield gold deposits host hydromorphically and mechanically dispersed Au and pathfinder elements in Fe oxide-rich pisoliths related to the underlying mineralisation. At these locations, Au concentrations reach tens to hundreds of ppb or more against a background of <5 ppb. Where multiple sedimentary units occur at a given site (e.g., Lancefield), stacked weathering profiles in each unit allowed transfer of Au, As, Cu and Zn across the weathering profiles, by groundwater and vegetation, as they evolved. Next youngest in the Phanerozoic sedimentary succession are Eocene–Miocene continental to shallow marine sediments deposited in the palaeochannels. Ferruginisation of palaeochannel sediments is widespread. Thin ferruginous gravel layers occur within the palaeochannel sediments but these are not extensive. The gravels are more abundant on the flanks of palaeochannels, where they represent benches of an earlier, broader channel, derived from eroded lateritic profiles during extensive weathering in the Late Mesozoic. Here in these environments, a geochemical footprint of a deposit may measure hundreds to several kilometres in length for Au and pathfinder metals anomalies in pisoliths (e.g., Moolart Well, Mt Gibson, Bull China, Empire gold deposits). This is due to mechanical dispersion followed by post-depositional hydromorphic and biological dispersion in recently formed goethite-kaolinite-amorphous Si-rich cortices, veins and voids of pisoliths. By contrast, hydromorphic dispersion in goethite-rich concentric pisoliths formed in the lacustrine clays in the centre of palaeochannel is restricted to tens of metres (e.g., Garden Well gold deposit).

There have been several stages of Au mobilisation, although the timing is unclear; the association with pedogenic carbonates, siliceous hardpan and alunite in Quaternary sediments, however, indicate that Au mobilisation is still active. Ultimately, more of such studies are needed to identify regolith materials and minerals that act as deep geochemical sensors and to provide exploration sampling media in areas of deep cover.

## Structural controls on the formation of asbestos in the Great Serpentine Belt

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The Great Serpentinite Belt (GSB) of NSW comprises a dismembered ophiolite sequence along the Peel Fault System (PFS). Earlier investigations of the formation of asbestos in the GSB, and the Thetford Mines in Quebec, resulted in the development of a kernel pattern serpentinization model driven by crystallization pressure into fractures of fresh peridotite. However, new data from the GSB suggest a major tectonic control, as discussed below.

A field study of the GSB determined four broad lithological groups associated with regional serpentinization, interpreted in order of development. They are: (1) a rectilinear framework of partially serpentinized harzburgite which under further serpentinization formed surrounded cores (kernels); (2) massive pseudomorphic serpentinite after harzburgite, preserved surrounding remnant harzburgite blocks or as large massive phacoids in shear zones; sheared serpentinite which occurs either as (3) phacoidal serpentinite within low strain zones grading to intensely deformed (4) schistose serpentinite with foliations sub-parallel to major fault planes and shear zones. Petrographic analysis showed that shear fabrics were associated with a continuous decrease in phacoid size from zones of lowest to highest strain. These shear fabrics are closely associated with increased chrysotile content, observed in both petrographic and XRD analysis. However, asbestiform chrysotile formed dominantly in angularly concentric and radiating vein arrays around kernel rims, or as tension gash arrays in phacoids.

A model is presented for the structural evolution of the GSB serpentinite during exhumation along the PFS. Harzburgite formed in the mantle (>15 km depth) and expanded during lithostatic decompression as it rose to higher crustal levels, forming a rectilinear array of fractures. Near the brittle-ductile transition, where meteoric water could ingress (~10-15 km), harzburgite hydrated along the fractures to form massive serpentinite by pseudomorphous replacement. With ongoing exhumation, strain was partitioned into shear zones forming phacoidal serpentinite, which evolved to schistose serpentinite with increasing strain, particularly along the bounding fault zones. Asbestos formed at this stage, associated with fracture opening, but mainly concentrated in the concentric rings of the kernels. Asbestos also occurs around phacoidal margins, but is commonly rotated into the bounding schistose serpentinite, indicating it developed during the earlier stages of deformation. Extensional forces aligned at high angles to the late NNW-trending foliations associated with sinistral strike-slip formation on the PFS, provided the conditions required for asbestiform chrysotile formation.

## Variation in leaf wax *n*-alkane properties across a precipitation and temperature gradient

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Leaf waxes are a major component of plant cuticle and are argued to function as an interface between the leaf and both the abiotic and biotic environment. Long chain *n*-alkanes are a component of leaf waxes and are hypothesised to be sensitive to climate. Temperature, humidity and water availability can influence the abundance and distribution of observed chain lengths in the modern environment (measured as average chain length; ACL). Analyses of the chemical composition of leaf waxes are a useful tool for quantifying and understanding past environments. The geological record preserves *n*-alkanes as constituents of leaf wax in fossil cuticle and as isolated molecules in sediment. In order to reconstruct past environmental change, an understanding of modern relationships between *n*-alkanes and climate is needed.

For this study we measured abundance, ACL and carbon preference index (CPI) of *n*-alkanes (*n*-C<sub>25</sub> to *n*-C<sub>35</sub>) from the leaves of the widely distributed evergreen species *Melaleuca quinquenervia*. Leaves were sampled from individual trees at field sites (n=25) along a precipitation and temperature gradient in the south-east coast and Cape York regions of Queensland. We chose to study *M. quinquenervia* in the modern environment because of its potential importance to paleoclimate reconstructions. Excellent preservation of sub-fossil leaves of this species exists in the Holocene lake sediments of Swallow Lagoon on North Stradbroke Island, Queensland. The sediments also have excellent potential for molecular preservation of *n*-alkanes.

The three *n*-alkane properties measured display strong, statistically significant ( $p<0.05$ ) negative correlations with combined winter and spring precipitation and statistically significant positive correlations against average winter and spring daily temperature. These results suggest a response in leaf wax production to seasonal aridity and temperature. They demonstrate that in dry and warm environments, *n*-alkanes are more abundant on leaf surfaces of *M. quinquenervia*. The results also indicate that longer chain length distributions with a higher degree of odd *n*-alkanes are produced in warmer and more arid environments. It can be inferred that water stress is driving an increase in leaf wax production to limit water loss, and higher temperatures are driving the production of longer and more odd *n*-alkane chain length distributions. Quantified records of Holocene climate in Australia are rare. The relationships derived from this study along with excellent sedimentary records from south-east Queensland have the potential to facilitate a better understanding of climate during this time.

## Quantifying lake hydrological and isotopic responses to climate change: A coupled hydrologic-isotopic mass balance model applied to two Australian maar lakes.

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A hydrologic-isotopic mass balance model was developed and applied to Lakes Bullen Merri and Gnotuk in the Newer Volcanic Province, Australia to investigate the influence of basin morphometry upon a lake's hydrological and isotopic response to climate change. Model calibrations were successful during a period of minimal water level change (~3 m) from 1965 to 2001; however no calibration was able to simulate an extreme lake water level change of ~15 m from 1889 to 2006. This is interpreted to reflect that catchment flow to the lake is not proportional to catchment area, suggesting an additional influence from groundwater, and demonstrating the need for long-term lake monitoring to document a range of lake conditions. The model broadly captures the trends observed in lake  $^{18}\text{O}$  and  $\text{D}$ , based upon a sparse monitoring dataset from 2006 to 2015. Both observed and modelled values indicate opposing trends in  $^{18}\text{O}$  and  $\text{D}$ , which implies lake water re-equilibration to past climate change. Experiments were carried out to explore the influence of lake morphology on both the timing and extent of isotopic responses to changes in hydroclimate. Following a shift in precipitation, lake water isotope ratios underwent transient excursions opposite in sign to the change in lake volume, before returning to an equilibrium value. Lakes with shallower basin slopes exhibited more rapid excursions with a lower magnitude. Lakes with longer residence times had longer and more subdued isotopic excursions. Applying a 1400 year hypothetical climate, with both El Niño Southern Oscillation (ENSO) type cycles and stepped hydroclimate shifts to Lake Gnotuk suggested that on the shallow slopes at lower lake levels, the seasonal isotopic cycle would obscure both ENSO cycles and hydroclimate shifts; whereas with higher lake levels and steeper basin slopes, the excursions following hydroclimate change may become identifiable. These results offer important insights into the selection and interpretation of lake isotope records as palaeoclimate tracers.

## Distribution, petrology, geochemistry and geochronology of carbonate assemblages at the Olympic Dam deposit

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The supergiant Olympic Dam (OD) Cu-U-Au-Ag deposit in South Australia is the type example of the iron-oxide copper-gold (IOCG) family. Hosted within heterogeneous breccia zones developed within 1.593 Ga Roxby Downs Granite (RDG) the deposit contains a volumetrically important and mineralogically diverse component of carbonates. Carbonates are almost always associated with ore minerals (e.g., Cu-Fe-sulfides, uraninite, coffinite, brannerite), implying a genetic relationship. A study of the gangue carbonates may therefore help improve our understanding of ore genesis at OD, yet there is very little published data. Most earlier workers favoured a broadly single-stage genetic model, with deposition of metals (and gangue minerals, including carbonates) in the same magmatic-hydrothermal cycle at ~1.59 Ga. In contrast, recent radiometric dating indicates that mineralization and gangue minerals formed episodically over a long period, requiring a re-evaluation of observed parageneses, mineral ages, depositional mechanisms and sources of metals and other components (e.g., carbon).

This study provides the first detailed and comprehensive petrographic, geochemical, and geochronological study of OD carbonates. The study is based on a large set of samples representative of the entire deposit and includes samples from lithologies for which very limited or no drillcore was available for the studies carried out earlier.

Carbonates are observed in all lithologies present at OD: weakly to strongly brecciated RDG, mafic-ultramafic rocks, felsic volcanics and clastic and carbonate sediments. Carbonates (Ca-Fe-Mg-Mn) occur as matrix in breccia, conglomerates and sediment, as breccia clasts, in veins crosscutting ore-rich breccia and other rock types, in amygdales and oolites, and in the form of massive laminated carbonate. Siderite and siderite-rhodochrosite-magnesite solid solution are by far the most common carbonate types, while calcite, dolomite-ankerite solid solution and REE-fluorocarbonates are locally abundant. Individual carbonate grains typically show some form of compositional zoning and replacement textures are common.

Strong textural evidence for the multistage nature of OD carbonates is supported by radiometric dating (Rb-Sr, Sm-Nd, Pb-Pb, and Lu-Hf) of carbonates and other minerals which indicates carbonate formation in at least 3 stages (~1.59-1.55 Ga, ~0.8 Ga, ~0.6-0.5 Ga), possibly more. Sr-Nd isotope systematics in carbonates are consistent with carbonate- and ore-bearing fluids being derived in large part from the host 1.593 Ga RDG and associated polygenetic breccia.

The stable isotope (C-O) data overlap the fields of several major C reservoirs (magmatic, sedimentary) suggestive of mixed fluid sources possibly including recycling of older carbonate for which there is abundant textural evidence.

The present work has helped to place diverse gangue carbonates and associated minerals within an emerging chronology for this multistage deposit. Carbonates appear to have formed at nearly every stage of the host deposit's evolution. The carbonates formed initially with the texturally earliest hydrothermal magnetite and apatite (~1.59-1.55 Ga) soon after emplacement of the RDG, followed by further periods at ~1.4-1.1 Ga (REE-fluorocarbonates), ~0.8 Ga, and ~0.5 Ga. Thus, deposition of carbonates at OD spans a period of more than 1 Ga. This chronology suggests that carbonate deposition and other aspects of the OD deposit were related to major tectonic-magmatic events.

## Inception and evolution of the Izu-Bonin-Mariana arc: results from IODP Expedition 351

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The Izu-Bonin-Mariana (IBM) arc has been regarded as an archetypal intra-oceanic arc. Its history is fairly well understood after a decade of marine and submarine studies involving in particular, deep-sea scientific drilling. Our understanding is that about 50 million years ago, either through spontaneous or induced subduction initiation, a relatively brief (a few million years) outpouring of basaltic lavas sourced from highly refractory mantle (so-called forearc basalts; FAB) marked the earliest magmatic expression of the arc. This was followed by rift-sourced boninitic magmatism before a chain of stratovolcanoes (Kyushu-Palau Ridge; KPR) developed that were dominated by low-alkali tholeiitic lavas. Backarc spreading in the Parece Vela and Shikoku basins around 25-20 Ma ago) split the active arc leading to cessation of magmatism on the KPR. Expedition 351 in mid-2014 recovered ~1600m of volcaniclastic-rich sediments and 150m of the underlying basaltic basement, in 4700m of water in the Amami-Sankaku Basin (ASB) adjacent to the eastern flank of the northern KPR. To the west of the ASB are a series of east-west-striking Mesozoic-early Tertiary arcs (Amami Plateau, Daito Ridge, Oki-Daito Ridge) that must have abutted the earliest development of the IBM arc. The primary aims of the Expedition were to determine the nature of the magmatism accompanying the earliest development of the IBM arc, the geochemical evolution of the arc through study of the volcaniclastics, determine if possible the mechanism (spontaneous vs induced) of subduction initiation, and infer the nature of the mantle sources involved from subduction inception onwards. All of these primary aims were achieved. The basement at Site U1438 comprises sheet flows of tholeiitic basalt derived from mantle sources that are more refractory than those tapped below mid-ocean ridges and most backarc basins. Olivine, spinel, and notably clinopyroxene dominate the sparse phenocryst assemblage. Muted trace element evidence exists of a subduction zone signature in terms of lithophile versus high field strength element abundances in these flows. The lavas are equivalent to the FAB recovered by dredging and drilling in the current forearc trench wall of the IBM arc. There is no evidence of uplift, crustal thickening, or shedding of sediment from the Mesozoic-early Tertiary arcs into the intervening basins. Given the evidence for an extensional environment of emplacement of the earliest IBM basement lavas, together with the extensive development of these magma types across- (~400km) and along-strike (1500km), the setting of the earliest development of the IBM arc is consistent with a spontaneous mode of subduction initiation. Extant subduction inception models are nevertheless over-simplified given the process must be strongly three-dimensional. For the IBM arc for example, northward propagation from a subduction zone on the southern boundary of the proto-Philippine Sea plate is plausible. Juxtaposition of old, dense Pacific plate lithosphere against the relatively buoyant lithosphere of the Mesozoic-Lower Tertiary arcs accompanying a change in regional plate motions could have been critical.

## A re-evaluation of the Kumta Suture in southwest India and its extension into Madagascar

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It has long been recognised that Madagascar was contiguous with India until the Late Cretaceous, however the timing and nature of the amalgamation of these two regions is still highly contentious. It has been suggested that Madagascar was contiguous with India by the latest Neoproterozoic to Cambrian, forming the Malagasy Orogeny [1]. Other models suggest a much earlier connection; that the Antongil Domain in Madagascar and the Western Dharwar Craton in India shared a common tectonic evolution history during the Paleo/Mesoarchean [2].

The geology of west peninsular India is poorly constrained, with limited information available from survey maps and published data. Currently available age data is insufficient to precisely correlate the southwest of India with eastern Madagascar. Despite this, it has recently been suggested that a newly defined, west-dipping, 15 km wide suture zone (the so-called Kumta Suture) separates a block centred on southern Goa, northwest Karnataka (the Karwar Block) from the Archean Dharwar Craton, and which forms a continuation of the Betsimisaraka Suture of eastern Madagascar [3]. It is suggested that this suture represents ocean closure during the amalgamation of Rodinia and occurred at c. 1380 Ma in the north; progressing toward the south at c. 750 Ma [3]. The implication that this subduction zone was active for an unlikely period of at least 630 million years has motivated us to re-evaluate the presence of the Kumta Suture; and its extension into Madagascar. Here we present preliminary U-Pb zircon data from magmatic and metasedimentary samples and structural field data from west peninsular India to further constrain the geology and timing of crustal formation and depositional age/provenance in this area. We address the Kumta Suture hypothesis and examine purported links between the Karwar Block/Kumta region and Madagascar.

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## Ordovician-Late Silurian geodynamics of north Queensland

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Palaeozoic continental growth and accretionary tectonism along the eastern margin of Gondwana is characterised by the inversion of back-arc basins and accretion of the magmatic arc terranes and micro-continental ribbons. Following the Delamerian Orogeny, roll-back of a west-dipping subduction system in the Early Ordovician lead to extension of the continental crust in the overriding plate along the eastern margin of Gondwana (Fergusson et al., 2007). In north Queensland this resulted in the separation of two micro-continental ribbons from the Australian continent analogous with the Lord Howe Rise. The two micro-continental ribbons represented by the basement rocks of the Carboniferous Hodgkinson Province and the Barnard Province comprise deformed Delamerian basement blocks that were subsequently stranded in an extended oceanic back arc region (e.g., Donaldsons Well Volcanic Member - Graveyard Creek Province), and deposition of the extensive turbidite successions of the Seventy Mile Range (Charters Tower Province) on a passive margin, the Judea Formation (Graveyard Creek Formation) onto an oceanic substrate, and the Pelican Range Formation and Wairuna Formation in the Camels Creek Province. The Lucky Springs Arc developed at ca. 455 Ma above a retreating east-dipping subduction zone that consumed the oceanic back-arc region separating the eastern margin of Gondwana from continental ribbon (basement to the Hodgkinson Province).

Ordovician back arc inversion was accommodated by initiation and subsequent retreat of an east-dipping subduction zone beneath the Hodgkinson Province basement ribbon and west-dipping subduction between the Barnard and Hodgkinson Province. Development of the Lucky Springs Island Arc at ca 455 Ma (Henderson et al., 2011) occurred at the edge of the Hodgkinson Province. The remnants of this continental arc and associated back-arc region are preserved as the Everetts Creek Volcanics and Carriers Well Formation in the Broken River Province (Vos et al., 2007). These rocks were entrained between the Gondwana and the re-accretion of the Hodgkinson Province basement ribbon at ca. 450-440 Ma. Tectonic melange (Henderson et al., 2011), imbricated turbidites (Judea Formation) and oceanic substrate (Donaldsons Well Volcanics), and the Wairuna Formation represent the remnants of a suture zone. Collision between the Barnard Province and the Hodgkinson Province was accommodated along the Russell Mulgrave Fault Zone, which we interpret as a suture zone between these two micro-continental ribbons. To the south, arc-related rocks of the Fork Lagoon Beds are also likely to record the accretion of an Ordovician arc onto the margin of the Anakie Inlier during ca. 450-440 Ma crustal shortening (Fergusson et al. 2007b, Wood 2007). To the north, the suture zone between the Hodgkinson and the Etheridge provinces is preserved in Ordovician Mulgrave Formation (turbidites and intercalated basaltic rocks) which characterised by a series of fault bounded slivers against the Palmerville Fault Zone. Linear and curvilinear trending positive magnetic and gravity anomalies can be interpreted to correspond with the suture zone between the eastern margin of Gondwana and the Hodgkinson continental ribbon from regional potential-field data and suggests that the region forms a Late Silurian to early Devonian oroclinal structure.

## Iron, Sulphur, Redox and Remanence: Petrophysical variability and geophysical insights into the Cloncurry District mineral system.

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The Uncover Cloncurry project was initiated in order to examine petrophysics, mineralogy, plus structural and chemical controls of approximately 20 deposits/prospects, including: iron oxide copper-gold (IOCG), iron sulphide copper-gold (ISCG), sedex, structurally controlled hydrothermal, and skarn styles of mineralisation. The aim of the project is to provide petrophysical, geochemical and geophysical insights that will assist future exploration, under cover, on the fringes of the Mount Isa Inlier. Part of the project, discussed here, is focussed on assessing the deposits / prospect petrophysics (i.e., variability in density, magnetic susceptibility and remanent magnetisation). The results are used to assess the mineral system as a whole and provide benchmarks for how particular styles of mineralisation might be targeted geophysically beneath significant cover. We assess the results in terms of alteration paragenesis and examine relationships between mantle fluids, redox state, geophysical expression and structural localisation.

Density ( ), magnetic susceptibility (K) and remanent magnetisation (J) measurements were made using a Metler Toledo MS204TS analytical scale, an Agico MFK1 kappabridge magnetometer and a CSIRO custom-made 2-axis flux gate spinner magnetometer respectively. The resultant data were subdivided into host rocks and ore zones based on their density (ore zone defined as >3 g/cc) and the ore zone petrophysics were plotted for all 20 deposits sampled. The results show a clear demarcation between the different types of deposits: Mt-rich IOCGs (e.g., Osborne, Starra), have high susceptibility but low remanence; Po-rich (ISCGs; e.g., Cormorant, Canteen) have high remanence but relatively low susceptibility; relatively oxidised IOCGs (e.g., Swan, Ernest Henry) tend to display mixed susceptibility values (reflecting magnetite and hematite content) and low remanence; Fe poor mineralisation styles (e.g., structurally controlled, skarn) generally have low susceptibility and their relative remanence values are dependent on their redox state, and or the grainsize of the magnetic carrier with higher remanence corresponding to Po-rich or fine-grained magnetite mineralogies.

The subdivisions were used as a basis for mapping petrophysical properties against the structural framework of the Cloncurry district. The mapping revealed a close spatial relationship between different types of mineralisation, and different structures. Po-rich "ISCG"-type mineralisation showed a close spatial relationship to the Cloncurry Fault Zone, a 1<sup>st</sup> order structure that underwent ductile deformation and reactivation up to about D<sub>4</sub> and sinistral strike-slip thereafter. Several of these Po-rich prospects (e.g., Canteen, Artemis) occur in close proximity to each other, and also Au-rich IOCGs (e.g., Eloise) suggesting a common basement structure may have been important in their metallogenesis. Many of the Mt-rich IOCG deposits (e.g., Starra, SWAN) have at least two main structural controls, one being the localisation of magnetite usually in relatively early, second order shear zones (e.g., the Starra-Selwyn Shear zone), and the other being third order NE-oriented cross-cutting ductile-brittle shears/ faults which are commonly cited as important pathways for Au and Cu-rich fluids at ca 1530 Ma. Most of the Fe-poor styles of mineralisation (e.g., Cameron River, Kalman, Trekalano) have a close spatial relationship with 1<sup>st</sup> order N-S brittle faults (e.g., the Pilgrim Fault) and third order NE-striking brittle faults.

## Quantifying structural control on ore deposition using anisotropy of magnetic susceptibility (AMS): Case studies from the Cloncurry IOCG/ Sedex province.

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The aim of the Uncover Cloncurry project is to provide petrophysical, geochemical and geophysical insights that will assist future exploration, under cover, on the fringes of the Mount Isa Inlier. Part of the project, discussed here, is focussed on the interpretation of anisotropy of magnetic susceptibility (AMS) data and the insights they provide into the tectonothermal history of the deposits, which can be related to the broader history of the province, in order to understand the relative timing of deformation and mineralisation at each deposit. AMS is a measure of the anisotropy of magnetic grains within a rock. Anisotropy data is presented as three perpendicular vectors: K1 (long-axis), K2, and K3 which define an ellipsoid that represents the average grain shape and orientation of magnetite (or pyrrhotite) within the rock. Rocks which have a strong alignment of the long axes of magnetite and / or pyrrhotite grains will have a strong anisotropy, which is defined as P (K1/K3). These rocks with high P may be lineation-dominant (prolate), as defined by L (K1/K2), or foliation dominant (oblate), as defined by F (K2/K3). The shortening direction can generally be inferred to be parallel to K3 (in strike at least).

The results of these studies are excellent, because significant anisotropy is present in almost all of the >20 deposits and the data are generally very well clustered, thus providing statistically robust results. In general, pre-Isan (e.g., skarn, sedex) and smaller epigenetic deposits produced very similar AMS results, with K1 generally oriented sub-vertical east or west, K2 oriented sub-horizontal north-south (or with both K1 and K2 sitting within a N-S foliation) and K3 oriented sub-horizontal (E-W). These orientations are consistent with the ca 1590 Ma D<sub>2</sub> deformation event which is the major E-W shortening event in the Mount Isa Inlier. By inference then this group of deposits have not seen any significant ductile deformation post-1590 Ma.

The majority of the larger deposits, particularly the IOCGs (e.g., Ernest Henry, Monakoff, Osborne, Kulthor, Starra and Swan), produced very different results, in most cases with K3 corresponding to NW-SE orientations ( $\pm 15^\circ$ ). These shortening directions are consistent with the D<sub>4</sub> event at ca 1530 Ma, which is generally thought to be the main Cu-Au mineralising event in the Cloncurry district. In many cases the AMS ellipsoid can be related to mapped structures at the deposit scale. For example, at Ernest Henry K1 and K2 define the NE-SW foliation mapped in the hanging and foot-wall shears, which form a jog between two N-S shear zones. K1 plunges moderately south, marking the intersection between hanging-wall shear and the N-S shears, and hence the movement vector.

In conclusion, the results suggest that: 1. Late (e.g., 1530 Ma) ductile deformation is critical precursor to the formation of medium to large Cu-Au mineral deposits and 2. SE-NW ( $\pm 15^\circ$ ) shortening directions appear to be favourable for mineralisation. The results are consistent with results from numerical deformation and

## **International Ocean Discovery Program (IODP): The Latest Incarnation of Almost Five Decades of Scientific Ocean Drilling Excellence**

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IODP (2013-2023) represents the latest phase of the longest running, most successful Earth sciences program in history. IODP builds on the Deep-Sea Drilling Project (1968-1983), Ocean Drilling Program (1983-2003) and Integrated Ocean Drilling Program (2003-2013). This phase is a collaboration, in which member countries (currently 26) bring diverse drilling/coring/sampling capabilities to explore Earth system evolution through geologic time. The United States supplies IODP's flagship – the leased commercial drillship *JOIDES Resolution*. The “JR”, as she is known by thousands of scientists and students who have sailed aboard her on more than 100 expeditions, has been serving the scientific drilling community since 1984. Upcoming JR expeditions include initial assessment of the Sumatra seismogenic zone, retrieving the preserved record of the Western Pacific Warm Pool, drilling into the Mariana convergent margin, a two-expedition continuation of IODP's campaign to understand South China Sea history, deciphering Cretaceous climate and tectonic history off southwestern Australia, and what is likely to be a long-term effort to assess plate interactions along eastern New Zealand's Hikurangi subduction margin. Recent deliberations have defined a long-term JR track, which will take her from the Indian Ocean/SW Pacific across the Southern Ocean and into the South Atlantic by ~2019. She will then operate in the North and South Atlantic and adjacent seas for several years. To address deep objectives within sedimented continental margins and in the crust, Japan contributes the riser-equipped *Chikyu*. Finally, the European Consortium for Ocean Research Drilling (ECORD) provides “mission-specific platforms” (MSPs) to address targets unsuitable for the other platforms, e.g., those in shallow water, like reefs, and in ice-covered high latitudes.

IODP is motivated by competitively reviewed proposals from the international community. These proposals respond to a decadal Science Plan, “Illuminating Earth's Past, Present and Future” (see [iodp.org](http://iodp.org)), developed in response to discussions among the world's best Earth scientists. This Plan encompasses three major themes: Biosphere Frontiers (“deep life”), Earth Connections (climate, geohazards), and Earth in Motion (planetary dynamics), in which are embedded 14 process-based challenges. Education and outreach are also fundamental to scientific ocean drilling; graduate students and educators sail on all IODP expeditions. Most proposals to use IODP's capabilities come from scientists in member countries and consortia, but proposals also include interested scientists from non-member countries. Funding to support drilling expeditions comes primarily from program partners, but IODP has recently implemented a “Complementary Project Proposal” (CPP) concept where outside entities (e.g., industrial concerns) can augment programmatic funding for viable science proposals. South China Sea JR expeditions are an example of a CPP.

IODP is interested in adding countries to its membership; conversations to do that are presently underway with Turkey, Morocco and South Africa. A robust international partnership is a key to the continuation of scientific ocean drilling. Plans for the next 5-year renewal phase are already underway.

## Triassic thrusting in the eastern Central Bowen Basin, Queensland

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Despite numerous detailed structural studies in the Bowen Basin and the adjacent New England Orogen, the evolution and kinematics of the Triassic Hunter-Bowen Orogeny and their impact on the eastern Bowen Basin are still not fully understood. Using gridded aeromagnetic data and 2D seismic reflection data, we conducted a structural analysis that characterises major faults in the eastern central part of the Bowen Basin, including the Miles, Burunga, Cockatoo, Taroom and Glebe Faults. The interpretation of gridded aeromagnetic data indicates that most of the faults are expressed by sharp lineaments in low to moderate amplitude anomalies related to intra-basin and basement rocks and developed in a narrow zone. The interpretation of seismic lines shows that faults are either east-dipping (Cockatoo, Miles and Taroom Faults) or west-dipping structures (Burunga and Glebe Faults). The dominant movement on all faults displaced the Early-Middle Triassic rocks of the Bowen Basin. Therefore, we propose that this main activity occurred during the last contractional phase of the Hunter-Bowen Orogeny in the early Late Triassic. There is some evidence of syn-depositional movement along the east-dipping structures such as the Cockatoo and Miles Faults. It indicates that these faults were older faults that have been reactivated during the last phase of the Hunter-Bowen Orogeny.

The geometry and kinematics of the east- and west-dipping faults seem to be different. The amount of displacement along the Cockatoo and Miles Faults increases from south to the north, showing the maximum fault throw of >800 m in the northern part of the Cockatoo Fault. In contrast, the Burunga and Glebe Faults are shallow décollements at depth, and their dip angle get steeper in Late Permian-Triassic units. Their hanging-wall anticlines are shown as doubly plunging propagation fault-related anticlines. We suggest that syncline geometry of the central Taroom Trough controlled the geometry of the west-dipping thrusts. Therefore, during Triassic contractional events, deformation in this syncline have been accompanied by basement décollements, dipping parallel to the trough slopes.

Our results reveal that thrusts in the eastern central Bowen Basin developed in a narrow zone with low amounts of shortening (~1%) in comparison to the structures in the eastern northern Bowen Basin which developed in a wider zone associated with higher amounts of shortening. This along-strike variation in strain could be due to the presence of crustal-scale thrusts in the northern part which produced the huge amounts of shortening. Alternatively, the distance of the eastern northern Bowen Basin to the Permian-Triassic subduction zone could be less than that of the eastern central part. Consequently, the intense deformation has developed further to the west in the north.

## **Variations in isochore thickness of the Karoo sediments in the Eastern Cape Province of South Africa, as deduced from gravity models**

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South Africa is the latest country in Africa exploring the idea of exploiting the field of shale gas, and the main Karoo Basin that covers up to 300, 000 km<sup>2</sup> and represents about 100 Ma of sedimentation spanning from 280 Ma to 180 Ma, is considered to be the most prospective area for shale gas exploration in South Africa, due to the presence of deeply buried and thermally mature black carbonaceous shales in the Ecca Group. Till date, the interconnectivity of dolerite intrusions at depth as well as the variation in isochore thicknesses within the Ecca sequence has not been established in order to ascertain if the thickness of the sediments across the area will support accumulation of hydrocarbons in areas that host source rock potential for hydrocarbon generation. In this study, we investigate the interconnectivity of dolerite intrusions at depth and the variation in the isochore thickness of the Karoo sediments using existing borehole data, elevation data, density data, Moho depth, and gravity models. The gravity model result shows that dolerite intrusions which are more prominent in the area are interconnected at depth, which could possibly affect the quality of the shale resources and probably pose threat by increasing the risk of fracking the Karoo for shale gas exploration. The isochore thickness maps derived from the gravity models revealed that the Beaufort Group is the thickest of all the geologic succession that make up the Karoo Supergroup with maximum vertical thickness of about  $6380 \pm 305$  m, followed by the Ecca and Dwyka Groups with maximum isochore thicknesses of up to  $3215 \pm 160$  m and  $728 \pm 24$  m, respectively. The maximum depositional surface (elevation) above the sea level for the Dwyka, Ecca and Beaufort sediments are about 900 m, 500 m and 125 m, respectively whilst the depth below sea level are 11000 m, 10000 m and 8000 m, respectively. The correlation of the isochore thickness maps with the depositional surfaces shows that the sediments in the basement highs were subsided, deformed, eroded and deposited in the basement lows. The basement highs possibly served as the source(s) area for the sediments in the basement lows thus basement highs are characterised with thin sediment cover whilst the lows have thick sediment cover.

## **Magnetic investigation and 2½ D gravity profile modelling across the Beattie magnetic anomaly in the south-eastern Karoo Basin, South Africa**

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The southeastern Karoo Basin is considered to be one of the most prospective area for shale gas exploration in South Africa, with a potential gas reserves that range from about 32 - 485 trillion cubic feet (tcf) of technically recoverable shale gas resources. The basin has several igneous intrusions that could possibly affect the quality of the shale resources. An interesting magnetic anomaly, the Beattie magnetic anomaly (BMA) is seen on the magnetic map of South Africa crossing the basin in a northeast – southwest (NE-SW) direction. To date, the source of the magnetic anomaly (BMA) and interconnectivity of the igneous intrusions are not well understood despite some 30 years of research in the area. Therefore the environmental impact of fracking the Karoo for shale gas could not be assessed despite the fact that the igneous intrusions are groundwater localizers in the Karoo. In this study, we investigate the interconnectivity of the igneous intrusions and possible location of the source of the BMA using magnetic and gravity methods. The gravity model results showed that igneous intrusions which are more prominent in the area are interconnected at depth, which probably pose threat by increasing the risk of fracking the Karoo for shale gas exploration. The result of the magnetic investigation and modelling of fourteen gravity profiles that crosses the BMA in the study area reveals that the anomaly, which is part of the Beattie magnetic anomaly tends to divide into two anomalies and continue to trend in an NE-SW direction. The anomaly become stronger or broader with depth which could be an indication that the source(s) is deep, possibly a buried magnetic body in the basement. The average depth to the top of the shallow and deep magnetic sources was estimated to be approximately 0.6 km and 15 km, respectively.

**Keywords:** Beattie magnetic anomaly, igneous intrusions, magnetic sources, Karoo Basin.

## **A lower crust and mantle electrical resistivity model of northern Queensland**

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Over the last fifty years a number of crustal-scale geomagnetic depth sounding (GDS) and magnetotelluric (MT) surveys have been carried out in northern Queensland to define various aspects of the deep structure of major tectonic provinces. Such surveys range from widely spaced (> 10 km between sites) magnetometer and long-period MT arrays from about 1970 to 2005, and more closely spaced (< 10 km between sites) broadband MT transects in the last ten years that generally have been coincident with deep seismic transects. Each survey has been interpreted independently and with differing objectives; our aim is to integrate data to form a much larger perspective to assess the regional crustal and upper mantle resistivity structures.

In our project, we have compiled all available deep imaging GDS and MT data through northern Queensland. For data older than about 1990, published data have been hand-digitized to produce consistent formats as for newer data. We assess the regional deep crustal resistivity in relation to major mineral systems and reassess the significance of the Carpentaria anomaly. Three types of modelling are being undertaken: a thin-sheet inversion of GDS data to yield constraints on regional crustal electrical conductance; 3D inversion of a combination of GDS and MT data; and detailed 2D MT inversions that provide more detail on the Moho to upper crustal connectivity.

In this poster we show progress to develop a new regional lower crust and mantle electrical resistivity model of northern Queensland, and in particular to investigate the link between resistivity anomalies and fluid pathways from mantle to upper crust.

## **Tuffs, dykes, xenoliths, glendonites, fossils and volcanoes; a review of the volcanology and sedimentation of the Mid Permian southern Sydney Basin.**

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This research focuses on the volcanology and sedimentation of the Mid Permian Southern Sydney Basin. A number of newly identified tuffs interspersed with the shallow marine sediments of the lower Shoalhaven Group are described. These tuffs appear to be laterally extensive, hence chronostratigraphic markers. Trace and body marine fossils are associated with some of these tuffs, including death assemblages, with at least one reworked tuff containing abundant augite crystals in pristine condition, travelling minimal distance before deposition and burial. The dykes along the coast south of Sydney have been reported as being generally Jurassic to Tertiary in age, however, a number of dykes which have intruded unconsolidated wet sediments, hence being penecontemporaneous with sedimentation, are described. These are associated with the proximal volcanoes responsible for the early latite eruptions of the Gerringong Volcanics (GV). At least one of these Permian dykes contains xenoliths, of which at least two different metasedimentary types have originated from underlying units, in addition to a rarer syenitic type from a lower crustal source beneath the Basin. Dropstones, probably transported from sea ice, of extrusive igneous material, both mafic and felsic, from eruptions prior to the first flows of the GV are also described. These dropstones, which sometimes exceed 1 metre in cross section, usually occur in horizons, likely due to short term climatic cycles, such as seasons. The numerous intercalated glendonite and concretion horizons which occur throughout the sedimentary units often exhibit very different morphologies, which may be associated with the local heat regime consequent to the volcanism. Glendonites at a number of localities are also associated with fossils, body and trace, where the fossil has acted as the catalyst for formation. Evidence suggests that the sources for these eruptions and intrusions were from volcanoes situated initially off the present day coastline to the south east, followed by at least one island volcano at Jervis Bay, with later development of a volcanic arc to the north east, also off the present day coastline, which was responsible for the extensive latite flows of the GV. An island composed predominantly of (Carboniferous?) granite probably existed in the south of the Basin. It is likely that these volcanoes were associated with subduction and stress related to foreland loading from the Currarong Orogen to the east, the south-easterly extension of the New England Orogen.

## Assessing the fidelity of marine microvertebrate oxygen isotope signatures and their potential palaeo-ecological and -climatic utility

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The biogenic apatite that constitutes conodont elements (feeding structures of extinct marine chordates) has become a preferred analytical target for Palaeozoic O-isotope studies investigating sea hydrology, surface temperature and palaeoenvironmental change. Despite their growing application in geochemical based palaeoenvironmental reconstructions, the paucity or absence of conodont fossils in certain facies necessitates greater flexibility in selection of geologically robust O-bearing analytical compounds. Microvertebrate teeth and scales offer a potential bioapatite substitute for conodonts from the mid Palaeozoic. Microvertebrate bioapatite is particularly advantageous given the groups fossil record extending from the Palaeozoic to the modern day and laboratory demonstration of apatite precipitation in isotopic equilibrium with the aquatic environment in extant species. Furthermore, microvertebrates have occupied fresh to fully marine environments since the mid-Palaeozoic, thus widening the scope in which bioapatite-based O-isotope studies can be undertaken, given conodont restriction to marine environments. However, significant tissue heterogeneity within vertebrates and differential susceptibility of these tissues to diagenetic alteration have been raised as significant barriers for their reliability in O-isotope studies.

Physically and thermally pristine microvertebrate and co-occurring conodont fossils from the Devonian and Carboniferous of the Lennard Shelf, Canning Basin, Western Australia, were analysed using bulk (gas isotope ratio mass spectrometry - GIRMS) and in-situ (secondary ion mass spectrometry - SIMS) methodologies, with the latter technique allowing investigation of specific tissues within vertebrate elements. The  $^{18}\text{O}_{\text{conodont}}$  results obtained are comparable to temporally and palaeolatitudinally equivalent areas in Western Europe and provide a baseline standard for comparison against  $^{18}\text{O}_{\text{microvertebrate}}$  values. Despite an absence of obvious diagenetic influences, bulk analysis of microvertebrate bioapatite (teeth and scales) yielded  $^{18}\text{O}$  values depleted by 2-4‰ relative to co-occurring conodonts. SIMS analysis of hypermineralised tissues in both scales and teeth produced  $^{18}\text{O}$  values comparable with those of associated conodonts, and reflective of realistic palaeo-sea-surface-temperatures. The susceptibility of porous fossil tissues to microbial activity, fluid interaction and introduction of mineral precipitates post-formation is demonstrated in microvertebrate dentine, which showed significant heterogeneity and consistent depletion of  $^{18}\text{O}$  despite the samples being thermally pristine. The hypermineralised tissues present in both teeth and scales appear resistant to many diagenetic processes and indicate potential for palaeoclimatic reconstructions and palaeoecological investigations where they can be specifically targeted. The development of robust palaeoclimatic records over ~450 Ma will provide vital context to the evolution of Earths biosphere and clearer understanding of likely future responses under a changing climate.

## A palaeoenvironmental proxy with more bite: assessing the applicability of O-isotopes in micromammal teeth

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The mineralised tissues of animals are formed from elements obtained from a combination of inherited parental material, ingested food and water as well as respired gases. In mature animals, locally ingested food and water are known to leave traceable O-isotopic signatures in the biogenic apatite of teeth and bones, allowing stable oxygen isotopes to be used as proxies for palaeoenvironmental conditions such as aridity and temperature. Since the development of precise analytical techniques to handle smaller biogenic apatite samples, the use of micro-mammal tooth geochemistry has been proposed for continental palaeoclimatic reconstructions. However, micro-mammal remains typically accumulate due to predation, and the preserved tissue will likely have undergone at least partial digestion. This raises questions regarding the integrity of isotopic signatures preserved in micro-mammalian remains from Cenozoic sequences.

In this study, the effects of digestion on rodent teeth were investigated to determine the predatory taphonomic disruption of geochemical signals in biogenic apatite. Incisors and molars from laboratory raised food mice were analysed by secondary ion mass spectrometry (SIMS) and gas isotope ratio mass spectrometry (GIRMS) to assess  $^{18}\text{O}$  signatures following ingestion and subsequent excretion or regurgitation by owls (barn owl and southern boobook), mammals (ghost bat and Tasmanian devil) and a reptile (perentie). Elemental abundances within teeth were also analysed via laser ablation inductively coupled mass spectrometry (LA-ICPMS). Disruption of primary geochemistry was compared against physical alteration using electron microscopy. The effect of digestion on elemental distributions and abundance varied significantly across and within tissue types. All analysed elements were affected by digestion (with the exception of Na and Si), but the amount of change was predator species dependant. Generally, the digestion of the teeth resulted in the enrichment of B, Mg, Cl, S, Cr, Ni, Zn, Mn and Cu, and the depletion of Ba and Sr, relative to undigested controls. Despite obvious physical and chemical alteration of ingested teeth across all predator species, O-isotope values appear relatively robust in co-occurring ingested teeth and were within the natural variation of undigested controls for all predator species except the barn owl (~0.7 ‰ depleted), and the perentie (~0.4 ‰ depleted). This was contrary to the physical examination, which showed greater damage in the samples digested by mammals. SIMS analysis showed particular depletion in  $^{18}\text{O}$  in the basal enamel of digested incisors, suggesting that less mature enamel is more susceptible to digestion-alteration. Dentine was also significantly depleted in  $^{18}\text{O}$  relative to enamel in incisors analysed by SIMS, which can be attributed to its less mineralised histology. Variations in  $^{18}\text{O}$  and trace elements are attributed to numerous factors including tooth histology, the species of the predator resulting in different gastric environments and digestion times, and the amount of exposure of the tooth to the gastric environment. Going forward, O-isotopes of micromammal teeth offer a potentially high-resolution palaeoenvironmental proxy and imply that a significant archive already exists in museum collections. However, precautions with respect to the predatory origin of the teeth and targeting of specific tissues are required for meaningful data interpretation.

## The answers are blowin' in the wind: ultra-distal airfall zircons, evidence of Cretaceous super-eruptions in eastern Gondwana

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The Siliceous Large Igneous Province that developed along the eastern margin of Gondwana during the Cretaceous is recognised as one of the most significant volcanic provinces of its kind preserved globally. As a result of regional uplift and erosion in the last ~100 Ma, evidence of the scale of volcanism is only truly realised by examining the extensive volcaniclastics preserved in once adjacent sedimentary basins along the eastern (Great Australian Basin - GAB) and southern margin (Otway, Bass and Gippsland Basins) of Australia as well as in the rifted fragments of Zealandia. Despite growing understanding of its extent and varied evidence of explosive eruptions (multi-kilometre scale calderas and thick pyroclastic deposits), this eastern Gondwanan volcanic province has previously been considered poorly prospective for preservation of super-eruptive events (Volcanic Explosivity Index > Magnitude 8). However, work presented here from new drillholes in Western Australia provides evidence for the contrary.

We report U-Pb ages and Hf-isotopic signatures of detrital zircons from drill core from the Madura Shelf, Western Australia. These zircons include a 106 Ma (Albian) component with unique eastern Australian age and Hf-isotope characteristics, which can be directly tied to the Siliceous Large Igneous Province, some 2300 km distant. Grain shape analysis demonstrates this young component experienced limited grain attrition, which contrasts with older, more abraded detrital components that are regionally present and temporally persistent. Zircon populations recovered from the new Western Australian cores have been compared with samples (i) derived directly and deposited relatively proximally (Winton and Mackunda Formations in the Great Australian Basin), and (ii) derived secondarily and deposited distally (Ceduna Delta) from the eastern volcanics. Palynology reveals the 106 Ma zircon population in the new Western Australian drillholes is syn-depositional, and adjacent sampling recognises it as stratigraphically isolated. Considering this, and the distinct lack of other significant Neoproterozoic and Phanerozoic zircon populations in the WA samples as compared to the fluvially-transported material in the GAB and Ceduna Delta, we interpret the young population to be volcanic airfall. Given the grain size and distance from source, such distal zircon emplacement requires previously undocumented 106 Ma super eruptions (>M8). An easterly source is consistent with the palaeogeographic position of Australia in the mid-Cretaceous, straddling polar latitudes. Furthermore, the 106 Ma zircons likely reflect southern hemisphere winter eruptions when tropospheric Polar-Easterly winds would have been favoured across the southeast of the Australian continent. These data foster important understanding of super-eruptions beyond the current Cenozoic bias.

## Utilisation of marine planation surfaces to constrain Cenozoic deformation, Western Australia

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Despite the relative isolation of the Australian continent from the active margins of the Indo-Australian Plate, and present-day deformation being difficult to resolve above background noise using GPS instrumentation, it is becoming increasingly apparent that significant deformation is occurring in Australia at different scales, rates and magnitudes due, in part, to (i) reactivation of existing structures and strain focussing in response to stress transfer to the plate interior, and (ii) dynamic topography (DT) in response to mantle heterogeneities over which Australia is rapidly migrating. Currently, there is a paucity of field data to better constrain: (i) spatio-temporal evolution of the Australian intra-plate stress field, (ii) dynamic topography models, (iii) the significance of structures in terms of seismic hazard and influence on basin evolution, and (iv) the degree of tectonic overprinting on palaeo-shoreline elevation data to facilitate better predictions of future sea-level response to changing climates.

This study investigated Cenozoic deformation of the onshore Eucla Basin, southern Australia through examination of the disturbance of fossil marine planation surfaces (in particular the basal contact of the Miocene Nullarbor Limestone Fm.) proposed as originally representing a quasi-horizontal benchmark. Digital elevation models (DEMs) of the present day erosional surface have recently been used to identify small-scale faulting and east-down DT tilting of the region. However, this surface is potentially (variably) overprinted by weathering processes and other landforms. Therefore, subsurface sedimentological benchmarks have been constrained from field and drillcore data and compared with DEM results. A total of 27 field sites (comprising caves, dolines, road cuts, cliffs, quarries etc.) were precision surveyed (+/- 15 cm AHD). Sedimentological data were also recorded and all horizons were examined for evidence of karstification, erosion or irregular depositional topography, to control for anomalous data. Supplementary data were sourced from online drilling records (63 sites –SA and WA Geological Surveys), published literature (24 sites) and logging archived drillcore (12 sites).

The results show a regional E-W elevation differential across the Miocene planation surface, which confirms that the basin has undergone a degree of long-wavelength tilting attributed to dynamic topographic uplift/rebound of southern Western Australia. Shorter wavelength deformation may indicate an isostatic adjustment from erosion of 1000 km<sup>3</sup> of limestone to form the Roe Plains. Surface faults scarps proposed from DEM analysis were confirmed by displacement of sub-surface horizons, indicating that the utilisation of digital elevation models to characterise surface fault scarps is a reliable approach in the Eucla Basin. Analyses conducted on the suite of onshore ~N-S trending faults suggest that they likely developed due to reverse reactivation under an E-W orientated neotectonic compressional regime with inheritance likely responsible for anomalously low 'vertical displacement:scarp length' fault ratios. Fault displacements of up to ~2 m/Ma on the Miocene surfaces and perhaps as much as ~5 m/Ma on younger Pliocene surfaces suggest fault-related elevation changes are significant at a local level (tens of km's). Stress field heterogeneity does not appear to have occurred across the basin, despite the existence of older continental-scale structures at depth (e.g. Lasseter Shear Zone or Mundrabilla Fault).

## **Does a first year field trip attract students to an earth sciences major?**

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Field work as a form of experiential learning is highly valued by geosciences academics. It provides an “unparalleled opportunity to study the real world” and allows students to be able to “better visualise the results of modelling outcomes through ground-truthing....”. In most undergraduate degree programs some amount of field work is compulsory. This situation has persisted despite the increasing logistical and financial complexities.

While the perceived benefit of field work is widely espoused, what is less clear is the utility of field trips in attracting first year STEM students with uncommitted majors into earth sciences as a study area. In South Australia, with geology being taught in only 5 schools in 2014, awareness of the earth sciences as a study and career pathway is low. The Department of Earth Sciences sources the bulk of its 3<sup>rd</sup> year graduates from the general Bachelor of Science program (around 150-200 new enrolments per year). These students as first year commencers generally take a wide range of level 1 science, with geology being the fourth subject choice for about half of that group.

We have run first year field trips for decades. One trip had been an overnight camp until 2012, when budgetary constraints dictated it became a one day field trip. The trips cannot be compulsory, as they are held on weekends, but we strongly encourage students to participate. While we attract a significant number of the general BSc degree program students into earth sciences majors, we have never quantitatively examined the enrolment trends of students who participate in the field trip vs those who do not. We have also not investigated the effects of shifting from an overnight trip to a one day trip.

On average, students who attend the first year trip have final marks about 5-7% higher than students who do not. Additionally, around 40% of students who attend the first year trip go on to a major in earth sciences, while only around 15% of those who did not attend a first year trip go on to major. It is difficult to know the attitude of incoming students to geology as a pathway, but there is certainly a correlation between first year field trip attendance and selection of an earth science major.

## **Lesley Russell Blake on Macquarie Island and at the Western Front**

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Lesley Russell Blake (1890-1918) was born in Melbourne and died on the Somme. His parents both died while he was very young, so he grew up with his aunt in Queensland, and studied at Brisbane Technical College and the University of Sydney. He then started work as a geologist-surveyor with the Queensland Department of Mines around Gympie in about 1907. His exact geological qualifications are unclear.

Blake landed on Macquarie Island in 1911, with Douglas Mawson's Australasian Antarctic Expedition (AAE). Blake arrived on Macquarie Island with George Ainsworth, leader and meteorologist and Harold Hamilton, biologist; Charles Sandell and Arthur Sawyer, wireless operators, arrived later. The camp was at the base of Wireless Hill on the northern tip of the island. A group of New Zealand oilers had a settlement nearby. The deaths of Ninnis and Mertz and the survival of Mawson on a sledging trip in Antarctica obliged the Macquarie Island group to stay for a second year. With the ship *SY Aurora* delayed in picking them up, they began to run out of food. Wekas, rabbits, elephant seal, and breast of penguin were added to the diet. Clothing and boots needed continual repair. Communal life was not always easy: Ainsworth was seen as authoritarian, elitist and inflexible. Mawson had instructed that nothing was to interfere with Blake's geological work.

Blake's main Macquarie Island work was surveying, using sighting poles and a theodolite in atrocious weather. His map was surpassed only in the era of satellites. Blake wrote of a "beautifully polished surface" on a boulder, and of "well-defined striae" that he attributed to ice-sheet glaciations (impossible on oceanic crust). Faulting on a spreading plate boundary is the principal geological factor: sealers in 1815 felt 22 earthquakes in 6 weeks, and while Blake was on the island a 6m tsunami inundated the isthmus connecting Wireless Hill to the rest of the island. They left the island in December, 1913. Blake eventually returned to Queensland and resumed work with the Queensland Department of Mines as a field assistant around the Gympie goldfield.

Blake first tried to join the A.I.F. by walking 30 kilometres to a recruitment post, and was eventually accepted for service in August, 1915, in the 5<sup>th</sup> Field Artillery Brigade, A.I.F. He received the Military Cross in 1916 on the Somme, for surveying (the skill he used on Macquarie Island) the front line for artillery barrages. Blake and King George V spent 20 minutes discussing Blake's Polar Medal before Blake excused himself from the King's presence, pleading a dental appointment. He spent 6 months behind the lines as a staff officer in 1917, planning artillery operations, and was promoted to Captain in 1918. He was mortally wounded in 1918 on the Hindenberg Line on 2 October, 1918. His wounds were dressed by Charles Morton, a mining engineer friend. He died the following morning. He was 28, and his fiancée never married.

## Mineralogy and geochemical footprint of the Bulldog Shale, Eromanga Basin, Australia: a new way to explore under cover

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Given the decreasing rate of mineral deposit discovery in recent years, it stands to reason that almost all ore deposits exposed at the Earth's surface have been discovered. This therefore takes the exploration frontier into progressively more covered terrains where there are greater challenges, expenses and investment risks for mineral exploration. In the case of South Australia, approximately 80% of the state is covered by post-mineralisation aged sediments (called 'sedimentary cover'). These sediments can bury prospective basement rocks to depths of several thousands of meters. It is therefore becoming essential for mineral exploration to improve efficiency, and to utilise techniques and methods that minimise the risks of discovering new mineral deposits. This may be done by utilising the younger cover sediments that overlie the mineralised basement rocks.

The Eromanga Basin is a Mesozoic sedimentary basin spread over South Australia, Northern Territory, Queensland and New South Wales. An Early Cretaceous marine transgression resulted in deposition of the basin-wide Bulldog Shale during the Aptian-Albian. The Bulldog Shale is up to 340m thick, and is composed of reduced mudstone. The formation conformably overlies a major confined aquifer, the Cadna-Owie formation.

For this study, a series of 13 open file exploration drill holes through the Eromanga Basin overlying basement rocks of the Curnamona Province in the central southern part of the basin were selected. Selection was made based on the drill holes containing well preserved examples of the sedimentary cover, and being proximal to iron oxide-copper-gold-uranium (IOCG-U) targets and U-mineralisation in the northern Curnamona Province (e.g. Beverley and Four Mile).

Spectral mineralogical (HyLogger™) and multi-element geochemical data (handheld XRF, whole rock geochemistry) were collected on the drill holes.

The HyLogger™ results provide an assessment of the mineral composition of the drill holes and reveal changes in mineral composition largely due to different weathering stages or source rocks, and showed that subtle variations in clay minerals, feldspars, sulphate, chlorite and muscovite composition can be recognised within the Bulldog Shale. The geochemical data highlight variations in element concentrations with depth within the Bulldog Shale, particularly with respect to zones of increased concentration of economic elements (e.g. Cu, W, Fe, Mn, As, Bi, Pb and Zn). No consistent correlation between mineralogical and geochemical variations was identified across all the drill holes studied.

Recognition of geochemically interesting zones preserving higher concentration of economic elements within the Bulldog Shale that may be potentially related to buried IOCG-U mineralisation suggests that the Bulldog Shale may be a potential sampling media in exploration using cover sequence sediments. However, further investigation is required into understanding this geochemical signature and the processes by which elements may be dispersed within the cover and into the Bulldog Shale.

## **The geodynamic significance of the Gilmore fault zone, Lachlan orogen: structural characteristics, kinematic history and timing**

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We re-examine the complex structural and kinematic history of the Gilmore fault zone (GFZ), a geodynamically significant structural element in various models of the tectonic evolution of the Lachlan orogen (e.g. terrane accretion, accretionary orogen or oroclinal bending). New field observations, mapping, microstructural analysis and structural interpretation of regional geophysical data (magnetics) have been undertaken along a ~550 km traverse of the structural zone. Preliminary results suggest the GFZ comprises a complex network of interconnected faults partitioning strain and recording multiple-episodes of deformation with contrasting kinematics. Aeromagnetic data, field observations and petrographic analysis reveal kinematic variations along the strike of the GFZ. The Nymagee-Bobadah region contains remnants of sheared clasts displaying dextral strike slip displacement which correlates with dyke orientations in 1VD geophysical images. A transition from dextral to sinistral horizontal displacement also occurs along strike, with dextral transport last identified near Bobadah and sinistral-transpressional movement first identified 20km south west of Condobolin. In the Nymagee-Bobadah region petrographic analysis further reveals dip-slip shear of the matrix associated with vertical lineations within east dipping subvertical shear zones. Evidence for overprinting strike-slip (early) and dip-slip (later) are observed locally in sheared conglomerate formations about 20km north east of Wyalong. Further south, the Snowy mountains region comprises mylonite and gneissic grade structures and is consistent with sinistral strike slip and sinistral transpression in aeromagnetic data, field observations and petrography. Strain analysis of inferred deformed dykes in the vicinity of the GFZ suggest sinistral-displacement is < 20 km in southern NSW. Similarly sinistral S-C fabrics observed in moderately sheared granite near Barmedman indicate modest horizontal displacement. Samples have been collected for further quantifying the age (Ar-Ar geochronology) relations of the overprinting fabrics observed. On-going work seeks to clarify which structures comprise the GFZ and how these inform interpretation of crosscutting shallow and crustal-scale structures in the vicinity of the GFZ apparent in modelled geophysical datasets (Venkataramani, this volume). If the GFZ is the NNW-trending structure extending toward Cobar and previously dated at 410-405 Ma, then it is the last major structure and was probably associated with basin inversion, consistent with overprinting relations observed locally. In this interpretation, the earlier structures record transpressional and -extensional events more closely related to construction of the Lachlan orogen.

## **Permeability Enhancement in EGS Reservoirs – Experiences from the Australian Geothermal Industry**

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In 2000, the Australian geothermal industry commenced the first exploration activities for deep Geothermal Energy resources able to be exploited for electricity generation purposes. Since then most of the projects undertaken have focused on developing either Engineered or Enhanced Geothermal System (EGS) resources, with eight wells having been drilled to, or close to, reservoir depths. Seven of these well have had unique hydraulic stimulation operations performed in order to characterise and enhance permeability of the reservoir zone. The wells have tested conditions in three markedly different geological terrains located within South Australia.

This paper reviews the activities and results of drilling and stimulation at these three locations, namely; Geodynamics Limited's Habanero Project in the Cooper Basin, Petratherm Limited's Paralana Project in the northern Flinders Ranges and Green Rock Energy Limited's Olympic Dam Project on the Gawler Craton.

## Geometry and evolution of deformation bands and their impacts on uranium-rich fluid flow in sedimentary basins

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Deformation bands represent tabular high strain zones in otherwise low-strain sediments. They form as a result of compaction through sediment loading or high horizontal stresses in porous sedimentary rocks, generally in the early stages of diagenesis. During their early growth stages, deformation bands can act as conduits for vast volumes of fluid through a sedimentary sequence; subsequently they may baffle fluid flow leading to reservoir compartmentalization in their later stages of development. Formation mechanisms for these discrete structures include: granular flow via grain boundary sliding and grain rotation, cataclasis through grain crushing, dissolution and cementation, and phyllosilicate smearing in clay-rich rocks. Understanding the influence of deformation bands on fluid flow throughout their evolution may provide insight into reservoir compartmentalization and refine exploration strategies for sediment-hosted mineral deposits.

While deformation bands have been a significant factor when investigating petroleum reservoirs, their influence to mineral systems hosted within sedimentary rocks of the brittle upper crust has been understudied. This preliminary analysis of the deformation band characteristics and evolutionary processes represents the framework for future research into deformation bands in the Oligocene-Miocene sediments that host the Beverly uranium deposit adjacent to the Paralana Fault in the northern Flinders Ranges; and the Mesoproterozoic sediments of the Cariewerloo Basin, proximal to the Olympic Dam IOCG deposit, NE of Port Augusta. The interplay between evolving deformation band geometry and permeability, and mineralizing fluid flow may lead to significant heterogeneity in the distribution of mineralization. Understanding how these dynamic processes interact may lead to revised genetic models for sediment-hosted uranium deposits, and new tools for their exploration and recovery.

## Nuna: An Australian perspective

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The Earth is punctuated by relatively transient periods of continental lithospheric amalgamation to form supercontinents. The Nuna Supercontinent formed between ca 2000 and 1800 Ma and is one of the largest episodes of continental amalgamation in Earth's history. In most Nuna configurations Australia occupies a central and important component of the supercontinent. From an Australian perspective, Nuna amalgamation involved rapid accretion in which approximately 60% of the continent formed between ca 1870 Ma and 1800 Ma, and was terminated by the accretion of the West Australian Craton (micro-continent). This amalgamation involved episodic accretion of small crustal fragments, continental ribbons and continental arcs along several continental sutures that are imaged in continent-scale magnetic and gravity datasets and regional seismic reflection data. Major suture zones have been imaged in seismic reflection and potential field data, providing insights into major terrane boundaries. These sutures include the south-dipping Willowra Suture (Goleby et al., 2009) and Atuckera Fault, which separates the proto-North Australian Craton (NAC) and the Aileron Province; the west dipping Gidyea Suture zone separating the Mount Isa terrane and Numil Province to the east; the west-dipping Rowe Fossil Subduction Zone (Korsch et al., 2012) bounding the Numil terrane and the Etheridge Province; the east-dipping Kalinjala Mylonite Zone (KMZ), which formed during collision between the Archaean nucleus of the Gawler Craton and the ca 1850 Ma Donington Suite. The KMZ is truncated by a west-dipping suture, which separates the Donington Suite rocks from the Proterozoic terranes to the east; the east-dipping Halls Creek Fault Zone. The collision zone between the West Australian Craton (WAC) and the NAC is more difficult to delineate but is interpreted to lie north of the Rudell Complex.

Reconstruction of the sutures zones and associated geological provinces, as well as unravelling the Gawler Orocline provides a different view of the growth of the Australian continent during amalgamation. It appears that many of the terranes were ribbon micro-continents that were accreted rapidly, most likely as part of a larger accretionary orogenic system. Many of the ribbons may have been derived from the proto-NAC because they have similar radiogenic isotopic signatures. Australia is interpreted to be located proximal to Laurentia during Nuna formation. The internal ocean appears to have developed between Australia and Laurentia after ca 1800 Ma, only to be closed during Mesoproterozoic orogenesis.

The most recent palaeomagnetically constrained Nuna configuration shows Australia facing an external ocean located outboard of the WAC. Our reconstruction suggests that the internal structure of the Australian continent point towards the southern margin of the Australia continent facing an external ocean. This margin preserves approximately 200 million years of subduction dynamics and crustal reconfiguration. This is a major observation that is not incorporated in current Nuna configurations and needs readdressing.

## Tectonic switches during the Palaeo-Mesoproterozoic transition: implications for mineral systems

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Proterozoic orogenic systems are largely defined by protracted events at time scales of 10's to 100's million years and often imply a relatively consistent tectonic regime (ie. crustal shortening). This is somewhat different to modern tectonic systems where individual events occur over smaller time scales of several million years, and tectonic mode switches are common, especially at convergent margins. We would argue that differences are related to the resolution of geochronology data and difficulties in reading the rock record, especially in terranes that preserve mid crustal levels.

We detail geological observations, geochronology, and geophysical interpretations from the Gawler Craton, Curnamona Province, Mount Isa terrane, Georgetown Inlier and Mount Painter Inlier to illustrate rapid changes in tectonic regime at the Paleo-Mesoproterozoic boundary of eastern and southern Australia. We have been able to reconcile a more complex evolution because in some terranes the upper crust is preserved allowing analysis of geochronology data in the context of geological overprinting relationships. The results indicate geological events at comparable time-scales to modern Earth plate tectonics as well as tectonic mode switches. Our interpretations suggest that crustal extension was occurring in the Curnamona Province at ca 1615 Ma and a rapid tectonic switch to orogenesis occurred during the Wartakan Orogeny (Gawler Craton) and the Olarian Orogeny (Curnamona Province) (ca 1611-1592 Ma). This was followed by another switch to crustal extension, intense plume-related magmatic activity and crustal anatexis (ca 1595-1580 Ma), and uplift in the Gawler Craton as well as rapid clastic sedimentation in the Mount Painter Inlier. These sedimentary rocks were buried to mid crustal levels, shortened and then exhumed in ~5-10 million years during the Painter Orogeny. This event likely produced metamorphic core complexes in the Mount Wood Inlier. Shallow level magmatic rocks were then emplaced between ca 1575 Ma and 1552 Ma coincident with renewed metamorphism, which possibly correlated with the Kararan Orogeny of the northern Gawler Craton. In Broken Hill, this event is characterised by the inversion of crustal-scale extensional shear zones and large-scale sheath folding in the eastern Curnamona Province. Renewed extension is recorded by the exhumation of the mid-crustal rocks in the Georgetown Inlier, and associated volcanism and sedimentation. This is coincident with anatexis ca 1545 Ma in the Broken Hill Block. Shortening in the Mount Isa terrane occurred at ca 1545 Ma, where the terrane deformation is characterised by dominantly strike-slip tectonics during late Isan Orogeny.

The complex evolution is driven by complex interactions at two convergent plate margins, coupled with the plume related magmatism. Such complexity is generally unresolvable during the Proterozoic.

This complex evolution also overlaps with a significant period of mineral endowment on the Australian continent including the largest Fe-oxide Cu-Au belt in the Gawler Craton and Mount Isa; sediment hosted Zn-Ag mineralisation in Mount Isa. Interpretation of these systems have also been controversial and subject to significant debate and is not discussed in this abstract. Nevertheless on the modern Earth it has been demonstrated that tectonic mode switches enhance mineral endowment, especially for mineralisation along plate margins.

## Tectonic evolution of the Leichhardt River Fault Trough

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The Leichhardt River Fault Trough (LRFT) is located within the western Mt Isa Inlier of northwest Queensland. It is comprised of Proterozoic sedimentary and volcanic successions that formed during repeated cycles of rifting and thermal subsidence, and have undergone several basin inversion events. The region is well exposed but is also characterised by a spectacular aeromagnetic imagery, which highlights several structural features associated with the basin evolution of the Mount Isa Inlier. To better understand the deformation history and complex overprinting relationships that formed the LRFT, aeromagnetic, gravity, and radiometric data are coupled with geologic data, and are interpreted to produce a structural map of the region. This data is then used to constrain 2D forwards models of the gravity and magnetic data, to better understand the 3D geometry of the folds and half-grabens within the LRFT.

The LRFT is characterised by large, fault-bounded north-plunging anticlines, which fold the Leander Quartzite, Mount Guide Quartzites, Eastern Creek Volcanics and Lower Myally sub-group (1800-1750 Ma) and E-W trending half-graben (infilled with Whitworth quartzite and Lochness formation of the upper Myally sub-group) and Calvert and Isa superbasin sedimentary succession (1660-1650 Ma)). Understanding the relationship and timing of basin inversion events that formed the Leichhardt anticline, and extension which formed the series of E-W oriented half-grabens has implications for understanding the tectonic evolution of the North Australia Craton.

Our interpretation suggests the N-S trending Leichhardt anticline formed before the development of E-W oriented normal faults bounding the half graben, which are infilled with ca 1690-1640 Ma succession. The implication of this interpretation is that a major inversion event pre-dates the development of the ca 1710 Ma – 1690 Ma Calvert Superbasin, consistent with unconformity relationships in the Lawn Hill Platform. The implication of this interpretation is that the bulk of the crustal shortening within the LRFT pre-dates the Isan Orogeny (1620-1520 Ma). Consequently there is requirement to reassess the correlation of shortening events across the Mount Isa Inlier and the tectonic drivers for such a large inversion event.

## Geochemical evidence for an evolving tectonic setting in the northeastern Aileron Province, central Australia.

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The Arunta Region in central Australia preserves evidence of a 1.5 billion year polydepositional and polytectonic history. The region is subdivided into three provinces, each distinguished by distinct protolith ages and a complex stratigraphic and tectonic evolution. The Palaeoproterozoic Aileron Province comprises a supracrustal succession that has been subjected to regional high-thermal-gradient metamorphism, deformation, and multiple episodes of felsic and mafic magmatism between ca 1790 and 1690 Ma. New geochemical data for intrusive rocks from a 150 km east–west-trending sector in the northeastern Aileron Province have revealed evidence for an evolving tectonic setting from continental back arc to intraplate.

In the Jervois Range area, ca 1790–1745 Ma magmatism is characterised by emplacement of voluminous I-type calc-alkaline and high-K to shoshonitic granitoids. The calc-alkaline intrusive rocks are largely granodiorite in composition with minor tonalite, monzodiorite and quartz monzodiorite. These rocks are metaluminous to peraluminous, strongly leucocratic and only rarely contain biotite or hornblende. Locally they are distinguished by a high-Al, high-Sr, low-Ti geochemical signature and are interpreted to have been derived from the fractionation of arc-type mafic magmas represented in Jervois Range by tholeiitic to calc-alkaline (meta)mafic intrusive rocks with MORB-like to back-arc basin basalt affinities. In contrast, the high-K to shoshonitic group consists of metaluminous monzogranite and syenogranite that are biotite-bearing with locally occurring hornblende and allanite. They are light rare earth element (LREE) enriched but strongly depleted in Ba, Sr, Nb and Ti and are interpreted as derived from partial melting of modified arc-type mafic underplate. High-K calc-alkaline (meta)mafic intrusive rocks show similar chemical signatures and are thought to represent high-level crustally contaminated magmas. Volumetrically minor S-type muscovite-tourmaline±garnet-bearing monzogranites and associated pegmatites are the youngest intrusive rocks in the Jervois Range area and inferred to be the highly fractionated end products derived from partial melting of metasedimentary rocks at ca 1690 Ma.

Compared to the Jervois Range area, magmatism in the Mopunga Range area to the west, is dominated by I-type 1730–1710 Ma metaluminous biotite and/or hornblende monzogranites that intrude interlayered ca 1790 Ma felsic orthogneiss and minor pelitic migmatite. Compositions for the felsic igneous rocks are uniformly high-K to shoshonitic and field relationships indicate that the younger intrusive rocks were derived from large scale partial melting of the orthogneiss. Mafic rocks are uncommon in this area and generally show crustal signatures such as LREE-enrichment and depletion in Nb and Ta.

Calc-alkaline plutonism in Jervois Range between 1790–1745 Ma is typical of that observed in continental back-arcs and provides evidence for the presence of an active plate margin to the south or southeast at this time. The transition to dominantly high-K magmatism in Mopunga Range at ca 1730 Ma implies a setting that is more “intra-plate” than back arc, a finding that is reflected in regional studies which have shown that magmatism becomes less arc-like and progressively more within-plate in character with time.

## Timing and duration of the Palaeoproterozoic tectonothermal evolution of the northeastern Aileron Province, central Australia

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The Aileron Province at the southern margin of the North Australian Craton preserves a supracrustal succession that was subjected to regional high-thermal-gradient metamorphism, deformation, and episodes of bimodal magmatism during the Palaeoproterozoic. A 150 km east-west trending zone in the northeastern Aileron Province comprises major tectonic areas separated by shear and fault zones, including the Jervois Range area in the east and the Mopunga Range area in the west. Both areas record evidence for sediment deposition in a high-thermal-gradient environment, contemporaneous intrusion of bimodal igneous rocks, and metamorphism. In this submission, geochemical tools and petrographic observations are used to integrate zircon and monazite chronologic data with *P-T-D* histories constrained using pseudosections and structural data.

In the Jervois Range area, sediment was deposited in a back-arc basin active until after ca. 1790 Ma. Metapelitic schists from the Jervois Range area contain cordierite and andalusite porphyroblasts interpreted to have grown during prograde metamorphism at *T* between 550 and 650 °C and *P* between 0.15 and 0.3 GPa. A  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $1789 \pm 10$  Ma (2 ) for monazite included in the cordierite is statistically similar to U-Pb concordia zircon ages between ca. 1790 and 1780 recording emplacement of bimodal igneous rocks interpreted to have intruded the still-active basin and initiated high-thermal-gradient metamorphism. Monazite included in andalusite grown due to heat from the intrusive rocks records a  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $1770 \pm 6$  Ma (2 ), suggesting the initial period of high-thermal-gradient metamorphism lasted at least ca. 20 m.y. The extensive metamorphism and continuing igneous intrusion present in both tectonic areas resulted in crustal-scale thermal weakening, progressive regional deformation, and subsequent strain localisation in an extensional setting. Normal movement along major fault and shear zones led to an isothermal increase in *P* in the Jervois Range area to >0.4–0.5 GPa at ca. 1760–1750 Ma as indicated by  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of monazite grown during this progressive deformation. The cessation of regional deformation after ca. 1750 Ma resulted in cooling and decompression of the regional system between ca. 1730 and 1700 Ma as indicated by  $^{207}\text{Pb}/^{206}\text{Pb}$  ages of zircon grown during the crystallisation of undeformed granites in both areas.

In the Mopunga Range area, the ca. 1790–1780 Ma igneous–sedimentary package was metamorphosed to supersolidus conditions and preserves a network of former melt-bearing veins showing pathways from sites of melt generation to melt accumulation in felsic igneous plutons. The timing and duration of supersolidus metamorphism is being tested; however, granitic melt generated during migmatite formation in the Mopunga Range area is interpreted to have migrated to, and accumulated in plutons that crystallised between ca. 1730 and 1700 Ma.

Previous work has interpreted the Palaeoproterozoic tectonothermal history of the Aileron Province to comprise a series of discrete short-lived igneous, metamorphic, and deformational pulses. New data for the Jervois Range area suggests this part of the Aileron Province experienced a single prolonged counter-clockwise *P-T-t-D* evolution, with a period of metamorphism between ca 1790 and 1750 Ma followed by isostatic cooling to ca 1700 Ma.

## Phase equilibria modelling constraints on the $P$ - $T$ conditions of eclogitised granulite in the Bergen Arcs, Norway

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Exhumed deep crust is rare and exposures that preserve both protoliths and altered domains are limited around the world. Mesoproterozoic anorthositic granulites exposed on the island of Holsnøy, western Norway, preserve different stages of progressive deformation together with the corresponding metamorphism that record the conversion to Siluro-Ordovician eclogites during fluid infiltration. Five different stages of deformation can be identified: 1) brittle deformation resulting in the formation of fractures and generation of pseudotachylites in the granulite; 2) development of mesoscale shear zones associated with increased fluid–rock interaction; 3) large-scale replacement of granulite by hydrous eclogite with blocks of granulite sitting in an eclogitic ‘matrix’; 4) complete conversion of granulite to eclogite within large-scale shear zones; and 5) break up of completely eclogitised granulite by continued fluid influx, resulting in the formation of potassium-rich mineral assemblages.  $P$ - $T$  constraints derived from phase equilibria forward modelling document a burial and partial exhumation path with peak conditions around 21–22 kbar and 640–660 °C. Fluid infiltration began on the prograde path and continued throughout the recorded  $P$ - $T$  evolution. However, in places limited fluid availability on the prograde path resulted in an excellent preservation of prograde mineral assemblage, allowing the burial path to be well constrained.

## Coupling dynamic topography with Stratigraphic Forward Modelling: case study Springbok Sandstone

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Although the exploration of Surat Basin increased in the last decades, the relationship between syn-depositional tectonics and sedimentation is still poorly known. This work focuses on a virtual reconstruction of the Springbok Sandstone stratigraphy, deposited during the Late Jurassic within the Surat Basin (Queensland). Stratigraphic Forward Modelling (SFM) will help in the reconstruction of stratigraphy in the places away from wells and below seismic resolution. The formation is ascribed by the literature to an extensive fluvio-alluvial system, which is conformably overlaid by the alluvio-coastal system of Westbourne Formation, but it unconformably overlays the Walloon Coal Measures (WCM). The Springbok Sandstone shows a completely different location for its depocenter compared to the underlying WCM, which could in part be due to erosion. The actual causes for this shift in depocentre can be interpreted by understanding the landscape evolution and the corresponding sedimentary fill in response to tectonic development of the basin.

Rather than cratonic sag, recent work in the Surat Basin suggests its origin is the result of dynamic tectonic tilting related to subduction. Shifting depocenters and uplifted areas expressed by an internal-basin widespread unconformity, are effects of the interplay between dynamic topography and surface processes leading to the deposition of Springbok stratigraphic heterogeneity. SFM coupled with geodynamic forward modeling provides a parallel, realistic landscape evolution of an active tectonic setting through iterative processing. The SFM model was composed of background layers (i.e. paleotopography and substratum geology), forcing (i.e. climate and accommodation space), sediment sources and supply.

To constrain the sedimentary facies and their dispersal, FMI and core analysis show an overall fluvial environment characterised by the gradual change from amalgamated to less amalgamated channels. The lower amalgamated section is characterised by the presence of channels filled by 3-m-thick downstream migration barforms. The upper less amalgamated section displays 10-m-thick storey of fining-upward sequences culminating in mudstone with coal accumulation. In the NW side of the basin paleocurrent measurements for the lower section flow S-SE, whereas the upper section shows a radial pattern, highlighting the presence of more sinuous channels but still with a main direction towards S and E. Further south on the eastern margin of the basin, paleoflow is pointing directly eastward.

Advancements in the SFM resulted from the constructive loop process such as: (i) the new paleotopography honouring the main zones of accommodation across the basin, (ii) the choice of hydraulic and solid parameters considering a scaling relationship between drainage area, bankfull discharge and W/T ratio, (iii) the depocentral and marginal simulated stratigraphy recorded by the model has many similarities with static geological models proposed by companies, showing different grain-size trends in different areas across the basin, and (iv) positive comparison between synthetic and real gamma-ray wireline correlations as validation tool for forward modelling.

## Age of Metamorphism in the Kanmantoo Sediments at Reedy Creek, South Australia

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The 524-515 Ma Kanmantoo Group metasedimentary rocks at Reedy Creek, in the eastern Mt Lofty Ranges in South Australia, experienced high grade metamorphic conditions during the 515-490 Ma Delamerian Orogeny. This resulted in extensive partial melting in spatial proximity to the Reedy Creek Granodiorite and associated diorite intrusions. The bulk of the Kanmantoo sequence consist of metapsammitic lithologies that have utility for determining the *P-T* conditions experienced by the sequence. However, locally thin (10cm) discontinuous layers of Mg-rich metapelite, that probably comprised original mud layers, have recrystallised to form thermobarometrically sensitive mineral assemblages.

Calculated pressure–temperature pseudosections combined with mineral compositional data from a migmatitic orthopyroxene–cordierite–spinel–biotite–plagioclase–magnetite assemblage, located approximately 500 m from the boundary of the Reedy Creek Granodiorite gives *P-T* conditions of approximately 3kbar and 800 °C. Spinel has overgrown sillimanite, and adjacent to the orthopyroxene bearing rocks are coarse-grained blocky sillimanite pseudomorphs after andalusite, indicating the rocks had a low pressure prograde evolution. A second metapelitic sample located approximately 2.5 km from the contact gives *P-T* conditions of around 4 kbar and 700 °C. LA-ICP-MS U–Pb monazite geochronology from the metapelitic assemblages yields metamorphic ages of c. 499 Ma. Field relationships indicate that the high-thermal gradient metamorphism in part predates the intrusion of the presently exposed Reedy Creek Granodiorite, an interpretation supported by our monazite geochronology. Nonetheless, there is a clear increase in metamorphic grade toward the contact with magmatic rocks. We suggest the km-scale region of high-grade metamorphism records the accumulated thermal impact of an extended period of magma transfer through the crust, with the presently exposed granodiorite representing a comparatively late stage of the magma transfer history.

## Metamorphic controls on U–Th distribution in the crust

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Metamorphism involving partial melting is a fundamental process leading to the geochemical differentiation of Earth's crust. A primary expression of this process is the formation of granites that contain a component of crust within them, and the generation of granulite-facies metamorphic rocks that reflect the residuum left behind after extraction of granitic melts. It is known that granites are typically enriched in the heat producing elements (HPEs) K–Th–U, so it stands to reason that residual granulites are depleted in those elements [1-3].

However, there are cases where residual, deep crustal granulites retain high radiogenic heat production. These regional-scale examples from southern and eastern India, South Africa, Brazil, and Finland demonstrate that the deep/lower crust is not necessarily always deficient in radiogenic heat production. Moreover, studies – including experimental – show that Th is less compatible than U in melt [4, 5], with the important implication that if monazite (the chief Th reservoir in rocks) can be retained in the residuum, granulite-facies crust maybe characterised by high radiogenic heat production. Such a view is in direct contrast with the standard view of geochemical differentiation of the crust.

Given the natural examples of deep crust that have high radiogenic heat production, supported by Stepanov et al. [4] and Rudnick et al. [5], a set of scenarios should exist in which melting and melt loss leads to enrichment in HPE concentrations in the metamorphic residuum. These scenarios are logically more likely to occur in rocks such as metapelites and metapsammites that contain abundant fluid, monazite and bulk compositions that are conducive to abundant melt generation.

In this study, K–Th–U concentration data and phase equilibria modelling are used to monitor the changes in crustal heat production arising from progressive up-temperature metamorphism, including melt production and loss. The study is focussed on a single metasedimentary unit within the Reynolds Range, central Australia, that records metamorphism from subsolidus (greenschist) to suprasolidus (granulite) conditions, where preliminary data indicates that radiogenic heat production increases as a result of partial melting and melt loss. Monazite geochemistry shows an increase in Th concentration with increasing metamorphic grade, so it is likely that a compositional threshold exists whereby melt loss leads to HPE enrichment in the residuum, principally via Th-hosting solid solution in monazite. Enrichment of heat production concentration in the residuum arising from melt loss has profound consequences for the tectonic stability of metamorphosed crust, the geochemical organisation of the crust, and its thermal potential [6].

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## **Expedition 369 off southwest Australia: Cretaceous tectonic and climatic history of the Naturaliste Plateau and the Mentelle Basin**

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Expedition 369 planned for September 2017 will drill several holes on the Naturaliste Plateau and the adjacent Mentelle Basin off southwest Australia. The purpose of the expedition is twofold. First, the unique tectonic and paleoceanographic setting of this region offers an outstanding opportunity to investigate a range of scientific issues of global importance, especially rapid climate change during the onset of the Cretaceous hot greenhouse. Second, equally fascinating and poorly documented is the sedimentary, tectonic and geodynamic history of the region.

Fulfilling the primary purpose of the survey will be the sampling of the Cretaceous succession at different locations to allow generation of paleotemperature and biotic records that will provide a new perspective for the Cretaceous hot greenhouse world, including data on the austral manifestation of the Oceanic Anoxic Events (OAE). The high paleolatitude (60–62°S) location of the drill sites is especially important because high latitudes are more sensitive to climatic changes than mid- and low latitudes. Such enhanced sensitivity should increase the size of the climatic signal recorded in sediments and maximise the resolution of the data generated. In addition to records of the Cretaceous hot greenhouse interval, the target sites should reveal regional climatic effects of the mid-Eocene–early Oligocene opening of the Tasman gateway and the Miocene–Pliocene restriction of the Indonesian gateway. Both of these gateways have profound effects on global oceanography and climate, extending to the present day.

The second purpose of the expedition is to drill deep holes into rifted basins that formed on the boundary between Australia, India and Antarctica before these continents drifted apart in the Cretaceous. The Naturaliste Plateau is believed to be underpinned by the crystalline continental crust cut by Mesozoic rifts and covered by an extensive carapace of volcanic rocks. Between the Naturaliste Plateau and the Australian mainland lies the Mentelle Basin. Limited data from the basin suggests that it was formed during the Jurassic to Early Cretaceous; however, earlier Permian rifting may have occurred in its eastern part. The expedition aims to recover a sedimentary record containing information on different stages of the Gondwana breakup, including final separation of India from Australia. The breakup at the southwestern corner of Australia was associated with significant intrusive and extrusive magmatism. The Bunbury Basalt lava flows and multiple volcanic facies recognised in seismic data on and above the Valanginian unconformity suggest excessive volcanism at the time of the breakup. At two of the planned sites an attempt will be made to drill through breakup-related volcanics, which will help document magmatic events before, after and during the breakup. Better knowledge of the magmatic history will allow exploration of possible temporal and causal relationships between high levels of volcanic activity and the onset of Cretaceous greenhouse conditions in the region. Expedition 369 provides a unique opportunity to study how the Earth's climate and oceans responded to elevated levels of atmospheric CO<sub>2</sub> and the role of local tectonic events in the onset of anoxic conditions.

## Rare Earth Scientists: using outreach to attract new students

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Undergraduate degrees in the Earth Sciences have traditionally found it harder to attract students than traditional subjects like biology, chemistry, physics and mathematics. With little geoscience taught during secondary education, it is becoming increasingly important to attract students using outreach programs. The School of Earth, Atmosphere and Environment (SEAE) at Monash University has been developing a wide-reaching outreach program for this purpose. Our program includes both in-house and external teaching, the development of a rock lending library, professional development for high school teachers, tours and activities in our new Monash Earth Sciences Garden (MESG), social media posts and public events in conjunction with local and regional cultural and scientific organisations.

The in-house outreach program features one-hour AusVELS-compliant, hands-on lessons covering a variety of Earth science subjects. These are taught by postgraduate students in small interactive groups and utilise multimedia platforms like Google Earth, NASA EYES and YouTube alongside experimental work and microscope activities. Schools are offered the opportunity for Monash scientists to visit and teach their students about Earth Sciences in a similar manner to our in-house activities. In addition, we have developed a rock lending library that includes excellent-quality, hand-sized samples of the major rock types with a lesson plan to help schools teach the rock cycle. The lending library rocks have been sourced from throughout Victoria to encourage students to learn more about the land beneath their feet.

High school teachers often do not hold a degree in an Earth Science subject. AusVELS-compliant professional development courses are now being offered in conjunction with TESEP in order to give them the confidence to teach Earth science subjects.

The new MESG has been a pivotal force in our teaching approaches. The new teaching garden, which was built as an outdoor teaching laboratory for undergraduate students, is now a major focus of our outreach activities. We have developed a guided tour of the garden, a one-hour lesson plan on the geology of the rocks, and are in the process of developing a detailed website and app on the geology of the garden, an augmented reality app, and a series of ‘science snippet’ videos on the different rocks in the garden and their geological stories. The MESG is actively promoted on social media.

The SEAE and members of staff actively engage the public on social media platforms such as Twitter, Instagram and Facebook. These are extremely useful tools to disseminate the research activities of the school, including fieldwork, to a worldwide audience and generate interest in our courses.

Finally, researchers from the SEAE actively engage with the local and regional community by giving talks at cultural and special interest clubs; organising public events in regional areas; and offer interactive activities during Open Day, with a range of hands-on experiments.

Increasing public awareness of Earth science subjects is crucial during early secondary school education. Fostering an interest of these subjects early-on should lead to increased student numbers at the tertiary level of education.

## **Improving Geological Interpretation using Magnetic Source Maps**

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Interpretation of airborne magnetic survey data for the purpose of making better geological maps is usually undertaken using images based on Total Magnetic Intensity (TMI) or vertical gradient data derived from the TMI data.

It is possible, by using a standard automatic curve matching method based on the Naudy and Shi technique, to analyse profiles of the TMI to produce maps showing the position of the actual sources of the magnetic anomalies. Elongate structures can be enhanced by applying the method along four different strike directions. This method produces an excess of information with millions of magnetic sources detected at different depths. As with photo-geological studies or satellite imagery, the geology can be recognised from the continuity of the signal pattern and in this way, separate the signal from the noise on the magnetic source map.

A magnetic source map has been constructed over part of the Adelaide Geosyncline and metamorphic basement in the western Eyre Peninsula; this shows dykes, faults, shear zones and sedimentary layers. These include a 100km wide, north east striking fault zone that appears to control the position of the diapirs in the central region of the Adelaide Geosyncline.

It also shows large linear structures which correspond closely with the structural corridors, observed on Landsat images and described by O'Driscoll, with an important difference; the O'Driscoll corridors show only the position of the structures, but the magnetic source map also shows changes in character along the strike, and consequently additional information about the structure.

## An Australian energy mix for the Anthropocene

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The impact of humanity on earth systems is now sufficiently large to be a significant geological agent and to recognise a new epoch, the Anthropocene. Over the past 200 years the energy industry, including fossil fuel use, has contributed to a re-shaping of the earth's surface and changes to the atmosphere, oceans and sediments. It is predicted that by 2050 around 30% to 60% more energy will be required to meet the demand from a growing global population that hopefully enjoys higher living standards. Increasing energy supplies while limiting carbon emissions is one of the largest challenges ahead and one where Australia has a role to play if there is to be a "good Anthropocene", where the human contribution to global climate change is addressed.

Current projections of Australian energy consumption patterns for 2049-50 map out a scenario where fossil fuels still supply over 80% of our energy, though oil and gas use is expected to grow at the expense of coal. The projections indicate a shift towards a lower carbon emissions energy mix in 2050 with no brown coal, an increased use of renewables and a small contribution from geothermal energy. It is uncertain what role carbon capture and storage will play in limiting emissions when accessing energy from fossil fuels. Australia is projected to be self-sufficient in gas but most of the oil used will be imported. However, exploration outcomes may lead to other futures that could include conventional oil discoveries in deep water frontier basins or production of unconventional liquid hydrocarbons from Paleozoic and Proterozoic petroleum systems in onshore Australia. Technological change is another uncertainty and can shift the energy mix dramatically in a decadal scale. For example the unconventional gas and oil revolution in the North America has unlocked vast resources and driven energy prices lower. Replicating the US experience in Australian basins has met with complexity above and below ground but a new export industry using coal seam gas has been established.

Alternate Australian energy futures have relevance beyond our shores as local consumption represents less than 30% of our energy production as Australia is a major supplier of coal, uranium, gas and oil and the world's eighth largest energy exporter. Australia has a third of the world's uranium resources and is on track to become the world's largest exporter of LNG, both industries that can help realise the environmental gains to be made when uranium and gas replace coal-fired power generation. Australia also has significant resources of some of the critical commodities, such as lithium, required in renewable energy technologies. Current low energy prices provide a challenging environment for continued investment but Australia still has abundant, diverse and high quality energy resources, and has built a reputation and record as a stable supplier of these vital commodities.

## Sedimentary basins for geothermal energy: the Montgomery House example

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The largest level of investment to date in Australian geothermal projects has been directed towards 'enhanced geothermal systems' (EGSs) and 'hot dry rock' (HDR) projects – drilling projects for power generation targeting deep aquifers with little to no primary porosity. Investment in geothermal projects in alternative geological settings, including shallower, sedimentary aquifer systems has received less investment attention.

The efficacy of geothermal energy projects strongly depends on a site's geological and hydrogeological conditions. The Perth Basin has proved to be an extremely prospective region for direct-use and ground source heat pump (GSHP) geothermal projects, due to its extensive sedimentary aquifer system. The Montgomery House project is an example of the challenges and opportunities that the Perth Basin presents.

Montgomery House is an historic Perth landmark that has been transformed into an 80-bed aged care facility by Aegis Aged Care. The challenges of providing air conditioning for such a large and heritage-sensitive site were matched by the challenges of its location – it borders a former rubbish disposal site and is surrounded by residences (and so is sensitive to drilling and testing operations).

The Montgomery House geothermal project is an open-loop system that accesses aquifers within the Tertiary Kings Park Formation. Two 155 metre deep production bores deliver 23 °C water to a heat exchanger. Discharge water is injected into the same aquifer via a 165 metre deep injection bore. This thermal energy is used to heat and cool Montgomery House buildings via an automated heating, ventilating, and air conditioning (HVAC) system.

The Montgomery House geothermal project will deliver considerable long-term energy savings. Over a 30 year operating period the system NPV (for a 5% discount rate) is projected to be about AUS\$1.5M and deliver over 8000 tons of carbon-emissions reductions.

## **Determining Stakeholder Perceptions for Geotrails, Geotourism and Geoparks in the Wheatbelt of Western Australia.**

**Alan Briggs**

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For many decades the trend towards large scale agricultural businesses in the Wheatbelt of Western Australia have led towards rural decline as the demand for human resources on farms diminishes. Tourism has been contemplated and promoted as a means to address rural decline. PhD research has been initiated in the Wheatbelt of Western Australia to discover stakeholder perceptions towards the development of geotrails, geotourism and Geoparks as a means for development of cultural, social and economic outcomes to address rural decline and improve the lifestyles of rural communities. Engagement and support has been a common reaction across the Wheatbelt. While the PhD research is focused on four central Wheatbelt Local Government Authorities (LGAs), additional case studies to the north (Perenjori) and south (Porongorup) have been developed as a consequence of early research. Additional case studies led to the development of a geotrail selection process to determine those places with the most potential for safety and success. This paper will report on the basis for the research and some of the interim findings which include LGA offers for support, funding from regional bodies, geotrail selection process and stakeholder perceptions and contributions towards establishing geotourism, geotrails and a Geopark.

## **Geotourism in Western Australia**

**Briggs<sup>1</sup>, Alan and Dowling<sup>2</sup>, Ross**

*Chair<sup>1</sup> and Deputy Chair<sup>2</sup>, Western Australian Geoparks Network, Perth, Australia*

Geotourism has been championed for a long time in Western Australia. The Geological Survey (GSAWA) and Department of Parks and Wildlife (DPAW) have published a number of books over many years fostering an interest in geology for travellers. These include the *Geology of - Perth*, and WA's *National Parks* (both GSAWA, 2007) as well as a *Geotrail of the Pilbara* (2009). DPAW has published a range of titles under its 'Bushbooks' series including the *Geology & Landforms of the – Kimberley* (1996), *South-West* (2001) and *Pilbara* (2005) as well as *Discovering Caves of Western Australia* (2009). In addition in the past decade there have been three global edited books on Geotourism by WA Academics Ross Dowling and David Newsome. These are *Geotourism* (2006), *Geotourism: The tourism of geology and landscape* (2010) and *Global Geotourism Perspectives* (2010). Finally there has been three conferences on the subject at the international (2008), state (2012) and national (2015) levels all hosted by the Forum Advocating Cultural & Eco Tourism [FACET].

In recent times geotourism has been given a boost in the state by the development of a number of geo - interpretive centres, trails and products. These include the geological interpretation of landforms in the World Heritage areas of Purnululu, Shark Bay and Ningaloo. A drive geotrail has been established in the Pilbara region and two geological walk trails have been established in Perth. New geological products in the south west of the state include the Granite Skywalk in Porongorup National Park, the Jewel Cave Preservation Centre and the Lake Cave Eco Interpretive Centre.

Thus geotourism is becoming a more recognised tourism product in Western Australia and now interest is also beginning to be shown in establishing geoparks in the state. In late 2015 a WA Geoparks Network (WAGN) was established to help inform a number of interested communities about the growing global UNESCO program.

This presentation will outline the growth of geotourism in Western Australia and how it is contributing to regional sustainable development.

## Developing and testing hydrogeological conceptual models – Some key learnings from the Broken Hill Managed Aquifer Recharge (BHMAR) project

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As part of a broader water savings strategy for the Murray-Darling Basin, the Broken Hill Managed Aquifer Recharge (BHMAR) project was tasked with identifying and assessing aquifer storage and groundwater extraction options in the Darling River floodplain of western New South Wales. Due to the lack of pre-existing information, the project required significant data acquisition. This included approaches not routinely used in Australian hydrogeological investigations, such as airborne electromagnetics (AEM), sonic coring, pore fluid analysis, downhole nuclear magnetic resonance (NMR) logging and river bathymetry/sediment surveys. It was the interpretation, integration and re-evaluation of these cross-disciplinary datasets during project phases that drove fundamental shifts in the conceptual understanding of groundwater processes in the study area.

The importance of river leakage for recharge to the shallow Quaternary alluvial aquifer and the deeper target Calivil Formation aquifer had been previously recognised. This was confirmed by AEM mapping of near-river groundwater freshening in both aquifers. The geophysics also mapped a significantly greater extent than previously thought of the lacustrine Blanchetown Clay separating these two aquifers. NMR logging and centrifuge permeameter tests confirmed very low hydraulic conductivity within this regional aquitard. This appeared contrary to emerging hydrographic and hydrochemical evidence for modern recharge to the underlying Calivil Formation aquifer, notably during episodic high river flows.

This inconsistency triggered a re-evaluation of the datasets as well as the conceptual model. Through advances in the processing and inversion of the AEM data, evidence for previously unrecognised faulting and structural disruption of the sequence finally emerged. This was collaborated with structurally controlled geomorphological features mapped by LiDAR and Landsat imagery, as well as with deeper regional structures identified by gravity and aeromagnetic datasets. The recognition of faulted disruption of the Blanchetown Clay aquitard critically provided the hydraulic pathway for near-river recharge to the underlying Calivil Formation aquifer.

Some key learnings can be made from the evolutionary path of the hydrogeological conceptual model, namely: (1) the element of hydrogeological surprise always prevails; (2) build a wide array of candidate conceptual models from plausible to fanciful to test; (3) collect data that can readily negate a candidate conceptual model; (4) take a cross-disciplinary approach that incorporates unconventional datasets; (5) underpin the conceptual model with sound geoscience; (6) always consider the intrinsic scale and domain of the input datasets during interpretation and integration; (7) check that the data could be wrong, as well as the conceptual model; (8) relatively fine-scale features can be disproportionately critical; (9) components of the conceptual model assumed to be reasonably constant may not be; and (10) “extreme” events can drive processes rather than “average” conditions.

## Constraints on Olarian-aged magmatism and deformation in the Yorke Peninsula

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The late Paleoproterozoic to early Mesoproterozoic marks an episode of intense poly-phase deformation and metamorphism associated with voluminous magmatism and generation of giant ore deposits within eastern Proterozoic Australia. Within the Olympic Domain in the eastern and southern Gawler Craton, South Australia, this event involved emplacement of the ca. 1595-1575Ma Hiltaba Suite (HS) (e.g. Creaser & Cooper 1993; Fanning et al. 2007) and the temporally equivalent ca. 1592Ma Gawler Range Volcanics (e.g. Fanning 1997). This granite suite was emplaced heterogeneously throughout the Gawler Craton into two main phases that are suggested to show geochemical and isotopic characteristics (e.g. Stewart & Foden 2001). The plutons also show a spatial distribution whereby younger granites are emplaced in the northern Nuyts Domain and the Olympic Domain within the Gawler Craton, however the data is limited.

In the Yorke Peninsula in the southern Olympic Domain, magmatism is seen as the deformed Tickera Granite, and the undeformed Arthurton Granite (e.g. Jack 1917; Wurst 1994). These granites intrude metasediments and metavolcanics of the ca. 1750 Ma Wallaroo Group (e.g. Cowley et al. 2003). Magmatic crystallisation ages for the Tickera Granite range from ca. 1597-1577 Ma (Conor 1995). Although the timing of emplacement of these granites falls within the timing of the HS magmatism, detail on the relationships of emplacement of the Tickera Granites in the context of the broader HS is lacking. This includes constraints on the relative ages of granite phases that can be observed within the granite, emplacement depths and the relative timing of magmatism and deformation of the Tickera Granite and the hosting Wallaroo Group.

This project is aimed at understanding the relative timing of emplacement of multiple phases of the deformed Tickera Granite at Point Riley on the western Yorke Peninsula. This will be done through assessing the intrusive relationships of the granite through detailed mapping in conjunction with whole rock geochemical and Sm-Nd isotopic analysis. Magmatism and deformation associated with emplacement of the Tickera Granite will then be placed in the context of the phases of the HS and the major ca. 1600-1575 Ma event.

## **Devonian Tolmie igneous Complex, northeast Victoria; 1960's findings and some later observations, interpretations, and misinterpretations.**

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The Tolmie Igneous Complex comprises porphyritic felsic volcanics and minor intrusives. It unconformably overlies early Palaeozoic rocks of the Lachlan Fold Belt. Apart from a small outlier in the Melbourne Zone, the Complex is in the Tabberabbera Zone east of the Governor Fault, the zone boundary. The Melbourne Zone outlier is intruded by Late Devonian granite, and truncated by the fault. The volcanics and the granite are overlain unconformably by Early Carboniferous red beds.

The oldest, probably Givetian, volcanics comprise at least four ignimbrite sheets, overlying and interbedded with conglomerates. The volcanics and conglomerates were folded. They are overlain, with a major angular unconformity, by a kilometre or more of Late Devonian volcanics of the main part of the Complex to the southeast; where a basal rhyolite is overlain, with a transitional boundary, by rhyodacite. These younger volcanics have fabrics indicating viscous flow, and have been interpreted as lavas or rheoignimbrites. Small intrusions of granodiorite porphyry occur around the margins of and also within the Complex. They are more mafic than, but otherwise closely related to the rhyodacite; and have been interpreted as feeders for the younger volcanics. They contain dark enclaves of hypersthene microdiorite.

With the exception of a hornblende bearing (I type) ignimbrite at the base of the volcanics 3.4 km north of Tatong, the rocks are peraluminous (S type), and contain almandine garnet and cordierite.

The above findings were made in the 1960's. Later mapping has filled a gap in the southeast, and mostly confirmed previously mapped boundaries. Palaeontology has confirmed the possibility of a Givetian age for the early volcanics; and recent U/Pb zircon dating of 377+/- 2 ma for the top of the rhyolite has confirmed that the younger volcanics are Late Devonian.

The stratigraphy of the early volcanics has been re-interpreted as comprising a single basal conglomerate overlain by a single thick ignimbrite. The interbeds of conglomerate were interpreted as fault slices of basal conglomerate. This is incompatible with outcrop patterns and the measured attitudes of bedding and fiamme. The major, (?)Tabberabberan, angular unconformity between the older and younger volcanics has been consistently ignored or downplayed in post 1960's publications.

A recent paper discusses the chemistry of many samples from the Complex. The I type ignimbrite, and the enclaves in the intrusions, were not sampled. The authors state that "there are no dark coloured enclaves of igneous rock in the rocks". The more mafic rhyodacites appear to be under-represented in the sampling. Chemistry of the younger volcanics is consistent with roof collapse of a vertically zoned magma chamber; and eruption of the rhyolite and then the rhyodacite through feeders now occupied by the granodiorite porphyry. These intrusives are more mafic than, but on trend with, rhyodacite samples in all variation diagrams in the publication; and not, as the authors find, a separate magma group. Removal of the upper part of the volcanic pile by kilometre scale latest Devonian/Early Carboniferous erosion accounts for absence of rhyodacite as mafic as the intrusives. The mechanisms of emplacement of the volcanics remain uncertain.

## Defining Stratigraphic Units; more than polygons in a GIS

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Geological maps and data sets provide useful information about the distribution and age of the geological units that they distinguish. They also provide a brief lithological description of the units. Some maps and tables behind GISs provide further information about unit groupings and geological provinces. What these sorts of products rarely do is give much information on the evidence behind the asserted age, how the unit boundaries were determined, or what the distinguishing or identifying features of a particular unit are. It is also rare to find information on the location of the type section or type area of a unit in these sorts of products. Stratigraphic unit definitions provide this valuable information and more, and set the benchmarks for possible future work in the area.

Writing unit definitions often seems to be seen as an administrative hurdle rather than an opportunity to clearly communicate what is meant by a stratigraphic unit name. There is a basic core of essential information required, with the most detail needed for units at Formation or Member level. This includes:

- ✓ Name and Rank (Group/Formation/Member etc, if not already included in the name e.g. Gundahl Complex);
- ✓ Derivation of name;
- ✓ Synonymy – history of recognition and description of the rocks comprising this unit;
- ✓ Type section or type area – co-ordinates, datum, an indication of the means of access to the site, State/Territory;
- ✓ Unit description (at least at the type locality) - lithology, thickness range (for bedded units), relationships with other units and boundary criteria, distinguishing or identifying features;
- ✓ Age range and evidence;
- ✓ Any correlations with other units.

Regardless of the quality of a written description of a unit, specifying a type section or type area location is vital. This not only allows visual inspection of a representative part of the unit by geologists new to the area, it also provides a definitive location where additional observations or measurements can be made (e.g. gamma logs, magnetic and other rock properties, radiometric dating) in the future.

Common sense will dictate which of the additional optional elements of a definition are most important to particular units. The goal is to provide enough information so that other geologists can recognise the unit, and its boundaries, when they see it in the field or in drill core. Additional information, such as geochemical or geophysical data, will assist with inferring the full extent of the unit, including undercover.

Australia adopted the practices set out by the International Stratigraphic Guide (ISG) in 1978. There are web resources and people (the Australian Stratigraphy Commission members in particular) who can help to interpret the ISG, and Australian procedures, to assist with writing unit definitions and redefinitions. There is also a resource of information available on existing published units, in the Australian Stratigraphic Units Database. Some 4690 units have been defined, but this is only 33% of the units recorded as being in current use, so there is plenty of scope for additional definitions to clarify the meaning of other unit names

## **Geoheritage importance of geological type sections and type localities - discussion and protocols for geoconservation**

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Equivalent in principle to type localities and type specimens in biology and palaeontology, geological type sections and type localities, whether for sedimentary, metamorphic or igneous units, are critically important sites as long-term reference localities and for geo-education of students. Unlike type specimens that are housed in museums or established institutions of learning, most geological type sections and localities are in field settings and, if they are not located in National Parks or other reserves with some legislated protection, run the risk of being destroyed, inundated, buried by earthworks, or otherwise modified.

The history of the geological sciences in Australia is such that a number of type localities, such as stratigraphic type sections, have been destroyed by local government actions, or developers through lack of knowledge of their importance, or lack of knowledge of their existence. Case studies of loss or severe modification of type sections include those of the Maxicar Beds (in a quarry) in the Perth Basin, now bulldozed and modified by earthworks, the Ranch Member and Bourimbla Limestone Member of the lower Daylesford Limestone once exposed in a road cut but now removed by road-widening, Narrabundah Ashstone Member type section degraded by neglect and teaching site modified by roadworks, and Cleifden Caves limestone and fossil site threatened by flooding. The United Kingdom, a leader in the field of Geoconservation and with a number of global stratotype section and point (GSSP) locations as well as many other type sections identified within its borders, provides models for preserving and managing important geological sites and type sections. There is involvement of whole-of-government and local governments in the registering and protection of important geological sites. Aspects of the United Kingdom model may be adapted to help secure geological type sections and localities in Australia. While some type sections and heritage localities are already protected, to improve the level of protection for more sites we propose a long term, multi-pronged approach: 1. creation of an inventory of all nominated locations (the Australian Stratigraphic Units Database will be a useful starting point); 2. registration of sites at Federal, State, and Local government levels where current legislation allows; 3. education of Federal, State, and Local governments to highlight the importance of type sections to science; and 4. securing more geological type sections and localities in some form of reserve.

## A Neoproterozoic and Cambrian multi-stage evolution for the Coolac Serpentinite, southeastern Lachlan Fold Belt, NSW

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The Coolac Serpentinite is one of numerous ultramafic bodies that occur throughout the Lachlan Fold Belt in New South Wales. Unlike many of the ultramafic rocks from other localities throughout the fold belt, a portion of the Coolac peridotites are only partially serpentinised, making them excellent candidates for petrographic and geochemical studies. The peridotites are mostly harzburgites and dunite is sub-ordinate. Podiform chromitites, pyroxenites, gabbros and granitoids intrude the ultramafic mass.

Harzburgite consists largely of olivine with forsterite contents consistent with their refractory nature ( $Fo_{90-91}$ ). Olivine has been re-crystallised into small, fresh neoblasts with former protogranular boundaries often marked by a network of magnetite. Orthopyroxene is largely altered to serpentine and occurs as bastites frequently with dissolved rims and/or embayments of olivine. Two textural types of clinopyroxene (one residual and one of igneous origin) are commonly present. Cr-spinel is either aluminous ( $Cr\# [Cr/(Cr + Al)] = 0.22-0.27$ ) when transparent in thin section or of a higher Cr content when isotropic ( $Cr\# [Cr/(Cr + Al)] = 0.42-0.45$ ). Bulk-rock middle- and heavy-REE patterns are consistent with melting models and suggest 15–20% partial melting of a depleted mantle source. This is in contrast to melting mineral indicators such as aluminous Cr-spinel, which suggests partial melting of only 9–11%. Whole-rock light-REEs are variably enriched and cannot be explained by residual melting alone.

A multi-stage petrogenetic model involving melt-rock interactions is suggested to explain the above observations. The model is constrained by new U/Pb zircon SHRIMP data from a tonalite (~501 Ma) derived from melting of altered oceanic crust and Nd isotope model ages (~660 Ma). This suggests that the protolith to the Coolac Serpentinite was formed during the break-up of Rodinia whilst the harzburgite was formed during a melting event post-convergent Delamerian Orogeny and subsequently re-fertilised. A U/Pb zircon isotope age of ~439 Ma from an oceanic granite intrusion into the harzburgite (Belousova *et al.* 2015) and a U/Pb zircon SHRIMP age of ~427 Ma on a pegmatite gabbro (Bodorkos *et al.* 2013) indicates that re-fertilisation of the harzburgites may have occurred during extensional episodes of phase 1 and phase 2 of the Benambran Orogeny.

## **Professor Walter Heywood Bryan MC: Queensland's Pioneering Geologist**

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Professor Walter Heywood Bryan in many ways was a pioneer and leader. In 1911, he was among the first students enrolling in the new Science course offered in the first year of the University of Queensland. Following completion of his B.Sc., he became the first Honours' graduate in Geology and Mineralogy at the end of 1914. WH Bryan enlisted in the Australian Infantry Force in June 1915 being first deployed to Gallipoli, Egypt and then the western front in France until the end of the Great War. His unit was the 2<sup>nd</sup> Australian Medium Trench Mortar Battery. Unfortunately, little is known of his time and experiences during the Great War. Like many veterans, his military service was something that was never spoken of on his return and with his children. He never joined the RSL nor attended Anzac Day services. Much of what is known comes from official records and his Military Cross honour that was awarded for gallant conduct near Strazeele, France, on the 4<sup>th</sup> and 5<sup>th</sup> May 1918. In the face of heavy artillery and machine gun fire, Lieut. WH Bryan repeatedly led his men with ammunition to gun positions under violent heavy artillery barrage, himself carrying several times, 2 bombs, weighing 54 lbs each. There they were able to take out machine gun positions and snipers' posts. These actions were a clear case of leading by example as highlighted in the Major-General's recommendation at the time, but also reflected his outstanding quality and value he placed on duty, that was to be evident again during WWII and throughout his academic career.

After demobilisation, WH Bryan undertook post-graduate study at Cambridge University, and then returned to Brisbane to become Lecturer in Geology at UQ. In 1926, he became UQ's first Doctor of Science and from 1948-1959 was Professor of Geology and Mineralogy when he retired. Demonstrating his continued sense of duty, during WWII he served as a Suburban Air Raid Warden in Brisbane, and as a mail censor.

His academic career was also pioneering, and broad in its approach and impact. His Honours research on the Enoggera Granite established igneous petrology and volcanology as continual areas of research throughout his career, including several papers on spherulitic devitrification. His pioneering work on the Brisbane Tuff led to it being included as the only Australian example in the seminal paper by Smith and Ross (1961) on Ash-Flow Tuffs. More broadly, he made significant contributions to the stratigraphy and geological evolution of Queensland, soil science, and marine geology. Importantly, he pioneered earthquake monitoring in Queensland following the 1935 Gayndah earthquake, and established the first seismological research station at UQ, being the Officer in Charge during its formative years. Reflecting his broader impact and desire to help others, he led efforts to utilise the seismological stations for cyclone monitoring and hazard mitigation, particularly for North Queensland. He also served on numerous committees including being Deputy Chairman of the Great Barrier Reef Committee and President of the Royal Society of Queensland.

## Apatite and zircon (U-Th)/He thermochronology of the Drummond Basin: insights into the thermal history of the northern New England Orogen

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Low-temperature thermochronology is commonly used to constrain burial and exhumation histories of sedimentary basins. The northern New England Orogen of Northeastern Australia is an unusually broad orogen characterized by repeated and generally superimposed, large-volume igneous and large sedimentary basin-forming events through the Paleozoic and Mesozoic. The implication is that older sedimentary basins may record significant and complex thermal histories with heating events in response to burial through sedimentary basin stacking and major igneous events, as well as cooling events in response to exhumation due to contractional or extensional tectonic drivers. We have undertaken a multi-dating approach examining sedimentary rocks from the Drummond Basin, a major Late Devonian-Early Carboniferous rift basin straddling the Early Paleozoic Thomson and Late Paleozoic New England Orogens. We have focused on dating samples from the Campaspe DDH-1 well in the northwestern part of the basin which provides a continuous ~550 m thick section through the upper Mt Hall and lower Raymond Formations. The well is located >800 km inland from the present-day continental margin. Our dating efforts include LA-ICP-MS U/Pb zircon and rutile dating, combined (U-Th)/He and U/Pb dating of detrital zircons (“double dating”) and single-grain (U-Th)/He dating of zircon and apatite.

A distinct euhedral zircon population yielded the youngest U/Pb ages at ~340 Ma, which is interpreted to record the depositional age and are sourced from contemporary silicic pyroclastic deposits that are interbedded throughout. Other detrital zircon age populations are identified, with age peaks at ~420 Ma, ~480 Ma and ~1200 Ma. Among all double dated samples, most of the paired zircon (U-Th)/He (ZHe) ages are 250-350 Ma, regardless of U/Pb age. Because the ZHe ages are concentrated regardless of the wide range of U/Pb ages, and most of ZHe ages are younger than the depositional age, we conclude that the ZHe system was partially to completely reset after deposition. Most (U-Th)/He apatite ages from the same samples are ~30-100 Ma. Our thermal modelling using QTQt software suggests a Tpeak of ~280°C was reached at ~300-290 Ma, followed by rapid cooling between 280 and 255 Ma. Our results suggest the Drummond Basin was buried more deeply than previously indicated from apatite fission track data. The timing of these events correlate with peak igneous activity of the Kennedy-Connors-Auburn Silicic Large Igneous Province, and then exhumation likely related to thrusting during the contractional Hunter Bowen Orogeny, respectively. Weaker, but prolonged reheating from ~240-100 Ma is indicated from the modelling, which is consistent with burial and subsidence related to development of the intracratonic Great Australian Basin during the Mesozoic. A final phase of rapid cooling beginning ~80-90 Ma records the widespread effect of epeirogenic uplift and exhumation in eastern Australia related to continental rupturing, opening of the Tasman Sea, and establishment of the continental passive margin.

## Discrimination of natural CO<sub>2</sub> sources within the Cooper Basin

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CO<sub>2</sub> that has accumulated within the Cooper Basin is assumed to have an inorganic source. It is either mantle-derived or was produced when magma degassed following emplacement. Another possibility is that carbonate rock became thermally altered and evolved CO<sub>2</sub>. An alternative hypothesis is that CO<sub>2</sub> was generated from an organic source, by thermal maturation of Permian coals.

Isotopic values of <sup>13</sup>C for CO<sub>2</sub> within the Cooper Basin are -6.9% PDB on average, supposedly too heavy for a coal source (-10 to -25%). This remains the basis for assuming an inorganic source. Two major magmatic events in the region emplaced Late Devonian Big Lake Suite and Late Carboniferous Moomba granites. Both granite suites were exhumed prior to burial of Permian stratigraphy so are unlikely to have provided heavy carbon to observed CO<sub>2</sub> accumulations.

Differential Thermal Analysis (DTA) curves demonstrating thermal decomposition of dolomite – CaMg(CO<sub>3</sub>)<sub>2</sub> – and calcite – CaCO<sub>3</sub> – show two endotherms at 772.6 and 834.0 °C. The former represents decomposition of CaMg(CO<sub>3</sub>)<sub>2</sub> to release MgO and CO<sub>2</sub>. The latter represents thermal decomposition of CaCO<sub>3</sub> with final release of CaO and CO<sub>2</sub>. Dolomite will undergo thermal decomposition at lower temperatures when chloride salts are present to promote the formation of MgO and CaCO<sub>3</sub>. However, temperatures within the Cooper Basin have not been high enough to break down carbonate material and produce the volume of CO<sub>2</sub> observed.

Gas composition and temperature data acquired at Cooper Basin exploration wells show that CO<sub>2</sub> concentration does not correlate strongly with temperature. A strong inverse correlation exists between CO<sub>2</sub> and CH<sub>4</sub> concentrations. When CO<sub>2</sub> concentration is plotted with wet gas index (WGI), two groupings are revealed. ‘k-Means’ cluster analysis using 16 gas sample variables, demonstrates that the same two groupings occur for CH<sub>4</sub> concentration with WGI. These groupings are also distinguished by temperature and depth. They indicate the gas was generated by thermal maturation of coals.

The assumption of a coal source leads an alternative interpretation of carbon isotope data. Alkyl chains in flora-sourced hydrocarbons are enriched in <sup>12</sup>C. Cleaving of methyl groups at low temperatures (low bond enthalpy) could have produced the low temperature gas group, which would be enriched in <sup>12</sup>C. By contrast, <sup>13</sup>C accumulates (at lower concentration) within aromatic structures and carbonyl functional groups. Higher temperatures (depths) would have been required to break down aromatic carbon bonds or oxygen-containing functional groups to produce the later-stage, higher temperature gas group. This group would therefore be enriched in <sup>13</sup>C. These gas generation stages are supported for the Cooper Basin by a strong correlation between vitrinite reflectance (VR), and both CO<sub>2</sub> concentration and <sup>13</sup>C CO<sub>2</sub> PDB.

Pyrolysis experimental data have shown that deeply buried hot coal can release <sup>13</sup>C CO<sub>2</sub> up to +18% PDB. Coal-rich formations within the Patchawarra Trough retain hydrocarbon producing potential at the historical maximum basin temperature. Thermal maturation of Permian coals could be responsible for the <sup>13</sup>C PDB values of CO<sub>2</sub> observed within the Cooper Basin. These coals are therefore a candidate source for Cooper Basin CO<sub>2</sub>.

## **4D Fracture Distribution as a Signature of Structural Evolution in the Otway Basin**

Burgin, Hugo, Amrouch, Khalid and Rajabi, Mojtaba

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An understanding of the distribution of natural fractures throughout time and space within sedimentary basins can enable the optimisation of exploration and production methods. Additionally insights into the structural and tectonic evolution of a region can also be obtained. Natural fractures within the Otway Basin (South East Australia) have been identified via wellbore image log data (from the Penola Trough) and outcrop analysis (along the Great Ocean Road), and have been catalogued with regard to their direction of dip, degree of dip and inferred chronological regime of paleo-stress.

Evidence for up to four paleo-tectonic stress regimes within the study area have been identified, with 8 individual fracture sets detected in well data and 6 sets detected from outcrop analysis at twelve localities within the study area. Once detected, each individual fracture set was assigned a conjugate pair based upon an inferred paleo-stress regime. Following the integration of well and field data sets, relative chronology between conjugate fracture pairs was determined via: the presence or absence of fracture sets within consecutive stratigraphic units, cross cutting relationships observed in the field and bedding / fracture orientation relationships.

The result was a more complete understanding of the history of regional tectonics within the Otway Basin. Initial extension within the Otway Basin was in all likelihood orientated NE-SW, occurring over a prolonged period (Berriasian-Albian) during the Early Cretaceous. Followed by a basin inversion within the Otway that occurred during the Mid-Cretaceous (Cenomanian-Turonian), orientated NE-SW and then by renewed extension in a NW-SE orientation. Lastly a change to a NW-SE compressional regime from the Eocene-Recent was recorded and it is consistent with the measured in situ stress found to be approximately NW-SE as well.

## Use of pXRD in the quantitative assessment of alteration in epithermal Au deposits

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X-ray powder diffraction (XRD) is a well-established tool in Earth Sciences, as it allows for the identification and quantification of mineral assemblages. For epithermal Au systems, the quantification of alteration mineral assemblages can allow geologists to characterise the geometry of a deposit or geothermal system and draw inferences regarding the fluid evolution and environmental conditions of deposition (e.g., pH, T). Traditionally, XRD devices have largely been restricted to laboratories; however, advances in XRD sample holders and X-ray sources have allowed for the development of portable XRD (pXRD) devices. This study assessed the validity of the Olympus Terra pXRD instrument for qualitative and quantitative studies of hydrothermal systems through comparisons with data from laboratory XRD (Empyrean II diffractometer) and XRF techniques for both synthetic mixtures of natural minerals and a variety of samples from the Kulumadau epithermal gold deposit, Woodlark Island, Papua New Guinea and a number of deposits from the Drake Goldfield of NE NSW, Australia.

Diffractograms of synthetic mineral mixtures with known concentrations of quartz, kaolinite, muscovite, albite, and pyrite were firstly analysed quantitatively using the Rietveld-based Siroquant technique and showed good overall agreement for both devices. Results from the pXRD unit for collection times of 5, 10, 20, and 40 minutes for representative samples spanning a range of rock types and alteration styles revealed that 5 minutes was sufficient for qualitative analysis, even of minor phases. Overall, the 5-minute collection time also yielded excellent quantitative results, but precision for minor mineral phases increased noticeably with increasing collection times. Quantitative mineral estimates for 20- and 40-minute data sets were compared directly to estimates made using the Empyrean II data and showed excellent correlation with  $R^2$  values of >0.90 for all major mineral phases (i.e., >5%). Due to its portability, robustness, minimal sample preparation, relatively fast collection times, and excellent correlation with laboratory-based XRD devices, the pXRD has been shown to be of great use for rapid acquisition of quantitative mineralogical data by the exploration geologist, allowing for more informed and faster decisions during drilling programs.

## The Stavely Project – UNCOVERing mineral potential in western Victoria, Australia using a multi-disciplinary approach

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The Stavely Project is a collaboration between Geoscience Australia and the Geological Survey of Victoria that was designed to investigate the four geoscience themes outlined by the Australian Academy of Science to address the decline in national exploration success. During 2014 fourteen pre-competitive stratigraphic drill holes totalling 2708 m were completed over an area of approximately 20,000 km<sup>2</sup> in western Victoria targeting portions of the Stavely Arc. The purpose of the pre-competitive drilling was to test regional geological interpretations, characterise and determine the thickness of cover and recover high quality samples for detailed lithological, petrophysical, geochemical and geochronological analysis in order to evaluate the basement rocks, including their potential to host significant mineral deposits. Interpretation of this data has provided a new regional geological framework that will ultimately reduce exploration risk.

The Stavely Arc comprises at least nine low- to high-K calc-alkaline volcanic fault-bounded belts of Cambrian age, 3-5 km wide and, collectively, up to several hundred kilometres in length. A combination of knowledge derived from the limited existing exposures, regional geophysics (magnetics, gravity and deep seismic reflection transects) historical open file drilling and new data from the pre-competitive drilling has allowed the broad delineation of these volcanic belts under cover. These constraints, in combination with the structural history of the overlying and well exposed Grampians Group, have also enabled a retrodeformation of younger Siluro-Devonian structures that dissect the Stavely Arc. This retrodeformation explains the nine fault belts as dispersed, reoriented fragments of three subparallel, regionally significant Cambrian belts of arc volcanic rocks. These volcanic belts are considered to represent fault-slices of a large, mostly-buried continental margin magmatic arc system that formed on the eastern margin of Gondwana in the Early to Middle Cambrian. Subsequently the arc was shortened, accreted and uplifted onto the margin during the Late Cambrian culmination of the Delamerian Orogeny.

The volcanic belts are separated by wider regions of deformed (newly recognised) Early-Middle Cambrian Kanmantoo and Nargoona Group metasedimentary rocks, Cambrian intrusives of arc affinity, including porphyries, have been emplaced into both the volcanic belts and intra-belt sedimentary rocks. The Cambrian rocks are unconformably overlain by a cover sequence of variable thickness. The cover rocks include the ?Ordovician to Late Silurian Grampians Group, Early Devonian Rocklands Volcanics (related to coeval granite emplacement), Permian fluvioglacial deposits, Mesozoic-Cenozoic fill of the Murray and Otway basins and Cenozoic lavas of the Newer Volcanic Group. Cover thickness of post-Silurian rocks within the project area broadly ranges from <50 m to 350 m.

Mineralisation of porphyry and epithermal Cu-Au, and volcanic-hosted massive sulphide affinity is known within the Cambrian rocks around Mount Stavely and the Black Range. Historical mineral exploration dating back to the early 1970s has been intermittent, relatively shallow and focussed on the most well (though still poorly) exposed portions of only two volcanic belts. Following the successful completion of the Stavely Project the buried portions of the Stavely Arc have been confirmed as being equally prospective with a new greenfields exploration search space having been identified.

## Structural setting of microplaty hematite mineralisation at the Mt Helen and Silver Knight deposits, Hamersley Province, Western Australia - implications for timing and regional exploration

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Iron mineralisation at BHP Billiton's Mt Helen and Silver Knight deposits, in the Hamersley Province, Western Australia, was discovered during reconnaissance exploration focused around the giant Mt Whaleback deposit. Both deposits are hosted within banded iron-formation of the Hamersley Group and consist of both martite-microplaty hematite and martite-goethite type mineralisation; however, the spatial distribution of these two mineralisation types indicates formation from distinctly different mineral systems.

Microplaty hematite mineralisation in both the Brockman (Mt Helen) and Marra Mamba (Silver Knight) Iron Formations displays a strong spatial relationship with the regional-scale Whaleback Fault, although the main orebodies do not occur in the immediate hangingwall to the fault at surface. Microplaty hematite mineralisation has to date only been identified on the southern limb of the regional-scale Western Ridge syncline, with recent exploration finding only unmineralised banded iron-formation on the northern limb and surficial supergene enrichment in the hinge zone.

Investigation of these deposits through surface mapping, drill hole logging, geochemical analysis, petrographic examination, structural interpretation and 3D modelling suggest specific structural controls played an important role in the formation of the microplaty hematite mineralisation. Second-order faulting related to the Whaleback Fault in conjunction with intense folding of the host stratigraphy likely created a zone of increased permeability adjacent to the main fault on the southern limb of the regional-scale syncline where the folding is most intense. Hydrothermal fluids ascending along the relatively narrow zone of permeability along the Whaleback Fault are interpreted to have then moved into the banded iron-formation upon encountering this zone of increased permeability; resulting in removal of gangue minerals and formation of microplaty hematite in their place. A later phase of martite-goethite type mineralisation also displays a spatial relationship to the Whaleback Fault and in places overprints the martite-microplaty hematite mineralisation.

Timing of the main martite-microplaty hematite mineralising event can be constrained relative to several major deformation events; particularly microplaty hematite mineralisation must have formed after the Ophthalmian Orogeny and either syn- to post-Whaleback Fault initiation. Subsequent movement on the Whaleback Fault during intra-cratonic reworking has almost certainly displaced the microplaty hematite mineralisation from its initial location, obscuring any hydrothermal alteration that was originally evident in the footwall rocks, and complicating exploration efforts.

Exploration in the Hamersley Province searching for high grade microplaty hematite deposits has been occurring since the 1960's. To date, the majority of deposits have been discovered through surface mapping and reconnaissance drilling; only a few deposits of note have been discovered through exploration for mineralisation blind to the surface. Historically, exploration targeting criteria has largely been based on studies of the giant Mt Whaleback, Mt Tom Price and Paraburadoo deposits with only limited success. Through a detailed understanding of the smaller deposits in the region, such as Mt Helen and Silver Knight, key elements of the mineral systems that formed the microplaty hematite mineralisation is becoming evident and will hopefully lead to more significant discoveries in the future.

## European Consortium for Ocean Research Drilling (ECORD) in the International Ocean Discovery Program (IODP) : new opportunities in scientific drilling

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The European Consortium for Ocean Research Drilling (ECORD) co-ordinates the contribution of 16 European countries plus Canada and Israel to the International Ocean Discovery Program (IODP). More than 80% of the ECORD annual budget, which is currently of about USD 18M, concern IODP expedition operational costs. The contributions to the ECORD budget are unevenly distributed between the member countries, from USD 5.6 M to USD 30,000. On the basis of their contributions, each ECORD member country receives a quota to participate in all IODP expeditions. In contrast, the participation of ECORD member countries to the ECORD educational programme is not based on financial contributions.

ECORD funds and implements mission-specific platform (MSP) operations for IODP as an independent platform provider. The development of the MSP concept allowed the ocean research community to work in technically challenging conditions where the US drillship *JOIDES Resolution* and the Japanese drilling vessel *Chikyu* are unable to operate (e.g. high latitudes and shallow-water environments) and has therefore added a new dimension to ocean drilling.

A five year, i.e. 2015-2018, operational plan for mission-specific platform expeditions has been recently defined ([http://www.ecord.org/pdf/ECORD-Headlines\\_6.pdf](http://www.ecord.org/pdf/ECORD-Headlines_6.pdf)) and will be achieved by balancing the numbers of low, medium, and high-cost expeditions; in addition, external co-funding and in-kind contributions will be added whenever possible to provide additional funding to support MSP expeditions. It reflects:

- ) ECORD's aim to deliver one MSP expedition per year on average for IODP.
- ) The diversity of science themes (geomicrobiology, tectono-magmatic processes, effects of large impacts on Earth's environment, paleoceanography, climate and ice histories) that are addressed by MSP expeditions in the new IODP.
- ) The efficiency of the MSP concept to implement drilling expeditions in a wide range of environmental and climatic conditions.
- ) ECORD's operational flexibility demonstrated by the use of various drilling systems (drill ships, drill platforms, seabed drills). In future, MSPs might include additional systems (e.g. specifically outfitted polar vessels, jack-up rigs, long-piston coring, anchored barges, etc.) as determined by scientific priorities and operational efficiency.

ECORD makes financial contributions to the US National Science Foundation (NSF) and the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) for support and access to the multipurpose drillship *JOIDES Resolution* and the riser-drilling-capable drilling vessel *Chikyu*, respectively.

A major responsibility of ECORD is to promote a wide array of educational activities that foster :

- the development of drilling proposals (MagellanPlus Workshop Series Programme in collaboration with the International Continental Scientific Drilling Program) ;
- the education and training of future generations of scientists (ECORD Summer Schools, ECORD Scholarships, ECORD Research Grants and ECORD Distinguished Lecturer Programme) ;
- the education of teachers (ECORD School of Rock).

## **Structure and provenance of Permian successions in the Texas Orocline (Queensland, Australia): Tectonic implications and significance**

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The southern New England Orogen is characterised by a series of orogenic curvatures (oroclines) that developed during the Early Permian. The Texas Orocline is the largest and most prominent part of the New England oroclinal structure. Within the Texas Orocline, lower Permian sedimentary successions (Bondonga, Silver Spur, Pikedale, Terrica, Alum Rock and Ashford beds) are preserved. However, it was hitherto unclear what tectonic processes were responsible for the development of these lower Permian successions and what was their relationship to oroclinal bending. New U–Pb igneous and detrital zircon ages from Permian successions in the Texas Orocline, in conjunction with new structural data from the Bondonga beds, provide new insights into the Early Permian formation of sedimentary successions in the Texas Orocline. Detrital zircon U-Pb ages provide new maximum age constraints of 302 Ma - 280 Ma for deposition. The lithologies, structural history and age spectra of the successions in the vicinity of the Texas Orocline suggest that they are correlative and possibly represent remnants of a single larger basin that was deposited during the Early Permian. The new Early Permian depositional age constraints for the successions, overlap with the emplacement time of S-type granites in the vicinity of the Texas Orocline, as well as with depositional age constraints of the succession of the Nambucca Block. The suggestion that Early Permian sedimentary basins in the Texas Orocline belong to the same extensional phase as the Nambucca Block, is consistent with recently published indications for the New England oroclines to be primarily controlled by trench retreat and back-arc extension.

## **Geological field guides as educational tools: the Coorong**

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The SA Division of GSA has a working subcommittee that has the dedicated function of preparing geological field guides. The target audience for these documents comprises persons who have an interest in our natural environments, but who do not necessarily have specialist education in Earth Science. While care is taken to avoid excessive and unnecessary use of jargon, where required, technical terms are used with appropriate explanations; ‘dumbing down’ is avoided and suitable references are cited for those who wish to seek further information. When prepared, a field guide is made available for downloading from our web site, free of charge. As web documents, it is relatively easy to prepare later editions should that be necessary. The over-arching aim of the subcommittee is to make a meaningful contribution to public education. In addition, we are aware that school and university students are being exposed to these materials.

The GSA field guide to the Coorong was one of the subcommittee’s earlier documents. The Coorong is a coastal back-barrier lagoon that, together with Lake Alexandrina and Lake Albert, constitute the modern estuary of the River Murray. The Younghusband Peninsula is a Holocene beach-dune barrier that originated as the rising postglacial sea transported sandy sediment shoreward from the exposed Lachepede Shelf. The peninsula stabilised following culmination of the postglacial marine transgression, at the same time isolating a narrow back-barrier lagoon, the Coorong, from the direct impact of the Southern Ocean. The Younghusband Peninsula and the associated Coorong lagoon extend from the mouth of the River Murray some 180 km towards the SE town of Kingston. Beyond Salt Creek the lagoon waters become increasingly ephemeral. The Coorong and associated features thus provide a landscape that underpins investigation of two major concepts:

- 1) Earth’s global climate has varied greatly during the Pleistocene; glacial and interglacial climatic events have been widely identified within a consistent chronologic framework; the present global climate is interglacial.
- 2) Sea level is lower during glacial times when much of Earth’s water is stored as ice on the land (e.g. Antarctica, Greenland); sea-level rises during interglacial times when meltwater from glaciers and ice sheets flows into the oceans; in the present warm interglacial climate sea-level is high.

In addition, the modern peninsula and associated back-barrier lagoon have consistently provided a robust model for the genesis of similar Pleistocene features of SE South Australia.

The Coorong is a landscape icon rated highly as a tourist attraction. It has importance for ornithologists and other scientists (including geologists) and is the ancestral home of the Ngarrindjeri people. There is a diverse group of people who might be interested in a well-presented and authoritative field guide to this area. The presentation will refer to parts of the Coorong field guide to illustrate the stages of development of the document, describing how sites were selected from a preliminary site inventory. These criteria include not only the potential contribution of sites to concept development, but also practical matters relating to safety.

## **The dynamics of a very large intra-plate continental basaltic volcanic province, the Newer Volcanics Province, South-eastern Australia, and implications for other provinces**

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The Newer Volcanics Province of South-eastern Australia is a very large, continental, basaltic volcanic province, with an area >23,000 km<sup>2</sup>, >400 monogenetic volcanoes; it has been active since ~8 Ma. Lava fields, shields, scoria cones are common, and there are >40 maars, and volcanic complexes. Maars occur dominantly in the south where magmas erupted through Tertiary sedimentary aquifers, whereas in the north over Palaeozoic crust, there are few. Complex interactions of magma volatile content, magma ascent rates, conduit characteristics, availability and depth of aquifers caused diverse eruption styles. Volcanoes commonly occur close to major crustal faults, which acted as magma conduits. There is no simple age pattern of volcanism across the province. Volcanism was probably triggered by far field lithospheric stresses that generated local windows of trans-tension in the crust where fault sets intersect, causing decompressional mantle melting. Variable rock compositions from picritic to basaltic andesitic, originated from differences in depth and degree of melting, and fractionation processes. Some volcanoes are polymagmatic, involving eruption of magma batches with subtle compositional variations. Regional geophysical datasets (heat flow, seismic tomography, magneto-tellurics, aeromagnetics) have clarified the regional characteristics of the province, whereas detailed, ground magnetic and gravity surveys resulted in new insights into the subsurface structure of maar diatremes. Contrary to existing models, maars in the Newer Volcanics Province have shallow diatremes, with multiple roots, resulting from vent migration and excavation within the rheologically weak Tertiary substrate that shallow host aquifers.

## The Siluran Lachlan Orocline: a geodynamic template for reinterpreting a reworked Adelaide Fold Belt (Flinders Ranges and Nackara 'Arc' included), Curnamona Craton rotation and translation, and Centralian Superbasin (and others) evolution.

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Upper age constraints for Arrowie/Stansbury Basin deformation to form iconic Adelaide (Delamerian) Fold Belt structures (e.g. Flinders Ranges, Nackara 'Arc') are poor. While  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of D1 metamorphic micas and Early Ordovician post-tectonic granites (e.g. Padthaway Ridge) unambiguously constrain D1 thrusting, folding and east-west-directed crustal thickening timing to the Late Cambrian Delamerian Orogeny, age and origin of low-temperature D2 structures (e.g. Flinders Ranges type-1 dome-and-basin interference patterns; regional-scale oroclinal bends of D1 structures – Nackara 'Arc'), are speculative. D2 could range from Late Cambrian to Mid-Devonian. Arrowie Basin age and similar D1/D2 structure morphologies underpin current assumptions of a Cambro-Ordovician D2, generally attributed to north-south crustal shortening within a convergent tectonic regime arbitrarily assigned to a 'late' Delamerian phase. D1 structures weaken northwards in the Flinders Ranges. Little evidence exists of Cambrian deformation in the Eastern Warburton or Amadeus basins. Conversely, D2 folds and faults intensify northwards into a region where diapirism, Silurian magmatism (e.g. British Empire Granite) and burial of Cambrian successions beneath Ordovician-Silurian sediments (Warburton and Amadeus basins) indicate post-Cambrian regional extension, decompression melting and subsidence. Previous back-arc interpretations for the Warburton Basin are valid, but fit Macquarie Arc (Lachlan Fold Belt) context best, given that Ordovician-Silurian basin fill – e.g. Innamincka Formation and Mudrange Sandstone – post-dates Delamerian Mt Stavely/Mt Wright arc/system extinction. Available regional constraints: paleomagnetic data, Early Silurian magmatism, Flinders Zone D2 fold morphology, Ordovician-Devonian basin histories and the continent-scale dextral transtensional setting of the Silurian Lachlan Orocline farther east, supports the hypothesis that Adelaide Fold Belt D2 is Early Silurian, a response to regional-scale dextral transtension. Underlying easterly asthenospheric flow gradients related to Silurian subduction rollback in SE Australia drove clockwise rotational (70-80°) rifting and translation of the northern Curnamona Craton along a ~600km arc, from its pre-Silurian position near the northern Gawler Craton. Rift-rotation was about a pivot near Kanyaka – coincident with the Nackara 'Arc' axis – and caused asymmetric extension of Adelaide Fold Belt rocks between the Gawler and Curnamona cratons, including regions now occupied by the Flinders Ranges and Warburton Basin with strikingly similar potential field (e.g. TMI) character to the greater Lachlan (Thomson) fold belt. The coincidence of the strongest north-south D2 shortening in the Northern Flinders with Ordovician-Silurian basin subsidence and Silurian magmatism is counter-intuitive, but consistent with reinterpretation of D2 folds, diapirs and thrusts as thin-skinned structures formed in response to extension superimposed on D1 Adelaide Fold Belt structures. D2 fold axes and faults lie parallel the principle extension/rift directions for Curnamona Craton translation and rotation, with little deflection approaching cratonic margins. Craton translation magnitude matches, in turn, the amplitude and inter-limb angles of the flanking Z-shaped Nackara/Grassmere oroclinal hinge couple. The Siluro-Devonian transtensional (Bancannia) and extensional (Menindee & Blantyre) rifts in the orocline eastern flank show its formation was extensional, matching the ~160km of Early Devonian dextral transtensional deformation along the reactivated Moyston Fault in the Nackara Hinge core (see: Cayley et al., 2016; this volume). This new model revolutionises Delamerian Orogen and Centralian Superbasin interpretation. It supports UNCOVER by providing a new structural template for reconstruction of pre-Silurian Curnamona Craton position and affiliation. The Broken Hill Block restores to a position adjacent to the northern Gawler Craton and southern Musgrave Block margin boosting, for example, the base-metals prospectivity of the poorly-explored Nawa Domain of the northern Gawler Craton.

## **Palinspastic retro-deformation of regional-scale aeromagnetic data - key to unravelling Early Devonian structural complexity that reworked the Cambrian Stavely Arc, western Victoria.**

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The Stavely Arc developed above a continent-dipping subduction zone active along the eastern margin of Gondwanaland in the Cambrian (Foden et al., 2006). Initially Japan-style, the arc-complex transitioned to an Andean-like convergent scenario at the end of the Cambrian, shortened and accreted to the margin. This is important, as the modern Andes host giant metals systems, and the geological setting suggests similar prospectivity may exist in the Stavely Arc in western Victoria.

Understanding Stavely Arc geology is challenging. The region has a complex history, the arc disrupted into an array of offset and variably-rotated fault-segments. Exposure is poor, most arc-segments buried beneath ?Ordovician-Silurian Grampians Group, Devonian Rocklands Volcanics, Murray Basin sediments and young basalt lava flows. Fortunately, exposed arc segments at Mount Stavely, Mount Dryden, and Black Range/Rocklands have characteristic magnetic and gravity character, allowing extensions to these belts to be interpreted beneath cover. Geophysical data, in combination with other geological constraints (especially drilling and the complex structural histories mapped in enclosing Cambrian metasediments and in the overlying Grampians Group), has allowed for the recognition of several additional arc fragments.

Explaining the full context of the complex present-day arc-fragment configuration has required advancing understanding of the tectonics of the Tasmanides. A key breakthrough is the realisation that a dextral transtensional deformation and magmatism regime active in the adjacent Lachlan Fold Belt in the Early Devonian (Cayley & Musgrave, in review) can be applied as a template to constrain retro-deformation solutions for Stavely Arc aeromagnetic data. Geophysical data allows large dextral strike-slip faults and associated vertically-plunging drag-folds and kinks with tens-of-km amplitudes mapped in Cambrian bedrock to be traced beneath the Grampians Ranges. The bedrock structures coincide in position with similar-style drag-folds (eg. Mafeking Orocline) and strike-slip faults developed in this cover succession. All appear to link east at depth into the footwall of a reactivated Moyston Fault. Overprinting criteria tightly constrains the Early Devonian age of this second generation of bedrock structures, and permits cover and bedrock structures to be retrodeformed together, using aeromagnetic data as a template. The palinspastically restored pre-Devonian Stavely Arc configuration comprises three sub-parallel, west-dipping and mostly west-facing fault slices of arc volcanics and related rocks. The fault belts lie subparallel to the Yarramyljup Fault to the west, and possibly represent successive footwall splays from this structure. The restored fault-belts are quite continuous along-strike and so provide a greatly simplified template for correlation of now-disrupted belt segments, for mineral exploration and for target selection. This restoration represents a start-point for understanding the nature of the Cambrian deformation that originally accreted the Stavely Arc and probably controlled the distribution of the metallic mineralisation developed within it.

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## The Pb-Isotopes of Olympic Dam and Beyond – The Uranium Story of the Gawler Craton

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The supergiant Olympic Dam deposit is the world's single largest reported resource of uranium, and yet it is the economically-significant quantity of this commodity which makes it unique among the IOCG class (Hitzman & Valenta 2005). Ideas on genesis have evolved from the sedimentary paradigm of Roberts & Hudson (1983), through magmatic-hydrothermal models involving the Roxby Downs Granite or mafic dykes (Reeve et al. 1990; Oreskes & Einaudi 1990; Johnson & Cross 1995), and more recently, a return to the influence of an overlying sedimentary basin (McPhie et al. 2011). More recent still is the evidence from multiple isotope systems evoking models with substantially younger mineralising-events (c.1300 Ma), perhaps over a period of 1000 My (Maas et al., 2011) and especially with regard to uranium-emplacement (Kirchenbaur et al. 2016). Since the Pb-isotopic system is largely a product of uranium decay it provides another approach from which to explore uranogenesis, with the additional benefit of comparison between the chemically-disparate, fractionation behaviours of Th and Pb.

Our research has attempted to identify the  $^{238}\text{U}/^{204}\text{Pb}$  ("μ") of the likely reservoirs contributing to Olympic Dam with equivocal results. First-pass LA-ICP-Q-MS analysis of single mineral phases in the Roxby Downs Granite (RDG), the dominant host of the deposit, suggest least-radiogenic,  $^{207}\text{Pb}$  vs  $^{206}\text{Pb}$  ("7/6") ratios of 0.947 with congruous  $^{208}\text{Pb}$  vs  $^{206}\text{Pb}$  ("8/6") ratios of 2.215 in alkali-feldspar. While these ratios are consistent with the Pb-Pb 'orogene' growth curve of Zartman & Doe (1981), they present model ages of ~1400 Ma - some 200 My younger than the U-Pb zircon-ages. For these data to be conformable either the RDG was originally derived from a high-μ source, or the alkali-feldspars we have investigated have been entirely recrystallised by late-stage fluids derived from a high-μ reservoir related to mineralisation. The former possibility is in agreement with least-radiogenic Pb of siderite (0.935), rare-galena (0.931) and chalcopyrite (0.925) which are slightly more uranogenic (8/6 ratios of 2.181, 2.178 and 2.150, respectively). The majority of chalcopyrite within the deposit, however, contains much more radiogenic Pb with 7/6 ratios of 0.6 – 0.1. Alkali-feldspars from other Hiltaba Suite Granites (1590 – 1575 Ma) were also analysed and present a case for regional variation of μ, with the Pegler Granite displaying older Pb-Pb model ages than expected (c.2090Ma) indicative of a low-μ reservoir, while the Kychering Granite shows Pb-Pb model ages in accordance with zircon U-Pb ages suggesting normal 'orogene-μ'.

This preliminary data suggests the sources for the 1590 – 1575 Ma magmatic event in the Gawler Craton are heterogeneous, and although early indications are that the RDG is associated with an anomalously high-μ source, further investigation is needed to confirm initial Pb are being measured and to better understand the implications for mineral exploration.

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## The interactions of Arsenic minerals and microbes in groundwater

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Arsenic (As) is still a global public health issue, particularly for groundwater contamination used for drinking water. It is widely distributed in the nature as minerals. The aim of this study is to understand the role of microbes for As-minerals dissociation in groundwater. 7 standard As-minerals were employed in bacteria-free groundwater and stored in vessels for 1 year without supplementary nutrients. The pH (6.7–8.4) and Eh<sub>S.H.E.</sub> (24–548 mV) was found to be changed between initial and final stages of 365 days incubation. The As dissolutions from arsenolite ( $4240 \pm 8.69$  mg/L) and native arsenic ( $4538 \pm 9.02$  mg/L) were detected higher, whereas moderately dissolved from orpiment ( $653 \pm 3.56$  mg/L) and realgar ( $319 \pm 2.56$  mg/L) in compare to arsenopyrite ( $85 \pm 1.25$  mg/L) and tennantite ( $3 \pm 0.06$  mg/L). The abundance of As-resistant *bacillus*, *coccus* and filamentous types of microorganisms on the surface of most of As-mineral was revealed by optical microscopic and scanning electron microscopic observations. The presence of DNA was confirmed by 4'-6-Diamidino-2-phenylindole (DAPI)-stained epifluorescence micrograph. Also the enzymatically active bacteria on the surface of As-minerals of realgar (As<sub>4</sub>S<sub>4</sub>) were detected using the carboxyfluorescein diacetate (CFDA) staining method. The microbes could enable to survive and mobilize the As in groundwater by bioweathering of As-minerals.

## Geology and Mineralization of the Mt Carbine Deposit, Northern QLD, Australia

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The Mt Carbine quartz-wolframite-scheelite sheeted vein deposit is located ~80 km NW of Cairns, Northern Queensland. It was the largest vein type W deposit in Australia and accounted for 43% of Australia's annual W production in 1986, prior to closure because of international Sn-W market crash. The hard rock resources at Mt Carbine at last review include indicated resources of 18 Mt at 0.14% WO<sub>3</sub> and inferred resource of 29.3 Mt at 0.12% WO<sub>3</sub> (Carbine Tungsten Limited Annual Report 2014). The vein system in Mt Carbine is hosted in Ordovician to Devonian Hodgkinson Formation metasedimentary rocks, which include turbiditic meta-sediments composed mainly of greywacke, siltstone-shale, slate, basalt, conglomerates and chert. There are at least 3 types of felsic igneous rocks in the mining district, including porphyritic biotite granite, equigranular coarse-grained biotite granite and fine-grained felsic dyke that cuts across the ore body. There is no observable contact between granite and the W veins, thus their relationship is unclear. Mineralized quartz veins and chlorite alteration occur in the porphyritic biotite granite, whereas no quartz vein and alteration are present in the fine-grained felsic dyke, indicating that the porphyritic biotite granite was earlier than mineralization and the felsic dyke later than mineralization. This observation is consistent with the latest dating results: the LA-ICP-MS zircon U/Pb age of the porphyritic biotite granite is 298 ± 3 Ma and the felsic dyke 261 ± 7 Ma, whereas the molybdenite Re-Os age from the mineralized quartz vein is 284 ± 1 Ma, and the muscovite <sup>40</sup>Ar-<sup>39</sup>Ar ages are 282-277 (± 1-2) Ma. There is no overlap between the 2 muscovite <sup>40</sup>Ar-<sup>39</sup>Ar ages, probably indicates there was some post-mineralization tectono-thermal activities.

There are four 30-40 m wide vein zones in the open pit with different orientations, with Zones 1 - 3 being ~300°/80° (strike/dip), and Zone 4 270°/65°. Based on drill core logging and open pit observation, the paragenesis sequence has been established. Stage 0 is represented by the deformed curvy and discontinuous quartz-dominant vein with minor to none W mineralization. Stage I continuous quartz-dominant veins have straight and continuous margin, and are composed of wolframite ± scheelite ± K-feldspar ± biotite ± tourmaline ± apatite. Stage II veins are straight & continuous, quartz-dominant with sharp boundaries, and contain chlorite ± scheelite ± wolframite ± cassiterite ± muscovite. Stage III is represented by undeformed straight and continuous quartz ± chlorite ± muscovite ± molybdenite ± arsenopyrite ± chalcopyrite ± pyrite ± pyrrhotite ± sphalerite veins, without W mineralization. Stage IV veins are featured by the undeformed straight and continuous shape and quartz ± calcite ± fluorite mineralogy without any W mineralization. The W mineralization is mostly in stage II quartz veins, with less economic W mineralization in the other 3 stages of veins. Ore minerals are wolframite and scheelite. Wolframite is typically euhedral and occurs in quartz veins, while the occurrences of scheelite are: (1) euhedral grains in quartz vein and, (2) pseudomorphing wolframite grains or cutting across wolframite grains as veinlets.

## Sedimentary facies within the Olympic Dam Breccia Complex: A potential metal source

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One of the largest known economic accumulations of metals, the supergiant Olympic Dam Cu-U-Au-Ag-REE deposit is hosted by a hematite-rich breccia complex (Olympic Dam Breccia Complex – ODBC) within a granite pluton. The ODBC is largely granite-derived with locally abundant felsic volcanic clasts, domains of sedimentary facies and multiple generations of mafic-ultramafic dykes. The sedimentary facies include quartz- and hematite-rich sandstone and mudstone, volcanogenic mudstone and sandstone, volcanogenic conglomerate, ironstone, tuffaceous mudstone and quartz-rich sandstone. The sedimentary domains have been interpreted as the remnants of a sedimentary basin that was present above and subsequently incorporated into the ODBC. If correct, the metal endowment of the sedimentary facies, as well as that of any basinal fluids, may have contributed to the deposit resource. Testing this hypothesis requires information on the provenance and relative timing of formation of the sedimentary facies.

Detrital zircon geochronology and petrography reveal the main sources of components in the sedimentary facies are Hiltaba Suite granite(s) as well as mafic and felsic Gawler Range Volcanics (GRV). Zircons in the tuffaceous mudstone have ~1590 Ma ages and demonstrate at least part of the sedimentary facies was contemporaneous with eruption of the GRV. The compositions of detrital Cr-spinel grains match those of GRV-age picritic dykes intruding the ODBC, suggesting that these ultramafic units contributed locally to the sedimentary basin. Weathering and reworking of the picritic units may have released and concentrated metals such as Cu into the sedimentary basin, to be subsequently incorporated into the ODBC.

The quartz-rich sandstone is petrographically similar to the regionally extensive, ~1400 Ma, red-bed Pandurra Formation, which infills the Cariewerloo Basin. It contains ~1600 Ma, ~1740 Ma, ~1900 Ma and ~2500 Ma zircons, similar to those in the Pandurra Formation. If this facies in the ODBC is the Pandurra Formation, it indicates that not only did the Cariewerloo Basin once extend over Olympic Dam, but that the ODBC was tectonically active at least 200 myr after initial formation. The Pandurra Formation is prospective for unconformity-related U deposits and may have served as a conduit for the introduction of oxidised, U-bearing, basinal fluids for 100s of myr after the initial formation of the ODBC.

Incorporation of the sedimentary facies into the ODBC may have been more significant than currently appreciated; a substantial proportion of the fine-grained component of the ODBC may be the result of disaggregation of the sedimentary facies. The potential involvement of sedimentary facies in the formation of Olympic Dam carries significant implications for the genesis of large IOCG-U deposits. The overprinting of an IOCG deposit by unconformity-related U in a sedimentary succession may help account for Olympic Dam's supergiant status.

## Direct temperature estimates of glendonite formation and transformation

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Glendonites are calcium carbonate pseudomorph minerals formed by the dehydration, during burial, of the mineral ikaite (calcium carbonate hexahydrate,  $\text{CaCO}_3 \cdot 6\text{H}_2\text{O}$ ). Ikaite forms between -2 to 7 °C (Bischoff et al., 1993, De Lurio and Frakes, 1999) in alkaline organic-carbon-rich sedimentary environments. The presence of ikaite and its glendonite pseudomorph has been used as an indicator of polar and glacial cold-water occurrences in Permian to recent marine deposits (Bischoff et al., 1993a, 1993b; Burchard et al., 1998, 2001; Selleck et al., 2007, Lu et al., 2012). In this work, we apply clumped isotope measurements for the first time, to natural low-temperature carbonate minerals, seeking to recover the temperature of formation of ikaite or of the transformation to calcite or of later burial events.

Clumped isotope analysis examines the affinity of heavy isotopes of carbon dioxide ( $^{13}\text{C}^{18}\text{O}^{16}\text{O} = ^{47}\text{CO}_2$ ) bonding together in favour of the lighter isotopes ( $^{12}\text{C}^{16}\text{O}^{16}\text{O} = ^{44}\text{CO}_2$ ) in  $\text{CO}_2$  evolved from the reaction of carbonates with phosphoric acid. This process of “clumping” is reported as a deviation of the abundance of mass 47 (largely  $^{13}\text{C}^{18}\text{O}^{16}\text{O}$ ) or  $\delta_{47}$  (in per mil ‰) relative to the natural random stochastic distribution. This deviation is sensitive to ambient temperature at the time of carbonate precipitation, so can be used to determine palaeotemperatures, and is independent of bulk isotopic composition of the precipitating host water.

$\delta_{47}$  can be measured to a precision of  $\pm 0.01 \text{ ‰}$ , implying a resolution, at Earth-surface conditions, of about  $\pm 2^\circ\text{C}$  from a sensitivity of about 0.004 per mil per degree Celsius.

Glendonites from nine localities around the world, including Siberia in northern Russia, western United States of America and various localities from inland and coastal Australia have been collected and their carbonate powders analysed for clumped isotopes. The specimens originate from a wide variety of geological settings and various geomorphological regimes and processes. Glendonites from near-modern analogue environments produce calculated  $\delta_{47}$  temperatures close to the likely initial ikaite formation temperatures. Thus glendonites from marine Neogene/Quaternary sediments off the coast of the Taymyr Peninsula (Arctic Siberia) gave temperatures of 7°C, whereas glendonites (thinolite) from non-marine Alkali Lake, Nevada, have temperatures of 6 to 10 °C. The calculated  $^{18}\text{O}_{\text{water}}$  value of the Taymyr glendonites (-0.7‰ SMOW) indicates that calcite preserves the  $^{18}\text{O}$  value of its precipitating seawater. Older, Permian glendonites from the Sydney Basin provide temperatures of 1.5 to 10°C, also indicative of likely near-original ikaite formation; however, their calculated  $^{18}\text{O}_{\text{water}}$  values are lower and indicative of post-depositional meteoric water exchange during burial. Some, more deeply buried Permian examples (e.g. Tunbridge, Tasman Basin) record higher temperatures (~65°C) as a result of such burial, although such numerical values may not be correct as they reflect isotopic diffusion and partial exchange.

## Post-Gondwana thermo-tectonic evolution of Tasmania and the South Tasman Rise

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Evolution of the eastern Gondwana break-up history of the SE Australia margin has been strongly influenced by two rift systems (the Southern Rift System, SRS, and the Tasman Sea Rift, TSR). These developed in response to landmass dispersal since Late Jurassic-mid Cretaceous time. Tasmania and the offshore South Tasman Rise (STR), lie in a crucial location at the centre of the previously adjacent Gondwana continental fragments (SE Australia, N Victoria Land and Zealandia) and potentially contain clues related to the dispersal and post break-up thermo-tectonic history.

We report the first systematic low-temperature thermochronological study on both onshore and offshore Tasmanian rocks, utilising apatite fission-track (AFT) and zircon and apatite (U-Th-Sm)/He (ZHe and AHe) dating techniques. These methods used together (typically temperature sensitive over a range of ~40-200°C) increase the resolution and accuracy of low temperature thermal modeling and provide a better understanding of cooling histories and rates, associated with tectonic processes. Various lithologies from onshore have been analysed, but here we mainly report data from the Middle Jurassic (~180 Ma) Tasmanian dolerites. The advantage of focusing on this unit, which heralded Gondwana breakup, is that it is widely distributed and was emplaced in a relatively short time. Offshore, we report data from dredged crystalline basement rocks, sampled during AGSO Cruise 147 over the western (W-) and eastern (E-) sections of STR, which was derived from two blocks of different tectonic affinities.

Time-temperature modelling of AFT, ZHe and AHe data indicates different regional thermal histories. A few samples from central and NE Tasmania, and from offshore basement highs in W-STR record pre-break-up ages (~290-110 Ma). This finding is in agreement with data reported from the SE Australian highlands, suggesting that prior to continental dispersal these rocks had cooled to <110°C and have not been thermally disturbed since that time. Most data elsewhere yield mid Cretaceous or younger ages suggesting distinct cooling episodes associated with regional tectonic events. (1) Mid- Cretaceous cooling restricted to the SE coastal area of Tasmania involving km-scale denudation (~3-4 km). This cooling is probably related to continental extension prior to the onset of actual seafloor spreading in the Tasman Sea and has been reported elsewhere in SE Australia. (2) Onset of opening of the Tasman Sea at ~80 Ma which resulted in newly formed ocean-floor followed by crustal thinning due to rifting between the E-STR and the Tasmania block. (3) Late Cretaceous-early Tertiary cooling, restricted to the western margin of Tasmania in response to amalgamation of the W- and E-STR blocks and transform margin tectonism to the west. (4) Early Eocene shift of relative motion between Australia and Antarctica that formed the Toogee Ridge in the northern W-STR. (5) Middle Eocene to Oligocene final clearance of continental break-up and onset of the opening of the Tasman Gateway in the southern section of the offshore escarpment defining the W margin of the W-STR.

## Towards a suitable natural standard for routine U-Pb dating of iron oxides

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Hematite and magnetite are important components of Iron-Oxide Copper Gold (IOCG) and Banded Iron Formation (BIF)-style deposits, both of which are widespread throughout the crust of South Australia. Anomalously high-concentrations of rare earth elements and Y (collectively, REY) and the elements U, W, Sn and Mo ('granitophile elements'), as well as distinct variation in chondrite-normalised REY-fractionation trends, have been reported for Fe-oxides from different parts of the Olympic Dam (OD) IOCG deposit [1]. In combination with preliminary U-Pb dating of Fe-oxides, these trace element patterns help define differences between samples from deep (early; ~1.6 Ga) and shallow (late; ~1.4-1.2Ga) parts of the OD breccia complex. Fe-oxide geochemistry also assists recognition of older (~1.8-1.75Ga), inherited BIF-type protoliths [2] on the margins of the deposit, encapsulated within the ~1.6Ga Roxby Downs Granite, hosting OD mineralisation. The reliability of Fe-oxides as a versatile tool for geochemical fingerprinting, geochronology and genetic modelling depends upon understanding the mechanisms of trace element incorporation/release, as well as greater insight into the causes of compositional heterogeneity observed in Fe-oxides from OD. These factors impact significantly upon the identification of natural material suitable for use as a matrix-matched standard for U-Pb geochronology applications.

Here we show that, at OD, high-W hematite is more widespread than the high-U type (e.g. at deposit edges and upper, middle part of the orebody). Considering that the presence of W is always a good proxy for U, we provide insights into the nanoscale characteristics of such hematite.

Larger unit cells (superstructures) that assume metal vacancies were inferred from Transmission Electron Microscopy (TEM) study of high-U, oscillatory-zoned hematite [3]. TEM study of high-W hematite (up to 1-2 wt.% W) and of low-U (hundreds ppm U) from the deep, SE lobe of the deposit [1,2] instead shows domains with a simpler, 2-fold superstructure (Liu and Ciobanu, unpublished data). Understanding the distribution of these domains relative to W-rich zones requires High-Angular Annular Dark Field (HAADF) and Scanning-TEM imaging. This was performed using the ultra-high resolution FEI Titan Themis TEM (Adelaide Microscopy) on a foil prepared *in-situ* by Focused Ion Beam-SEM. The sampled hematite co-exists with high-U hematite in dated high-grade ore [3]. HAADF-STEM high-resolution imaging shows defect-free, compositionally homogenous hematite except the presence of darker areas, a few nm in width. The 2-fold superlattice, detected only by electron diffractions is restricted to such areas. HAADF-STEM imaging shows coherent lattice fringes across the boundary between hematite and inclusions of a W-bearing mineral, wolframite, 10-20 nm across. This suggests W substitution into oxygen sites, which may be a more robust mechanism for trace element incorporation than the direct metal-for-metal substitution suggested for high-U hematite [3]. Further work will be undertaken to better assess the dark areas attributable to O vacancies, and provide a key to understand how the crystal structure behaves during trace element incorporation/release.

### References

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## **Outback Geotourism in South Australia: a bridge between the rocks and a dry place**

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The “Outback” of inland South Australia is a largely untapped resource for modern geotourism. It lies within the rugged regional terrains of arid-land and desert landscapes hidden “beyond the bitumen” of industrially and agriculturally developed and populated southern SA. Here excellent, but largely isolated, examples exist of entrepreneurial geotourism innovation. These range from the well-established and popular “drive through the ages” geotrail of Brachina Gorge in the Flinders Ranges including the Ediacaran golden spike, to the outstanding organ pipe, columnar jointed lava geosites of the Gawler Ranges and the rugged exploration history of Arkaroola and the Mt Painter inlier, best revealed in the book “Geology is Fun” by former local geotourism legend Reg Sprigg.

Interpretation of these sites is by geological signs, local guides and leaflets. However, without the impetus of geopark recognition, the development of regionally integrated geotrail guides or the use of new multimedia, digital and aerial video and mobile visual aids and apps, there is little likelihood of accelerated growth in much needed geodiversity recognition, geoconservation and geotourism.

The recently opened Witchelina conservation property in the Willouran Ranges of far northern SA is another outback geosite, as yet undocumented for its obviously rich geotourism potential. Sensational areal visages of folded early Adelaidean stratigraphy, complex thrusts and faults and enigmatic possible salt-tectonic related piercement structures provide an inventory of geosites which are embedded in a remote and rugged terrain criss-crossed by established 4WD tracks. Current geological investigations in the area offer the opportunity to integrate active geoscience research with visitor experience studies to further expand outback geotourism in South Australia.

Visitor segmentation studies suggest that it is important to consider visitor experiences on-site from a ‘desired experience’ perspective. These studies have looked at the behaviour of visitors at both natural and cultural sites, in a number of countries, to evaluate the most meaningful and successful visitor experiences. Four categories of ‘desired visitor experiences’ have been established: Social Visitors, Learn Together Families; Intellectual Visitors and Sensualists; all of these groups could be engaged by the geotourism opportunities at SA outback geotourism sites, such as Witchelina.

Tourism Australia is responsible for marketing Australia as a destination for international visitors interested in nature-based tourism and works cooperatively with key partners, including the South Australian Tourism Commission, using the global marketing campaign *‘There’s nothing like Australia’* as the creative platform to promote Australia’s nature offering to the world. Outback SA can provide sustainable desired visitor experiences in geology, landscape, flora and fauna, as well as prospects for engaging in star-gazing in pristine Outback skies and engagement with indigenous Aboriginal culture, both traditional and contemporary.

Enhancing outback geotourism could go a long way towards extending a bridge between SA rocks and a dry place!

## Unravelling the Giant: Evidence for post-mineralisation modification of the Olympic Dam Cu-Au-U-Ag deposit, Gawler Craton, South Australia

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The Olympic Dam (OD) iron-oxide-copper-gold-uranium-silver deposit formed during the ~1.59 Ga Kararan orogeny shortly after emplacement of widespread post-collisional Hiltaba Suite Granitoids and Gawler Range Volcanics; including minor ultramafic-mafic subsidiaries. The complex geology and sheer size of OD has been the focus of the wider academic and exploration community since its discovery in 1975 and has witnessed a multifaceted evolution of ideas proposed for its ore genesis and geotectonic setting. However, there is now growing evidence that supports OD evolving progressively over ~1.0 Ga, responding to major tectono-thermal events (e.g. 1.3 -1.1 Ga, 0.825 Ga, and 0.5 Ga) implying several post-mineralisation modification events that have shaped the.

Since 2005, underground development and drilling programs (>1000km of diamond drill-core) into the Southern Mine Area (SMA, ~70% of the OD Mineral Resource) have generated new geological, geochemical and structural datasets providing on-site mine geologists the opportunity to re-evaluate previous geological and structural interpretations of the deposit.

Recent underground mapping in Mine Area A (one of 5 mine areas within the SMA) has identified post-mineralisation deformation event(s) that have caused major reworking and structural dislocation of mineralised hematite-rich breccia and associated lithotypes. Evidence of up-to ~150 metre structural offsets of lithotypes and associated mineralisation as down-thrown blocks was discovered verifying a newly orientated, strong structural control on contemporary mineralisation trends. Further investigation led to the discovery of a large-scale listric normal fault system within a localised negative flower structure extending throughout the mine area and potentially across to neighbouring areas within the SMA. As a direct result we see an inverted mineralogical zonation pattern throughout Mine Area A demonstrated by shallow, bornite-chalcocite(-hematite)-dominant assemblage hosted within down-thrown, rotated ‘blocks’ in the deepest parts of the orebody; in contrast to pyrite-chalcopyrite(-magnetite)-dominant assemblage evident in the shallower-levels. In some places the listric normal faults are ‘infilled’ with coherent Gairdner Dolerite Dykes, which may have acted as conduits for the rising magmatism.

The negative flower structural architecture is heavily influenced by the long-lived Masher’s fault zone (i.e regional Jubilee fault zone), in-which all identified listric normal faults terminate at this structure creating a series of localised extensional duplexes. Later, reactivation of the listric normal faults under an interpreted transpressional regime is evidenced by rheologically-constrained (or weaker) blocks of rock mass that have been in-turn thrusted with minor strike-slip displacement along these structural zones suggesting local basin inversion. Evidence for widespread uranium +/- copper-gold remobilisation is interpreted to have also occurred in response to this later, deformation event.

Although, these deformation events are poorly constrained, the listric normal faults within the extensional duplex architecture are not observed to intersect the overlying, unaltered Neoproterozoic to Cambrian sedimentary rocks therefore constraining the event to have occurred >1.59 Ga and <0.75 Ga. We propose this was most likely in response to the break-up of supercontinent Rodinia at ~850 Ma. Later, metal remobilisation, reactivation and localised basin inversion of said structural architecture occurred post-Adelaidean sedimentation (i.e. >0.515 Ga), most likely during the Delamerian Orogeny during assembly of supercontinent Gondwana (0.515 – 0.485 Ga).

## The International Ocean Discovery Program (IODP): *JOIDES Resolution* operations in the Indian Ocean (2014–2016)

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The *JOIDES Resolution* has been operating in the Indian Ocean since November 2014, conducting a series of expeditions focused on: 1) the history and evolution of the Monsoon climate system, 2) the erosional history of the Himalayas, 3) the history of warm water flow from the Western Pacific Warm Pool into the Indian Ocean via the Indonesian Throughflow and the transport of ocean heat out of the Indian Ocean into the Atlantic via the Agulhas Current, and 4) the nature of deep ocean crust as exposed on the Atlantis Bank (Southwest Indian Ocean Ridge).

Expeditions 353, 354, 355 and 359 provided histories of precipitation and runoff in the Bay of Bengal and Laxmi Basin, as well as the influence the Monsoon development on the Maldives carbonate platform. Combined with the Asian Monsoon Expedition (346) results, these expeditions will redefine our understanding of the Monsoon climate system.

Expeditions 353, 354 and 355 recovered sediments that document the uplift and erosional history of the Himalayas, making it possible to examine the roles of tectonics and climatic change in the denudation history of this mountain chain, the result of a major continent-continent collision.

Expedition 356 cored a latitudinal transect off the northwest coast of Australia, obtaining a Miocene to Holocene record of Indonesian Throughflow, Indo-Pacific Warm Pool and climate evolution. Expedition 361 (under way as of the writing of this abstract) is drilling a transect of sites off the southeastern coast of Africa to document the evolution of the Agulhas Current and its effects on South African climate. Results from these two expeditions, combined with the Western Pacific Warm Pool Expedition 363, scheduled for late 2016, will provide major constraints on the globally important transfer of oceanic heat through the Indian Ocean.

Expedition 360 was the first leg of a multiphase drilling program that ultimately aims to drill through the Moho seismic discontinuity at a slow-spreading mid-ocean ridge. This expedition achieved the deepest igneous rock penetration from the seafloor during a single *JOIDES Resolution* expedition (789.7 mbsf) and recovered 469.4 m of core that constrains the spatial and temporal scales of magmatic accretion of the plutonic lower oceanic crust and the mechanisms by which it is exhumed.

Operationally, two recent developments have contributed significantly to the success of these expeditions: 1) Deployment of a drill-in casing reentry system significantly reduced the time required to prepare holes for deep penetrations during Expeditions 354 and 355. Application of this drill-in approach with a modified reentry and release mechanism allowed bare-rock spud-in and installation of a reentry and casing system during Expedition 360. 2) Deployment of the recently developed Half-Length Advanced Piston Coring system continued to make it possible to recover soft sediment from greater depths than previously possible, extending the time range of sediments suitable for high-resolution paleoceanographic study. Notably, the use of this tool during Expedition 354 made it possible to recover turbiditic sands from the Bengal Fan system—a critical objective of this expedition.

## **Analytics for material classification in a connected world**

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Material classification of geological samples is increasingly important throughout the life cycle of a minerals project from initial targeting to mine planning and scheduling. The minerals industry is living through a period of rapid change with two major technological changes; 1, the interconnectivity of devices and data often referred to at the Internet-of-Things (IoT), and 2, new technology allowing real-time data collection during drilling. With pressure on the economic factors of exploration and mining driving a focus on productivity and efficiency how will we be doing business in the future?

Uptake of new technology such as portable XRF and VNIR systems have led to increases in the rate at which we can generate geochemical data as we drill. A key problem is managing the flow of data from the tool to the tablet of the decision maker, even with good communication systems the data needs to be validated, audited and controlled for use. Developments in cloud-based data systems can be used to provide the connectivity platforms that link the tools to the decision makers in real time. Drilling in Africa, reviewing the assay data in Perth.

However in many cases the geologist is now faced with overwhelming data but is no better off with respect to making the right decision. So how can we turn data into information? Analytics can be used to turn data into knowledge. In the simplest form this includes Exploratory Data Analysis in desktop software; giving the geologist tools to quickly assess the quality and meaning behind the data relationships. More advanced analytics using approaches like Artificial Neural-Networks will be required to automate the processes of material classification such that assay data can be turned into rock properties via cloud-based Software-as-a-Service platforms. Drilling in the Pilbara, mine planning in Perth in real-time. The geologist will have time to think not drown in data.

Using the REFLEXHUB-IQ system we have made geochemistry and gamma data available in near-real time to the geologist remote from the site of drilling. Consuming the data into tools such as ioGAS enables us to provide quick, first pass, automated logging support through analytics such as Self Organising Map (SOM) analysis. For instance Ti data is shown to map basalt flow boundaries that are not detected in traditional logging, or SOM classifications can be used to aid cross hole correlation of distinct chemical units. The ease of this process, with IoT enabled technology, provides a clear application into the day to day exploration and mining workflows, and supports the process of decision by the geoscientist.

## **Sedimentary processes, stratigraphic sequences, and middens: the link between archaeology and geoheritage – a case study from the Quaternary of the Broome region, Western Australia**

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The cliffted and active dune coastal region of Broome provides an excellent record of Pleistocene and Holocene stratigraphy of desert environments interfacing with the Indian Ocean. The Mesozoic Broome Sandstone is the basal stratigraphic unit in the area, and this is overlain by Pleistocene red desert quartz sand (the Mowanjum Sand) that has expression geomorphically as linear dunes. Modern coastal processes of waves, wind, and tide have resulted in development of distinctive sedimentary bodies (stratigraphic units) that are clearly linked to sedimentary environment. The Mowanjum Sand reworked by coastal winds generated/generates the landward ingressing orange quartzose Churchill Sand. The Mowanjum Sand where reworked by waves and abraded to white sand with addition of carbonate grains forms the principal component of the beaches and, with aeolian action, the coastal dunes or inland ingressing white dunes (Shoonta Hill Sand). Quartz sand in the low tidal zone, inhabited by a diverse biota forms the shelly Port Smith Sand. Carbonate mud influx from the open sea accumulates in the tidal zone as the Samphire Calcilitute – its low-tidal expression is replete with fauna and is often mollusc-rich forming shelly carbonate mud; its upper-tidal expression is inhabited by mangrove systems forming root-structured, shelly carbonate mud.

These sedimentary bodies and their stratigraphic units form a template with which to slot in and interpret archaeological middens and Indigenous occupation over the past 5000 years in a context of coastal occupation, coastal stability, mean sea level changes, climate changes, and availability of marine food and freshwater. Shell middens and stone artefacts occur in definitive layers or horizons in relation to the stratigraphic array, sometimes *in situ*, and other times reworked as sheets and plumes, and understanding their inter-relationships has enabled unravelling of the archaeological history and relating Indigenous occupation to biofacies and lithofacies.

The array of sedimentary, biofacies, and stratigraphic units are of National geoheritage significance in their own right. The addition of archaeological deposits as stratigraphic units provides a link between geoheritage and archaeology, where the archaeological materials are viewed as part of the complex stratigraphic story, part of the coastal history, and part of the geoheritage story.

## Full Plate Topological Reconstruction of Gondwana Amalgamation

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We present the first full plate topological reconstruction for the Neoproterozoic-Cambrian construction of the supercontinent Gondwana. The reconstruction uses GPlates and incorporates the limited well-constrained palaeomagnetic record for the Neoproterozoic as well as considerable geological information as to the nature and evolution of the plate margins. Here we have expanded the continental plate-margin record (such as continent-continent collisions, intra-continent rifts and continent-margin subduction zones) with extensive geochemical and geochronological data from Neoproterozoic intra-oceanic subduction zones; the volcanic arc products of which occur, often highly deformed and metamorphosed, within the Gondwana-forming orogens that lace Africa, India, Antarctica and South America.

Here we present new U-Pb, O and Hf zircon and Nd whole rock isotopic data from Ethiopia, Egypt, Oman, Madagascar, Saudi Arabia and India that, along with published data from other workers, constrain the subduction history of the Mozambique Ocean, and from that the nature of the plate boundaries between Neoproterozoic India, Azania and both the Congo-Tanzania-Bangweulu Block and Sahara Metacraton of Africa. These form the core of the global plate topological reconstruction that we have constructed. The reconstruction forms an imperfect early version. More complementary data will enhance the reconstruction and we encourage the collection and publication of these data to improve this model.

The production of full-plate topological reconstructions now allows tectonic geographic controls on other earth systems to be investigated, such as the possible role of volcanism on initiation of the Cryogenian, or the nature of Mantle convection in the Neoproterozoic.

## Testing Azania: Using Detrital Zircon U-Pb Ages and Hf Isotopic Record to Constrain Tectonic Affinities Within the East African Orogen

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Azania was proposed as a Neoproterozoic continent that consisted of rocks now lying in southern India, central Madagascar, East Africa and Arabia. The continent was hypothesised to have originated against eastern Africa in the earlier Proterozoic, but to have rifted off it by Tonian times when it was separated from East Africa by oceanic crust. The original model had this continent then reassembling with the Congo-Tanzania-Bangweulu Block at ca. 640 Ma and then Neoproterozoic India colliding with the resulting amalgam at ca. 550 Ma. A variation of this model was later published where Azania collided first with India and then later with African Gondwana. What these models share is an ‘African’ origin for central Madagascar and its corollaries and the presence of a cryptic suture that separates Azanian rocks from those of Neoproterozoic India in eastern Madagascar; a feature named the Betsimisaraka Suture.

Other workers developed competing models where Azania did not exist as a separate continent, but formed in the Neoarchaean to Palaeoproterozoic and accreted immediately after formation to the Dharwar Craton of India to form a ‘Greater Dharwar’ continent that remained an accretionary margin through much of the Proterozoic to eventually collide with African Gondwana in the Ediacaran along one ocean suture. Other models have proposed hybrids where Azanian Madagascar is part of Greater Dharwar, but additional enigmatic microcontinents occur in southern Madagascar/southernmost India, or that the whole of Madagascar forms a number of discrete small Neoproterozoic microcontinents that progressively accreted to India.

The original arguments for the existence of Azania are based on the origin and tectonic affinity of the voluminous Palaeoproterozoic detritus found within pre-orogenic metasedimentary rocks in Madagascar (and subsequently southern India). These studies were initially based on U-Pb SIMS and LAICPMS zircon ages alone and showed that regions assigned to ‘Azania’ had detritus with ages consistent with rocks known from eastern Africa but absent in southwestern India. Subsequently, other workers proposed that these apparently diagnostic sand grains may have been transported across much of India from east and northeast Indian sources as there are basins in India of the right age (the so-called Purana Basins), but at that time with no information of the age of the detritus filling the basins. New U-Pb and Hf isotopic data suitable for this fingerprint-like analysis has recently been published from many of the Purana basins of India and from ‘Azanian’ terranes in southern India and Madagascar, but until now comparable Hf isotopic data has been missing from eastern Africa. Here we present the first results from an on-going project to collect these data and use these multi-proxy isotopic fingerprints to test the ‘Out-of-Africa’ model for Azania.

## U-Pb and Hf Zircon Data Sources the New Zealand Torlesse and the Ceduna Sub-Basin Sediment Origin to Queensland, Indicating Widespread Mesozoic Erosion and Sediment Distribution

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Extensive volumes of sediment deposited in the Mesozoic subduction-accretion complexes along the margin of eastern Gondwana (Torlesse terranes of New Zealand and basement of New Caledonia) and in extensive rift-passive margin basins within Australia and along the future Australia-Antarctica margin (Ceduna sub-basin) preserve zircon U-Pb ages that have been used to suggest an origin in northern Queensland. Here we present extensive new U-Pb and Hf detrital zircon data from the Rakaia Terrane New Zealand and from the Upper Delta lobe in the Ceduna Sub-basin (from the Gnarlyknots 1A well). We complement these data with <sup>40</sup>Ar-<sup>39</sup>Ar detrital muscovite ages to examine the degree of zircon recycling.

In the Rakaia Terrane, new detrital zircon data yielded age populations at 1100-980 Ma, 580-450 Ma, ca. 320 Ma and ca. 230 Ma. Hf(t) values of these zircons largely range from -6 to +6 and the trace element concentrations suggest that the zircons are primarily sourced from granitoids. The <sup>40</sup>Ar-<sup>39</sup>Ar analysis yielded two ages with the first at ca. 340 Ma and the second at ca. 250-220 Ma. The U-Pb ages and Hf(t) values for the Ordovician and older zircons are most similar to those from the Lachlan Fold Belt while the younger zircons show a close similarity to those from the New England Fold Belt. Multidimensional scaling maps suggest a strong association between zircons from the Rakaia Terrane, north eastern Queensland and the Lachlan Fold Belt. The detrital muscovite data, however, is consistent with an exclusive New England source. Combining the data from different isotopic systems and different minerals, we interpret the Triassic provenance of the Rakaia Terrane as being derived from the New England. The presence of Cambrian and Precambrian zircons, but only Phanerozoic muscovites, is interpreted as demonstrating that zircons were recycled in the New England region from older rocks now exposed in the Lachlan Orogen.

Detrital zircon Hf isotopic data presented here fingerprint the original source of the upper delta lobe zircons to NE Australia, with data comparing well with similar U-Pb and Lu-Hf isotopic data from the Lachlan Orogen, the New England Orogen, the eastern Musgravian Province and the northern Flinders Ranges. We discuss the variation in origin of these two Queensland derived Mesozoic systems within the tectonic geography of the times.

## How many times did Proterozoic Australia disperse and re-assemble?

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Over 2/3 of the Australian continent consists of Proterozoic fold belts containing Archean nuclei, and can be broadly subdivided into the North (NAC), South (SAC) and West Australian (WAC) cratons. These amalgamated to form “proto-Australia”, but when? The NAC and SAC formed during the late Paleoproterozoic (1900-1600 Ma) as part of a vast, S-migrating, accretionary orogen, and many consider that the WAC accreted to the NAC (Yapungku Orogeny) during this period. Thus, proto-Australia seemingly had formed by 1600 Ma, but already, it was dispersing. Geological evidence from the southern Arunta region suggests the SAC rafted from the NAC by ~1600 Ma, as part of the Mawson continent. Also, recent metamorphic studies on the Rudall Complex suggest that the HP-amphibolite facies metamorphic events associated with the collision of the WAC and NAC, the so-called Yapungku Orogeny, occurred at ~1300 Ma, not 1800-1760 Ma, and followed a series of higher-T events associated with accretionary orogenic processes. Did proto-Australia form at 1300 Ma?

Protoliths to the Musgrave belt originated as a continental arc along the WAC margin at ~1690 Ma, and its rapid evolution to oceanic character (from zircon Hf arrays) suggests it had rafted off as a continental ribbon by 1600 Ma. However, the younger Musgrave zircon (Hf) array indicates continuous magmatic arc activity until 1200 Ma, and its distinctive inverted U-shaped pattern is evidence for a Proterozoic Wilson cycle (or supercontinental cycle!), culminating with terminal WAC-SAC collision along the Albany-Fraser orogen at 1200 Ma. Subsequent tectono-thermal activity between 1200-1120 Ma recorded in the southern Arunta region and Musgrave orogen was dominantly extensional tectonism associated with granulite to UHT metamorphism, and voluminous high-T granitic intrusions. Orogen-scale contractional mylonite zones dated at ~1130 Ma indicate that the NAC and SAC amalgamated at this stage. Did proto-Australia form at 1100 Ma?

Interestingly, MT data recorded beneath the Amadeus Basin suggest S-directed subduction during NAC-SAC collision, with the Musgraves as the upper plate. This “upper plate” also contains enigmatic younger (~1070 Ma) mafic dykes with island-arc affinities, extending over 300 km across-strike, implying a new cycle of subduction, consistent with paleomagnetic evidence that Australia was not amalgamated at this stage. Initial magmatism coincides with generation of the 1070 Ma Warakurna LIP and opening of the Centralian Superbasin, implying strong post-collisional, intraplate extension. However, younger Neoproterozoic mafic rocks in central Australia have persistent negative Nb-Ta anomalies and increasing positive wholerock Nd isotopic values, implying ongoing subduction-modified rather than intraplate magmatism. 650-600 Ma Barrovian metamorphism in the western Musgraves also suggests ongoing orogenesis. Inverted U-shaped Hf arrays from zircons derived from Paterson province granites and Centralian Superbasin sediments further imply a (modified?) Wilson-cycle occurred between 1000-550 Ma. Archean model ages from evolved zircons indicate a WAC source and hence, S-directed subduction, and 590-540 Ma eclogitic rocks in the Petermann orogen probably reflect this event. However, a large ocean was not produced: the geodynamic setting was probably more like post-Pangean Europe-Africa interactions. Proterozoic Australia did not consolidate until 550 Ma, just before the Tasmanides began.

## Seamless Geology of New South Wales

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The New South Wales (NSW) Seamless Geology Project is a five year initiative of the Geological Survey of New South Wales. The project aims to compile the best available vector geological data for NSW into an internally consistent geodatabase. Historically, geological mapping by the Geological Survey has been restricted to series mapping projects at scales ranging from 1:25 000 to 1:250 000, which has resulted in the creation of datasets that are often somewhat irreconcilable at a regional or statewide level. In addition, mapping has traditionally focussed on documenting the exposed geology, with little attempt made to project rock units or structural features under cover. Owing to this approach, interpretation of the NSW basement geology under cover is also limited.

The specific aims of the NSW Seamless Geology Project are: (i) To develop a consistent, statewide stratigraphic nomenclature scheme for all NSW units and to fit the existing geological mapping to this scheme; (ii) select the appropriate 'best available' datasets for different areas; (iii) edge-match the geology between existing map sheets; and (iv) interpret the basement geology under cover. The resulting NSW Seamless Geology geodatabase comprises a series of layers which include: (i) solid basement geology of Precambrian provinces and Paleozoic orogens; (ii) Paleozoic and Mesozoic sedimentary basins; (iii) Mesozoic igneous rocks; and (iv) Cenozoic sedimentary and igneous rocks.

Once completed, the NSW Seamless Geology geodatabase will provide an important reference tool for mineral explorers. As the dataset will be the provide the best available mapping in a seamless coverage – not just at the surface, but also in overlapping strato-tectonic layers – exploration companies will be able to 'peek' under covering basins and surficial deposits to assess the possibility of basement mineralisation. In the past, undercover parts of the state have remained as basement 'blank spots', thus rendering them potentially underexplored.

The datasets from the NSW Seamless Geology Project will also form the basis for many other important outgrowth projects including a NSW Statewide Metamorphic Map, 3D geology datasets covering local and regional areas, and an outcrop geology map which uses soil thickness mapping data from the CSIRO.

The NSW Seamless Geology datasets will be rolled out in individual UTM Zones starting with Zone 56 (covering the coastal regions of NSW). Work commenced on Zone 56 early in 2014 and concluded with the official release of the Seamless Geology dataset in February 2015, which is available for free download at: <http://www.resourcesandenergy.nsw.gov.au/miners-and-explorers/geoscience-information/products-and-data/geoscience-data-resources/geoscience-data-packages/data/seamless-geology-data-package-zone-56>.

Work on the project has moved on to UTM Zone 54 in western NSW, which is scheduled for completion and release in mid-2016. A highlight of the Zone 54 dataset will be a seamless merge of the Geological Survey's very detailed mapping and interpretation of the mineralised Willyama Group Proterozoic sequences of the Broken Hill area. Also of interest to mineral explorers will be the detailed interpretive seamless geology of the largely subsurface Lachlan Orogen, Delamerian Orogen and Thomson Orogen.

In addition, a simplified version of the product has been released for mobile phones and tablet computers, enabling the Seamless Geology datasets to be viewed in the field on mobile devices without an internet connection but still using the devices' GPS capability.

## **Pyrite Variation within the Mount Isa Copper System; Geological and Structural Controls.**

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The giant Mount Isa copper system (North West Queensland) has received a great deal of research over its 90+ year mine life, but the distribution and geochemical variation of pyrite has not been thoroughly investigated.

This project has collected samples from the alteration halo of the X41 ore body and a series of exploration targets up to 5km away from the ore body. The distribution of pyrite has been assessed based on lithological and structural controls and paragenesis of the sulphide stages, with the variation of sulphide species having been established.

Geochemical investigations of the different pyrite species present in the near-mine environment have allowed the individual trace element signatures of pyrite to be defined. Research methods include drill core inspection and sampling, paragenesis studies using optical microscopy, secondary electron microscopy (SEM) and compositional analysis using electron microprobe and LA-ICP-MS.

Defining the trace element signatures of the different ore bodies has potential to assist vectoring for near mine exploration and potential depth extensions to the ore bodies. Geochemical characteristics from different ore bodies can also be compared to establish whether all of the ore bodies were formed coevally from the same hyper-saline fluids, or whether there were episodic ore forming events from an evolving fluid source.

## Structuring & metamorphism of Yorke Peninsula: effects of the olarian orogeny in the southeastern gawler craton

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The discoveries of the iron oxide-associated Olympic Dam and Moonta-Wallaroo Cu-Au deposits were separated by more than a century, however it was the latter that provided the stepping-stone for WMC (Western Mining Corporation) to locate the former. The over-arching condition that affected the eastern margin of the Gawler Craton and the western Curnamona Province at c.1590 was intense deep-seated heating, but components critical to IOCG mineralisation include early Mesoproterozoic magmatism (the Gawler Range Volcanics/Hiltaba Suite/Ninnerie Supersuite/Benagerie Volcanics LIP), intense widespread hydrothermal alteration, deeply plumbing faults, with perhaps the proximity of a pre-existing saline sedimentary succession being critical.

There is an apparent spatial match between the Olympic IOCG domain of the eastern Gawler Craton and late Palaeoproterozoic sediments, including the ~1760 Ma evaporite-bearing volcano-sedimentary Wallaroo Group. These sediments have been interpreted to be the fill of a back-arc basin that migrated easterly, with the 1720-1640 Ma Willyama Supergroup of the Curnamona Province being the youngest remnant. The basement of the Yorke Peninsula is the metagranite-dominated Donnington Suite (Parker, 1993; Cowley et al. 2003), which was metamorphosed to upper amphibolite-granulite facies grade during the ~1850 Ma Cornian Orogeny (Reid et al. 2008).

Commencing at approximately 1620 Ma (Teale and Fanning, 2000; Forbes et al.. 2008) the effects of the Olarian Orogeny reversed the depositional trend by progressing westerly with metamorphism in the Yorke Peninsula dated at about 1580 Ma. Granulite facies at Broken Hill grades northwesterly to greenschist facies at Portia and Kalkaroo. This general pattern is repeated in the Yorke Peninsula region where granulite-upper amphibolite facies rocks were emplaced by thrusting on the Fleurieu Peninsula, and exist on central Yorke Peninsula in the vicinity of Curramulka (BHP 1986) and Hillside (Teale et al. 2016). A possible folded contact separates the high-grade metamorphics from the greenschist facies Wallaroo Group that extends northward past the Moonta-Wallaroo Mines.

Outcrop is sparse on Yorke Peninsula so that any structural interpretation must rely on aeromagnetic imagery. A northeasterly-trending grain relates to long-limbed isoclinal folds, which in the vicinity of Wardang Island are refolded. At Wallaroo North Beach sub-horizontal ductile isoclinal folds were refolded under more brittle conditions to form upright structures (Wurst, 1994) in which the axial fabric hosts calcsilicate alteration. This scenario is identical to that of the southern Curnamona Province during the Olarian Orogeny where alteration and hydrothermal brecciation were coeval with the later brittle event but not the earlier ductile nappe formation. The Tickera Granite is a complex wherein earlier components contain a vertical NE-trending metamorphic foliation (Jack, 1917) but the latest does not. Northwesterly dipping thrust-sets control the Cu-Au mineralisation at the Moonta Mines (O'Driscoll 1942). Consistent with Dentith (2004), if the NE trend is equated with the compressional direction of a thin-skinned left-lateral shear couple, the mineralisation, of the Wallaroo Mines is within strike-slip and R-synthetic structures, and of Hillside in the R'-antithetic Pine Point Fault zone.

## An amphibole perspective into magmatic processes at Sangeang Api volcano, Indonesia

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A key issue in understanding the petrogenesis of subduction zone magmas is the identification of the competing influence of processes that occur at their primary mantle wedge source, versus those that are imposed when these magmas ascend through the crust. Sangeang Api is an active volcano in the eastern Sunda Arc of Indonesia. Erupting most recently in May/June 2014, Sangeang Api produces silica-undersaturated, shoshonitic trachybasalts to basaltic trachyandesites. Entrained within, and interpreted to be coeval with, the lavas are abundant gabbro and pyroxenite xenoliths. These are interpreted as the result of intra-crustal cumulate processes. Sangeang Api provides a natural laboratory in which to study geochemical processes resulting from crustal level magmatic differentiation.

Recent analysis by Ridolfi et al. (2010, 2012) quantify the response of complex solid solution in amphibole to the composition of coexisting melts, allowing it to define magmatic pressure, temperature, water content and oxidation state. Amphibole (Pargasite – Mg-Tschermarkite solid solution) is a common phase in both the Sangeang Api lavas and their coexisting cumulate xenoliths. Amphibole is observed in lavas primarily as phenocrysts and xenocrysts, often displaying disequilibrium textures, that are likely inherited from disaggregated cumulates. Amphibole is common in the gabbroic xenoliths (making up to 60%) and is mostly a primary cumulate phase, but can be an intercumulus or poikilitic phase. In the pyroxenites, amphibole is rare and only found as an intercumulus phase.

Using the Ridolfi et al. (2010, 2012) formulations we have calculated the physiochemical conditions of the Sangeang Api melts in equilibrium with amphibole. Results of amphibole analysis define a continuous pressure range from 0.34 GPa to ~1.0 GPa (equivalent to 12-34.4km depth) for each of the lithologies. Calculated temperatures show amphibole crystallisation over a very narrow range from 978°C to 1176°C. Amphiboles within gabbros record pressures and temperatures across the entire spectrum and the highest calculated figures for both. Pyroxenite analyses record lower calculated pressures and temperatures than much of the gabbro analyses, suggesting that in these cases amphibole crystallised from later percolating fluids. Calculated water contents fall with decreasing pressure and temperature from 3.2wt.%H<sub>2</sub>O to 7.6wt.%H<sub>2</sub>O, a process that can be modelled by the initial addition of 3900ppm CO<sub>2</sub> to the magma and progressive decrease to 1500ppm CO<sub>2</sub>. The calculated decrease in both H<sub>2</sub>O and CO<sub>2</sub> suggests that magmas ascended on a vapour-saturated degassing curve. Redox states range from  $\zeta$ NNO+0.05 to  $\zeta$ NNO+1.2 and become more reduced, approaching the NNO buffer, at lower pressures, possibly due to sulphate degassing during ascent. Sangeang Api records continuous crystallisation of amphibole from depths below the local Moho (~34km) to the mid-crust (~14km) in a series of crustally stacked and variably fractionated magma chambers and conduits that are indistinguishable within our data. Magmas were volatile-rich at depth and degassed as they ascended, decreasing in redox state.

Ridolfi, F., Renzulli, A., Puerini, M., 2010, *Contributions to Mineralogy and Petrology*, vol. 160, no. 1, pp.45-66.

Ridolfi, F., Renzulli, A., 2012, *Contributions to Mineralogy and Petrology*, vol. 163, no. 5, pp.877-895.

## **Heritage stone designation: A new geological standard**

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Heritage Stone designation has developed rapidly at an international level since it was first mooted in 2007 and is currently supported via

- ) Heritage Stone Task Group (HSTG) of the International Union of Geological Sciences (IUGS).
- ) International Geoscience Programme (IGCP Project 637 – Heritage stone designation).
- ) Commission C-10, Building Stones and Ornamental Rocks of the International Association of Engineering and the Environment (IAEG C-10).

Under the current HSTG Terms of Reference, a Global Heritage Stone Resource (GHSR) may be recognised if most of the following attributes prevail

- ) Historic use for a period of at least 50 years.
- ) Wide-ranging geographic utilisation .
- ) Use in significant public or industrial projects.
- ) Common recognition as a cultural icon.
- ) Ongoing availability of material for quarrying.
- ) Potential benefits arising from GHSR designation.

If not, as an alternative to GHSR status, a heritage stone that has national, regional or local significance may be determined.

Overall, heritage stone designation is considered valuable because it:

- ) Promotes greater awareness of stone and its widespread utilisation in human culture.
- ) Offers a means to formalise selected characteristics of stone material, for professional purposes.
- ) Facilitates safeguarding of heritage stone resources from subsequent sterilisation.
- ) Encourages proper management of stone extraction operations thus facilitating future availability.
- ) Enhances international co-operation in the research and utilisation of natural stone resources.
- ) Highlights the positive attributes of stone in terms of sustainability and regional development.

In Australia, given its small population, youthful history and relative isolation there are few stones that can qualify for GHSR status. The most likely candidate is “Sydney sandstone” which has international usage extending back to 1830s. Two excellent books illustrating the heritage of Sydney sandstone as well as a major dedicated technical monograph provide valuable support for such recognition.

Another likely Australian stone of international significance is “Victorian Bluestone” which is utilised extensively around Melbourne and western Victoria. The heritage of this Cenozoic basalt is currently the subject of doctoral research at Federation University by Susan Walter who has already determined several bluestone varieties.

In South Australia, Mintaro Slate, has been quarried since 1854 as a flagstone for use in steps, sills and paving around Australia. Some export has occurred, international awards have been received and the material has been used to manufacture billiard tables.

A modern example of a probable GHSR, also in South Australia, is “Imperial Black Granite”, which has been quarried since 1958, 100 km east of Adelaide. Imperial Black has had intensive monumental use around Australia together with utilisation as cladding in modern office buildings and as paving and walling in Australia’s National Parliament in Canberra. It is also widely used for paving in the City of Sydney. The material has also been exported and has notably been used internationally for the Australian Embassy in Tokyo, Japan and for a major War Memorial at Le Hamel, France.

## **Tectonic, eustatic and sedimentary controls on palaeoenvironmental evolution in a foredeep setting close to an active margin, Late Permian to early Triassic northern Bowen Basin.**

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Lithofacies and petrofacies evidence from Late Permian strata of the northern Bowen Basin give new insights into sedimentary response to magmatic arc initiation and development during compressional tectonism near the eastern margin of the basin. The sedimentary succession of the Nebo Synclinorium southwest of Mackay hosts significant economargic coal deposits at various stratigraphic levels, the development of which are strongly influenced by the interplay of tectonics and eustatic/base level fluctuations and the impacts these have on local depositional systems. The stratigraphic record is particularly sensitive to arc initiation and ongoing volcanism, by virtue of its palaeogeographic position in the foredeep of the retroarc foreland basin.

Field-based mapping and multiple stratigraphic transects in the Carrinyah Park and Elphinstone areas of the Nebo Synclinorium formed the basis of facies analysis of the succession and resolution of depositional environments. Petrography, including provenance analysis, was undertaken on 30 stratigraphically controlled outcrop samples. Six petrofacies through the Permian Back Creek and Blackwater Groups and the Triassic Rewan Formation indicate provenance evolution from a transitional continental and recycled orogen source prior to arc initiation, followed by sediment source switching to an undissected magmatic arc, then a transitional arc source. A final transition to a recycled orogen source in the Rewan Formation results from erosion of the fold and thrust terrane associated with the Hunter-Bowen Orogeny east of the basin. Compositional change in sediment fill through basin evolution is coincident with sequential changes in depositional systems and the character and distribution of depositional facies. Variable sediment influx at the basin margin, primarily controlled by volcanism and later uplift of the fold-thrust terrane, directly impacted fluvial styles changing them from high energy, braided systems at times of high influx to more sinuous, meandering systems at times of low influx. Importantly, regionally observed eustatic variation, felt locally as base level fluctuations, modified local alluvial plain fluvial systems in the study area to control development of peat mires in a range of environments, resulting in variation in coal quality and coal seam geometry in the Moranbah, Fort Cooper and Rangal coal measures.

The evolution of depositional environments throughout basin history is quite specific to the palaeogeographic location close to the basin's eastern margin (proximal to tectonic activity) and at the northern end of the basin (distal to marine connectivity). Site-specific depositional features reveal the interplay of extrinsic controls on the sedimentation style and autochthonous sedimentary processes. This has consequences for 1) stratigraphic architecture in which facies associations and sequence stratigraphic trends complicate and hinder simple lithological correlation to elsewhere in the Bowen Basin and, 2) the development of coal seams, in which peat mire type and distribution reflects the particular fluvial system that developed at different phases of basin evolution and under different sediment influx regimes. If considered in a palaeogeographic context relative to basin evolution, the sedimentology and stratigraphy of coal deposits in the synclinorium succession can be more meaningfully and actualistically interpreted with application to exploration and coal resource definition.

## Sedimentology and Salt-Sediment Interaction in a Clastic Fluvial-Deltaic System from the Adelaide Rift Complex of South Australia

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Marine deposits in salt-tectonized provinces form a significant portion of the world's hydrocarbon bearing strata, and new outcrop studies on these environments are particularly important in understanding the internal architecture of similar settings in productive regions. Ancient depositional systems that are well-exposed over a wide area provide an insight into these systems not possible in the subsurface. The Ediacaran (~565 Ma) Bonney Sandstone and Billy Springs Formations in the Flinders Ranges of South Australia are part of a fluvial-deltaic to shelf-slope system that formed on the passive margin of the Australia-East Antarctica subcontinent at the time of deposition. Despite extensive outcrops over hundreds of kilometres, few studies have been conducted on these formations. In the Bonney Sandstone, abundant coarsening-upward parasequences were deposited as part of a highstand systems tract that thickened significantly to the north. These intervals are often characterized by scours, lateral accretion, trough cross-stratification, and wave and current ripples, and were likely deposited in marine setting with significant fluvial influence. Detrital zircon geochronology suggests that sediments were ultimately sourced from the distant Musgrave Province, rather than the adjacent Gawler Craton, implying that sediments may have been transported up to 600 kilometers through the tectonically controlled Willouran Trough. Further north, the time-equivalent Billy Springs Formation is dominated by muds and slumps, indicating the presence of a deeper depocenter and increasing accommodation to the northwest. Both formations also show evidence of concurrent diapir activity, with numerous diapir bodies intruded into the Bonney Sandstone. Adjacent to diapirs, Ediacaran sediments were often deposited in rim synclines (minibasins) where they contain features not seen elsewhere in the formation. In the Mt. Frome minibasin, the Bonney Sandstone lacks the parasequences seen elsewhere, and is instead characterized by interbedded silty shales, sands, and abundant gravels. Measured sections along the diapir margin show significant lateral facies change, controlled by faulting and topography along the contact. Pebble-filled channels, mass flow deposits, and heavy mineral sands all likely originate from the exposed diapir, which formed a topographic high and shed clasts into the minibasin. Outcrop exposures of salt-tectonized basins are relatively rare around the world; thus, the sediments discussed here allow for an exceptional view into a setting that is most often seen only in core or seismic. This type of detailed observation can be used to develop better facies models that improve our understanding of the source, seal, and reservoir potential of ancient depositional environments, as well as providing valuable insight into the paleogeography of Precambrian Australia.

## Abandonment of the Paleoproterozoic Lincoln Complex, Gawler Craton, South Australia.

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Early mapping of the Gawler Craton on Eyre Peninsula recognised the metasedimentary and igneous character of the rocks but struggled with the complex interleaving of gneissic, schistose, quartzitic and granitoid units (Parker, 1993). As a result, the metasediments were given a confusing range of stratigraphic names. The gneissic and granitoid suites were described as being basement to, intrusive into, or higher grade equivalents of, the metasediments and thus were also given conflicting names; Lincoln Gneisses (of Flinders Series; Tilley, 1921) was the first use of the name 'Lincoln'. Thomson (1969) described the total succession simply as Cleve Metamorphics.

Following detailed mapping on central-southern Eyre Peninsula and Middleback Range, emphasising structural relationships, the stratigraphy of the metasediments was redefined (Parker and Lemon, 1982). Rb-Sr and U-Pb geochronology have been important in unravelling the complex intrusive history and the relationships of the gneissic rocks to the metasediments. Some gneisses are now known to represent basement to the metasediments, while others are younger intrusives.

Eyre and Yorke Peninsulas expose a complex of mainly granitoid rocks, interpreted now as intrusives into the metasediments and their basement. These granitoid rocks were grouped as Lincoln Complex by Thomson (1980) and considered to be emplaced during the Kimban Orogeny over the broad interval 1850-1700Ma (Parker, 1993). The term has also been applied loosely since to undated deformed granitoid outcrops across the Gawler Craton.

Recent geochronology and geochemistry allows better separation of intrusive events, and has prompted abandonment of the term Lincoln Complex. The youngest phase (1750-1700Ma) of the former Lincoln Complex is now the Peter Pan Supersuite (Wade and McAvaney, this volume), applying to intrusives of the refined Kimban Orogeny; three suites are recognised. The oldest ex-Lincoln Complex phase, Donington Suite (1850-1845Ma, Cornian Orogeny) is now a stand-alone unit. Several other units assigned to the former Lincoln Complex are now placed into the basement of the metasediments or the younger Tunkillia Suite (1690-1670Ma); other units occupy the gap between the Donington Suite and the Peter Pan Supersuite.

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## Organic and inorganic geochemistry of the Mesoproterozoic Roper Seaway

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The ca. 1.4 Ga Roper Group of the McArthur Basin, northern Australia, comprises the sedimentary fill of one of the most extensive Precambrian hydrocarbon-bearing basins preserved in the geological record. It is interpreted to have been deposited in a large epeiric sea known as the Roper Seaway. This study presents hydrocarbon biomarkers, high-resolution trace element redox geochemistry and neodymium isotopes of immature to mature black shales ( $T_{max} = 394^{\circ}\text{C}$  to  $502^{\circ}\text{C}$ ; Average =  $425^{\circ}\text{C}$ , st.dev. =  $17.7^{\circ}$ ) to understand the microbial diversity and palaeo-environment of the Roper Seaway.

Indigenous extractable biomarkers from the Roper Seaway describe a water column dominated by cyanobacteria with large scale heterotrophic bacterial reworking of the organic matter either occurring within the water column, or in microbial mats. Evidence for microbial reworking includes a large unresolved complex mixture (UCM) and high ratios of monomethyl alkanes relative to *n*-alkanes— characteristic features of indigenous Proterozoic bitumen. The 2,3,4- and 2,3,6- trimethyl monoaryl isoprenoid series, commonly used biomarkers for photic zone euxinia, were below detection limits in all samples analysed, suggesting that the photic zone of the Roper Seaway was not euxinic. Complementary trace element data also supports this observation with a negative cerium anomaly hosted in the black shales. Steranes, biomarkers for single-cell and multicellular eukaryotes, were below detection limits in all extracts analysed, although probable eukaryotic microfossils have been identified in the same drillcore analysed in this study. These results suggest that eukaryotes, while present in the Roper Seaway, were ecologically restricted and contributed little to the net biomass.

Trace element data suggest that the shallow oxic layer overlay deeper anoxic to intermittently euxinic waters in the Roper Seaway. The deep water anoxic and sulfidic conditions are inferred by the trace element abundances of molybdenum, vanadium and uranium which developed due to high organic carbon loading. This is consistent with models that suggest euxinic conditions cannot develop until the flux of organic matter is significantly greater than the flux of bioavailable iron ( $\text{Fe}^{3+}$ ), which permits sulphate reduction to proceed. We propose that the high organic matter flux was the result of increased nutrient loading to the Roper Seaway from weathering of the continental hinterland. Data from both major and high field strength elements (niobium, tantalum, zirconium, hafnium) together with neodymium isotopes ( $^{143}\text{Nd}/^{144}\text{Nd}$ ) indicate that a likely source for this enhanced nutrient delivery was a shift in sedimentary provenance to a more primitive (mafic) precursor lithology. This switch in provenance would have provided an increase in phosphorus delivery to the Roper Seaway, contributing to high primary productivity and the onset of euxinia, hence promoting organic matter preservation. The increased flux of phosphorus into the Roper Seaway correlates with an increase in total organic carbon (TOC), extractable organic matter (EOM; mg/g rock) and hydrocarbon concentrations.

The complementary inorganic and organic datasets and model serve as a basis for understanding the temporal evolution of the deepest sections of the Roper Seaway, finer scale changes in the palaeo-environment and microbial diversity at this time and highlights the strength of a multidisciplinary approach.

## Reconstructing the record of Continental Flood Basalt (CFB) and Ocean Island Basalt (OIB) geochemistry: initial results from a data mining approach.

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Large Igneous Provinces (LIP) result from the extrusion of  $>10^6 \text{ km}^3$  of mafic volcanic rocks, typically in less than a few million years. Although their geodynamic origin remains controversial (Sobolev et al. 2007; Wang et al., 2015), their association with super-continental break-up is well established (Courtillot et al., 1999). They are also closely coupled to many Phanerozoic environmental catastrophes including mass extinctions, oceanic anoxic events and climatic perturbations (Wignall, 2001; Sobolev et al., 2011; Schaller et al., 2011; Blackburn et al., 2013). For these reasons, records of LIP emplacement are important in understanding both the geodynamic and environmental evolution of the Earth.

Unfortunately, given the geodynamic and environmental importance of such records, the ongoing destruction of oceanic crust at subduction zones, results in the OIB record (i.e. isolated ocean islands, seamounts and oceanic plateaus) being largely confined to those occurrences that can be observed on the present day expanse of oceanic crust. Consequently, the OIB record is nearly entirely limited to the past  $\sim 180$  million years. This contrasts with the relatively well documented occurrences of CFB which stretch well into the Precambrian (e.g. Ernst et al., 2008), as unlike their OIB counterparts, CFB are preferentially preserved within cratonic interiors. Despite this, a small number of accreted ophiolites have been argued to be the preserved fragments of a largely lost OIB record (e.g. Coffin & Eldholm 2001, Moores 2002), raising the possibility that a OIB record may be preserved in convergent margin settings, if such fragments can be successfully identified. Due to the ever growing size of online geochemical databases, data mining may be a valuable tool in helping to compliment the existing CFB record, but also a possible step towards a OIB record.

Utilising these large databases of geochemical analyses ( $>80,000$  analyses) we have undertaken kernel density estimation (KDE) to identify key geochemical characteristics that distinguish CFB and OIB geochemistry from other forms of igneous geochemistry (e.g. convergent margin volcanism), these geochemical characteristics include Fe/Mn (specifically in cation units), primitive mantle normalised Ba/La, Ti/Lu as well as Pb and Nb anomalies. From this statistical approach geochemical ratios such as Fe/Mn,  $[\text{Ti/Lu}]_{\text{PM}}$ ,  $[\text{Ba/La}]_{\text{PM}}$  and  $\text{Nb}^*$  and  $\text{Pb}^*$  anomalies have allowed us to largely distinguish CFB, OIB, MORB and arc magmatism.

Application of these ratios to our basalt database has allowed us to generate a record of CFB and possibly a partial OIB record. This OIB record yields expected modern OIB occurrences (i.e. Hawaii, Ontong Java, Ninetyeast Ridge), but also older occurrences with distinctly OIB geochemistry, examples include the Permian aged Mino-Tamba ophiolite and the Archean Hemlo-Black River Assemblage. In total this data mining approach has revealed potentially numerous OIB occurrences stretching back to 3800 Ma.

## **Experimental analogue study - How does organic matter affect the head velocity and run-out distance of cohesive sediment gravity flows?**

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Experimental models of submarine sediment gravity flows, rarely accessible or observable in their natural environment, have been the primary analogue from which the current understanding of this complex sediment transport process has developed. Despite over 50 years of multi-disciplinary research on the flow mechanics and deposits these flows, the flow dynamics and depositional processes of clay-rich gravity flows remain poorly understood. Cohesive clay can alter the flow rheology as a result of the electrochemical forces of attraction between individual particles. These forces may induce particle aggregation, leading to the formation of floccules and more pervasive cohesive structures, called gels. Through flocculation and gelling, clay particles can enhance or dampen turbulent forces in sediment gravity flows, such that increasing the cohesive sediment content causes a transition from turbulent, Newtonian flow, via transient-turbulent flow, to laminar, non-Newtonian debris flow. Because the flow rheology controls the depositional style, a thorough understanding of how flow composition relates to flow rheology is essential for our interpretation of the architecture and the palaeo-environmental setting of submarine deposits in outcrop and core.

In the natural environment, clay-rich sediments are commonly associated with the presence of organic matter. The effect of organic matter, in particular 'sticky' extracellular polymeric substances (EPS), on the flocculation and gelling within clay-laden flows is reasonably well known for tidal flows in shallow-marine environments, but the impact of cohesive organic matter on the dynamics of sediment gravity flows has not been explored yet. A complex interaction between physical and biological forces has been found to influence the stability of sedimentary deposits. Here, the influence of similar interactions for clay and EPS suspended within sediment gravity flows is presented.

The above research gaps were addressed by means of flume experiments that recorded changes in dynamic behaviour of sediment gravity flows with variable amounts of biologically cohesive xanthan gum (a commonly used proxy for natural EPS) and physically cohesive kaolin clay (one of the most common clay minerals on Earth). Provisional results indicate that very small quantities of EPS – several orders of magnitude smaller than the quantity of clay – are sufficient to enhance flocculation and reduce flow velocity compared to a flow that lacks EPS. This finding has the potential to change our understanding of sediment gravity flows in the natural environment, in particular those that result in the organic rich, fine-grained deposits regarded as potentially favourable source rocks.

## **Basement architecture of the Pilbara Craton and influence on iron mineralisation in the Hamersley Province, Western Australia**

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Basement architecture underlying the Hamersley Province of Western Australia predominantly formed during the Archaean assembly of the Pilbara Craton's granite-greenstone terranes and subsequent rifting coeval with deposition of the Fortescue Group. Historically, the significance of large crustal-scale structures has primarily been considered in exploration targeting for hypogene microplaty hematite mineralisation; however, the influence these old basement structures have had on the spatial distribution of supergene iron deposits in the region has been largely overlooked.

Through analysis of geological maps and interpretation of regional gravity and magnetic datasets, the fundamental architecture of the Pilbara Craton can be delineated, revealing a number of significant structural features in the basement that appear to have had a major influence on the younger structures developed in the Hamersley Province. Characteristics of the structural domains are predominantly influenced by; a) granite vs. greenstone volume, b) granite-greenstone geometry, c) accretionary sutures between Archaean terranes, and d) Fortescue Group aged rift basin architecture.

Structures developed during the Paleoproterozoic Ophthalmian Orogeny vary significantly across the province and display a strong spatial correlation with underlying domains in the cratonic basement. Heterogeneous strain partitioning between the western and eastern portions of the Ophthalmian Fold Belt appears to be controlled by a northeast trending structure. The western part of the fold belt is characterised by broad regional-scale folds and normal faults that mirror the dome-and-keel geometry of the underlying granite-greenstone basement. The eastern portion of the fold belt is characterised by shorter wavelength folding, often with associated thrust faults, forming an arcuate belt north of the Sylvania Inlier and overlying the Wonnsmunna Dome. An additional structural sub-domain occurs in the eastern Ophthalmian Fold Belt where northeast trending normal faults are common and probably represent vertical accretion of basement structures into the supracrustal rocks.

Iron enrichment of banded iron-formations requires the removal of significant volumes of gangue, typically chert, from a relatively impermeable rock. Whether the iron mineralisation forms from hypogene or supergene fluids, the creation of permeability in the rocks is a critical component of any mineral system; thus zones of increased damage to the rocks have greater potential to form microplaty hematite and/or goethitic iron ore deposits.

Examination of the spatial distribution of iron deposits across the Hamersley Province shows a strong correlation with the intensity of deformation which is interpreted to coincide with zones of increased permeability in the host rocks. Therefore it can be inferred that the basement architecture of the Pilbara Craton has directly influenced the formation of both hypogene and supergene iron ore deposits in the Hamersley Province. This understanding allows us to better understand the structural setting of existing deposits as well as to develop a predictive model for targeting both extensions to known deposits and blind mineralisation beneath barren cover.

## Three-dimensional subsidence history of the Michigan basin: long-term interplay between mantle dynamics and plate boundary forces

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Intracratonic basins are features of continental interiors worldwide, including North America, which contains the Paleozoic Michigan, Illinois, Williston and Hudson's Bay basins. While the geometry and internal structures of these basins are well known, high-resolution three dimensional subsidence histories and the effects of regional tectonics during their development have not been explored in detail. The Michigan basin is an intracratonic basin situated within the North American (Laurentian) continent. It is located on the continental-interior platform, on which a relatively thin veneer of Phanerozoic sedimentary strata overlies crystalline basement rocks. The Michigan basin is described as a region of relatively thicker sediment accumulation within this platform and it displays a broadly circular geometry with a diameter of ~450 km. A thick sequence of infilling Paleozoic sedimentary rocks dips concentrically towards the center with its deepest point at a depth of approximately 5000 m. The basin is bounded to the north by the Canadian Shield, to the east and southeast by the Algonquin and Findlay Arches, to the southwest by the Kankakee Arch and to the west and northwest by the Wisconsin arch and Wisconsin dome. The Michigan basin began to form within the interior of the Laurentian continent during the early Cambrian, following the breakup of Rodinia. Sediment accumulation, dominated by carbonates, was essentially continuous until the middle Carboniferous, which is marked by a regional unconformity.

A digitized set of over 57,000 well logs was subjected to quality assessment and quality control and subsequently backstripped. 3D plots of the results for each formation within the basin highlight the total and tectonic subsidence history of the basin during the Paleozoic. The plots show that vertical surface motions within the Michigan basin were driven by a primary and long-lived process characterized by a circular, basin-centered pattern of subsidence, punctuated by at least two periods of horizontal compression that were contemporaneous with the Taconic and Acadian orogenies in Eastern Laurentia. A possible mantle downwelling beneath the Michigan basin, driven by the effects of supercontinent breakup in the late Precambrian may account for the quasi-circular background subsidence, present in most recorded periods of sedimentation. The effects of the Ordovician Taconic and Devonian Acadian Orogenies overprinted the circular deposition patterns, tilting the basin and generated what appear to be short-lived, low-amplitude folds, sub-parallel to the Algonquin-Findlay and Wisconsin arches. These results are discussed in light of recent geodynamic models of lithosphere-mantle interaction (drip tectonics and mantle downwelling) and long-wavelength lithospheric folding. We also compare the findings with the record of brittle deformation within Paleozoic rocks exposed in and around the Michigan basin in the USA and Canada.

## Illuminating Victoria's Lithospheric Structure – AusLAMP Victoria

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The Australian Lithospheric Architecture Magnetotelluric Program (AusLAMP) is a multi-year collaboration between Geoscience Australia, State/Territory geological surveys, universities and AuScope to acquire long-period magnetotelluric data at a nominal  $0.5 \times 0.5^\circ$  ( $\sim 55 \times 55$  km) station spacing. Here we present results from the 2014 maiden AusLAMP deployment over the state of Victoria.

Long period instruments from AuScope were deployed for a duration of 3–4 weeks at 99 sites. Each instrument records two horizontal components of the electrical field and three components (two horizontal and one vertical) of the magnetic field. Time series electrical and magnetic field data were processed in the frequency domain and analysed for a number of parameters, including the orientation of the electrical strike to understand variation in the gross conductivity properties of Victoria. More detailed analysis involved inverting the data for a three-dimensional model of conductivity within the crust and mantle using ModEM running on the *raijin* supercomputer at the National Computational Infrastructure national facility. Models were run for a number of data errors/misfits to influence the smoothness of the model and to allow the best inversion model to be selected.

Previous MT coverage for Victoria was mainly broadband transects which only allowed 2D section profiles to be analysed. The AusLAMP data allows the full 3D space to be modelled for the first time. Comparisons of the MT model results with other available datasets, such as the 3D geological model of Victoria, and seismic tomography reveal excellent agreement between independent datasets and provide insights into geological processes.

In the mantle, the combination of MT results with seismic velocity models allows delineation of regions of metasomatised mantle. Within the context of the Uncover exploration themes being developed, the regions above the margins of such metasomatised mantle can be preferred regions for mineral exploration. In the crust, the regional ‘map-like’ coverage of AusLAMP highlights a series of conductive anomalies running northeast across the State. Some of these anomalies had been recognised in the 2D broadband transects and were thought to be related to young Newer Volcanic magmatic activity but the linear trend evident in the 3D data, that extends into eastern Victoria away from the volcanics, better matches the distribution of Devonian granite intrusions. The northeast trending anomalies thus possibly mark the fossil metasomatised ascent paths of the granitic melts, as they rose through the crust after the dominant north-south structural trend of the hosting bedrock had developed.

## **Towards Constraining Amplitude, Wavelength and Rate of Australia's Dynamic Topography**

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Qualitatively Australia has become known as the “tilting continent” arising from the interplay between Australia’s rapid northward motion and density anomalies within the convecting mantle. Here we present quantitative measurements of the amplitude, wavelength and rate of this combined effect. We measure the amplitude and wavelength of present-day dynamic topography through careful calculation of offshore residual topography and long-wavelength admittance between gravity and topography onshore. Our results show the present day dynamic topography of Australia is much more varied than a wholescale tilt of the continent. Present-day dynamic topography varies vertically by  $\pm 1$  km (water-loaded) at wavelength down to  $\sim 600$  km (e.g. Eastern Highlands where the Great Escarpment can be shown to be the present day expression of dynamic support). Offshore, we constrain the rate of dynamic topography through subsidence analysis with careful attention to sediment compaction parameters. Onshore, we constrain uplift history using longitudinal river profiles which act as tape recorders of past uplift as knick-zones kinematically advect up stream. Our inversion for uplift rate using longitudinal profiles honours all independent estimates of uplift around Australia with a single set of erosion parameters, constrained using incised basalt flows from the eastern highlands. These results surprisingly imply that Cenozoic long-term landscape evolution of Australia occurs irrespective of climate changes and underlying geological substrate. We find offshore dynamic topography subsidence rates of up to 75m/Myr and onshore uplift rates of up to 40m/Myr.

## **Australian Architecture Reference Model (AusARM) – Towards lithospheric architecture model accessibility**

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The emerging economic imperative to improve resource exploration success in regions obscured by cover rocks and the unabating academic desire to understand deep Earth processes has resulted in a bloom of continental scale datasets and architecture models pertinent to the study of the Australian lithosphere. Geoscience Australia, as the national geoscience data custodian, has fostered much of this activity though over the last decade significant data acquisition and model development has occurred within the state and territory surveys and academia. Despite this activity models and underlying datasets of the Australian lithosphere remain hard to discover, particularly by industry. In order to facilitate accessibility and community exchange of models Geoscience Australia is working towards an Australian Architecture Reference Model (AusARM) where models developed by the Earth Science community can be discovered and downloaded within the EarthSci 3D visualisation tool ([www.ga.gov.au/EarthSci-AusARM](http://www.ga.gov.au/EarthSci-AusARM)). AusARM is a discovery tool and maintains links to publications and institutional downloads, ensuring authors receive full credit for their work and data. In addition to AusARM, Geoscience Australia is developing a database—Estimates of Geological and Geophysical Surfaces (EGGS)—that will store various calculated/measured/interpreted constraints on the depths of geological surfaces, such as stratigraphic surfaces, the Moho, major faults. The plan is that these estimates will be available for use ( by the geoscience community. Here we make a case for collaboration and transparent exchange of models and underlying point datasets.

## **Seamount volcanism at Site U1431, South China Sea, International Ocean Discovery Program Expedition 349**

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IODP Site U1431 in the South China Sea is located near the fossil spreading ridge of the East Sub-basin. Drilling at this site penetrated the 200 m thick, volcaniclastic apron of a middle to Late Miocene (~8–13 Ma) seamount. The apron is sandwiched between non-volcaniclastic units that represent the background pelagic and turbidite sedimentation.

The seamount sequence includes dark greenish gray sandstone, siltstone, and claystone in upward fining sequences interpreted as turbidites intercalated with intervals of volcaniclastic sandstone and breccia up to 4.8 m thick. The breccia is typically massive to weakly graded and poorly sorted with angular to subangular basaltic clasts, and minor reworked subrounded calcareous mudstone, mudstone, and sandstone clasts. The base of many beds has reverse grading. Volcaniclastic sandstone interbedded with the breccia layers is graded and has current ripples and parallel lamination indicative of high energy flow conditions during sedimentation. The breccia and sandstone beds were most likely deposited as a series of high-concentration sediment gravity flows in an abyssal plain environment. This interpretation is supported by their largely massive to weakly graded structure, poor sorting, and reverse-graded bases. Many breccia and sandstone beds are overlain by finer-grained graded beds that likely represent the finer sediment that remained in turbulent suspension above the coarser detritus.

Glassy clasts in the breccia and sandstone range from blocky to bubble-wall in shape and massive to amygdaloidal and aphyric to porphyritic in microstructure. All glassy clasts are angular to irregular indicating little shape modification during transport. Crystals of plagioclase and clinopyroxene are abundant both as single crystals and in the glassy and trachytic basalt clasts. Other mineral grains include olivine, amphibole, and biotite and accessory apatite and Fe-Ti oxides.

Preliminary geochemical work indicates that the composition of glass particles in the volcaniclastic layers varies from basanite to trachyte with compositions similar to ocean island basalt and to other seamounts in the South China Sea. The more evolved compositions indicate periods of quiescence between eruptions. Very low alkali contents of some glass may indicate alteration of the glassy volcanic clasts.

Beds in the seamount sequence range in age from  $8.03 \pm 0.02$  to  $9.36 \pm 0.06$  Ma (2 ) based on preliminary  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology of plagioclase, hornblende and biotite separated from the base layers of individual turbidite beds. This indicates an eruption duration of at least 1.3 Myr during the deposition of the entire seamount apron section. From the middle the sequence (698–828 mbsf) we measured 12 mineral separates from 6 samples that are reproducible in age within  $9.15 \pm 0.05$  Ma (2 ). In combination with the variable geochemistry of this mid-section, this narrow age range of 50 kyr may indicate that the contained mineral clasts are from beds sourced from a series of rapid eruptions on the seamount.

## The Gap Zone mineralisation (Prominent Hill IOCG deposit, South Australia): a zoned system in carbonate wallrocks that was produced when orogenic pyrite vein stockworks reacted with copper-bearing sulfate-rich fluids containing isotopically heavy sulfur

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The supply of reduced sulfur to form iron oxide copper-gold deposits (IOCGs) appears to be a critical step for ore formation. In this study we evaluate mineralogical zoning, and combine it with sulfur isotope analyses, to obtain an insight into sulfur supply mechanisms at the Gap Zone ~1.5 km west of the main Malu orebody at Prominent Hill. The Gap Zone is not typical of other Mesoproterozoic Prominent Hill mineralisation, in that it comprises chalcocite-bornite networks in a coherent rock mass, rather than the more typical disseminated copper sulfides within hematitic breccia seen in Malu.

Gap Zone mineralisation is contained within several thick (10-100 m) meta-carbonate units. These units have been rotated to sub-vertical, and are separated from felsic Neptune Volcanics (Gawler Range Volcanics correlates) to the south by barren hematitic breccias. Steep north-dipping faults separate each of these units, and are inferred to link below to the major Hangingwall Fault system to the north.

In detail, Gap Zone copper mineralisation (with grades in the tenor of 1-20% Cu in metre intervals) is distributed within three carbonate units that have each experienced intense alteration and veining. The original limestones were carbonaceous with some disseminated pyrite. The earliest vein networks were pyrite-dominated, and were succeeded by more oxidised copper sulfide assemblages. These show zonation from south to north: silica-hematite-barite, chalcocite-hematite-barite, chalcocite-bornite +/- barite, to bornite only. There is a trend of more oxidising assemblages having replaced more reduced assemblages.

The Gap Zone bulk sulfide sulfur isotope median (conventional analysis, hand drilling; drillhole D576) is  $\delta^{34}\text{S}$  = -2 to +2‰ (range of -10 to +18‰), compared to a median of ~-8 to -2 ‰ for the Malu breccia zone sulfides (range of -28 to +4‰; T Schlegel et al. 2015 SEG conference abstract, Hobart). Chalcocite exhibits the whole isotopic range seen in the mineralisation. Both of these mineralisation types display very large sulfur isotopic ranges, that are typical of *in situ* fractionation during deposition, either through fluid mixing or through partial reduction (either biologically or abiologically) of an isotopically heavy sulfate mineral or fluid. There is a correlation in the Gap Zone between higher abundances of pyrite pseudomorphs, better copper grades, and heavier isotopic compositions, and the hypothesis is advanced that this is consistent with reduction of fluid sulfate by oxidation of earlier pyrite. Larger amounts of reduction resulted in sulfide isotopic values that approached the sulfate composition, which was likely in excess of 18‰ (very similar to typical Mesoproterozoic seawater sulfate or its evaporate-derived equivalent). The average heavier isotopic range of Gap Zone sulfides compared to Malu is therefore attributed to more efficient sulfate reduction in the former.

A model is advanced in which a sulfate-rich Cu fluid was channelled up along faults and through vertically oriented breccia bodies (now manifested as barren hematite alteration) and structurally induced to encroach into and replace swarms of pyrite veins that had formed in a prior pulse of orogenic activity against the Hangingwall Fault. This replacement resulted in shells of mineralogically and isotopically zoned copper mineralisation within individual carbonate units, and now show mineralogical and sulfur isotopic similarities to many sediment-hosted copper deposits.

## **A one-thousand-year record of tsunamis on the Aitape coast, Papua New Guinea.**

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An intense and tightly focused tsunami struck the Aitape coast of Papua New Guinea in July 1998. In the aftermath of the tsunami there was speculation that this section of coast might be inherently at high risk from tsunamis and so should not be reoccupied. In this context, and as part of a campaign to fully document the 1998 tsunami, we sought to determine whether there had been major damaging tsunamis in the past and, if so, how frequently. There had been none in the past 110 years according to written records, but there was a strong oral tradition of a major tsunami at some time in the past that was so violent and damaging that it had buried houses and had caused the ancestors to flee to other parts of New Guinea and the islands. Near the Otu mouth of Sissano lagoon we discovered an intermittently exposed underwater face that includes a one-metre section of interbedded argillitic sediment and peat. We interpreted the face to record a series of subsidence events, each of which was marked by the burial and humification of organic matter that had accumulated on the floor of a swamp. Subsidence on this coast is confirmed by pollen studies which show gradual marine incursion into a shallow freshwater lagoon, and by the presence of submerged reefs offshore. The lowermost of three distinct peat beds, at 4.0 m water depth, was sampled and radiocarbon-dated at 990 +/- 70 years BP (BP = before 1950 CE). A sample of the uppermost peat, at 3.25 m depth, was lost into the water column because it was sandy and incoherent, and so could not be dated. We sampled what we assumed to be the same peat, the sandy uppermost peat, by drilling. The drilled peat contained sand, pebbles as large as 4 cm, and marine shell fragments. It is likely that this material was deposited by a major tsunami, having been carried into a coastal swamp by the encroaching wave. A sample of this peat was radiocarbon-dated at 381 +/- 57 years BP. A lower sandy peat bed was dated at 870 +/- 60 years BP.  
Conclusion: It is likely there was a major tsunami at about 870 years BP, and a major devastating tsunami at about 380 years BP. The results can be confirmed by re-sampling the underwater sediment section but this is not easily done because of shifting sands, turbid water and strong currents, and because of local beliefs and sensitivities. As regards tsunami risk, parts of this coast remain unoccupied because of higher risk due to proximity to the water's edge, lack of access to escape routes, and the focusing of tsunami energy by seafloor relief. All new settlements are inland.

## The influence of fault and fracture networks on permeability anisotropy in porous sandstones: a case study at Castle Cove, Otway Basin

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Recent studies on natural structural permeability have significant implications for reservoir appraisal and development within petroleum systems. Faults and fractures can serve as hydrologically conductive conduits for significant fluid flow (Sibson 1996). Previous investigations have been concentrated on the fault and fracture permeability of low porosity (<5%) host rocks, rather than porous sedimentary rocks, which more commonly form reservoirs. Here we present results from a well exposed fault system within the Otway Basin at Castle Cove, Victoria. Castle Cove provides excellent exposures of the lower Cretaceous fluvio-marine sediments of the Eumeralla Formation, which is a fine-grained volcanogenic sandstone at this locality. The Castle Cove fault is a ~northwest dipping, ~northeast–southwest striking fault with a strike length of approximately 22 km. The fault originated as a normal fault during the Cretaceous but was subsequently reactivated as a reverse fault during the Cenozoic. This study assesses the relationship between faults, damage zones around faults, and fractures related to fault growth. Permeability anisotropy, produced during deposition and later deformation, is also investigated and results are compared to a similar study by Farrell et al. (2014). Fractures were mapped at varying distances from the Castle Cove Fault plane and the interconnectivity of fractures was evaluated. At distances greater than 150 m from the fault, fractures trend north-northwest–south-southeast. Within the damage zone adjacent to the fault, fractures are more dense (~4.5 fractures/m), are orientated parallel to the fault (i.e. northeast–southwest), and are likely related to initial fault formation or fault reactivation. The majority (approximately 80%) of fractures were closed with siderite or calcite cementation. However, many of these are optimally oriented with present-day stress conditions for reactivation and have the potential to act as hydrologically conductive conduits should they be reactivated.

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## Comparison between Marine Isotopes Stages 2 and 4 in the Australian region based on a core obtained from Sprigg Canyon, offshore Kangaroo Island

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Much emphasis has been placed over several decades on the Last Glacial Maximum [LGM] spanning the period of 21,000 { 3,000 cal. years BP, especially because this was the period of time when sea level had dropped by the order of 125 metres and extensive ice sheets covered a large part of the northern hemisphere. This period is referred to as Marine Isotopic Stage [MIS] 2. During that time in Australia, aridity prevailed (with even desert dunes extending as far as parts of Melbourne and NE Tasmania) and glaciers were present but covered only a very small area on the mainland and were a bit more extensive in Tasmania. At that time, mean annual temperatures both on land and at sea were substantially lower compared to today, with evidence in Australia on land temperatures being of the order of 8-10°C, with comparable temperatures in the surrounding oceans, except in the Indo-Pacific Warm Pool where shifts were not as significant.

Here we examine the previous cold interval MIS 4 in the Australian region, a period of time which so far has been poorly documented worldwide. Its timing spans the 71,000 to 59,000 years BP period. Already, MIS 4 moraines in the Snowy Mountain region in SE Australia were more extensive than those at MIS 2, and dissolution of carbonates in deep-sea cores offshore Victoria were more extensive during MIS 4 compared to MIS 2. Nevertheless, sea level had not dropped as extensively as during MIS 2.

New evidence will be presented from deep-sea core MD03-2607 obtained from a platform located in Sprigg Canyon, offshore Kangaroo Island off the mouth of the River Murray. For the interval in the core spanning MIS 4, we obtained high-resolution stable isotope data from planktic foraminifers, sea-surface temperature data based on alkenones, and Nd isotopes and rare earth elements that can inform on erosional changes in the Murray Darling Basin. In addition, we will present XRF core scanning data for that interval.

Our intention is to explain why Australian glaciers were more extensive during MIS 4, both in SE Australia and Tasmania. We will also assemble data for other regions going as far as New Zealand and Papua New Guinea, both onshore and offshore.

## **A high-resolution record of oceanic changes offshore southern Australia spanning the last 55,000 years; implications for southern hemisphere westerlies**

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We have chosen to study in great detail 2 deep-sea cores located offshore southern Australia for their records of sea-surface temperature, the structure of the thermocline at the core sites and the occurrence of aeolian dust. The 2 cores are under the pathway of the Leeuwin Current [LC] which is an unusual poleward surface current that partly originates in the Indo-Pacific Warm Pool in the tropics and circumnavigates Western Australia and that at times can travel as far as Tasmania.

The waxing and waning of the LC offshore southern Australia is directly linked with the position of the westerlies south of Australia. When the westerlies are close to Australia, the LC's influence is minimal and southern Australia benefits from abundant rain [with large lakes filling up] and cooler temperatures. The opposite occurs when the LC is predominant and SST are generally warmer and the water column offshore southern Australia is more stratified.

We already demonstrated for the upper portion of one of the cores that when the LC is strong and SST are warmer, this coincides with cold Heinrich events in the Northern Hemisphere. Thus, the bi-polar seesaw is well defined in our cores and this relies on good chronologies. We now document such changes back to Heinrich event 5.

We will compare our records with others in the Southern Hemisphere and document the overall importance of the westerlies in controlling surface ocean currents, sea-surface temperatures, and even glacial activity on land.

## Evolution of the Meso-Cenozoic passive margin of southeastern India (Tamil Nadu) using apatite fission-track thermochronometry

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After rifting from Gondwana in the Late Jurassic – Early Cretaceous, and subsequent opening of the Indian Ocean basin, the continental margins of India developed into typical passive margins. Extensional tectonic forces and thermal subsidence gave rise to the formation of both on-shore and off-shore basins along the southeastern passive margin of the Indian continent, along the Tamil Nadu coast. There, basins such as the Cauvery and Krishna-Godavari basin, accumulated Meso- and Cenozoic (Early Cretaceous to recent) detrital sediments coming off the rifted blocks and the Tamil Nadu hinterland. In places, deep rift basins have accumulated up to over 3000 m of sediments. The continental basement of Tamil Nadu is chiefly composed of metamorphic rocks of the Archean to Palaeoproterozoic Eastern Dharwar Craton and the coeval Southern Granulite Terrane (e.g. Peucat et al., 2013). Several crustal scale shear zones crosscut this assemblage and at least some are considered to represent Gondwanan sutures (Santosh et al., 2012). Smaller, younger granitoid plutons intrude the basement at several locations and most of these are of Late Neoproterozoic age (Glorie et al., 2014). In this work metamorphic basement rocks and the younger granitoids were sampled for an apatite fission-track (AFT) study. A North-South profile from Chennai to Thanjavur mainly transects the Salem block of the Southern Granulite Terrane, and crosscuts several crustal scale shear zones, such as the Cauvery, Salem-Attur and Gangavalli shear zones. Apatites from over 30 samples were used in this study. AFT (mean) ages all range between about 190 and 120 Ma (Jurassic – Early Cretaceous). These mainly represent the slow, shallow exhumation of the basement during the rift and early drift phase of the Indian plate from Gondwana. AFT mean track lengths vary between 11 and 13 µm and are typical of slowly exhumed basement. Thermal history modelling (using the QTQt software by Gallagher, 2012) confirms that internal regions of fault blocks experienced a slow and steady cooling to ambient temperatures throughout the Meso-Cenozoic, while younger samples, mainly positioned close-by or inside the shear zones, additionally record a more moderate to rapid cooling since the Early Cenozoic.

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## Gateway to the Sub-Arc Mantle through the Brothers volcano: Volatile Flux, Metal Transport, and Conditions for Early Life

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Hydrothermal systems hosted by submarine arc volcanoes differ substantially from those in spreading environments in commonly containing a large component of magmatic fluid. Our primary scientific goal in drilling Brothers Volcano of the Kermadec Arc, as set out in IODP Proposal 818, is to discover the fundamental, underlying processes that drive these differences. This magmatic hydrothermal signature, coupled with the shallow depths of these volcanoes and high volatile contents, strongly influences the chemistry of the fluids and the resulting mineralization, and likely has important consequences for the biota associated with these systems. Given the high metal contents and very acidic fluids, these hydrothermal systems are also thought to be important analogues of many porphyry copper and epithermal gold deposits mined on land.

The proposed drilling has four objectives:

- ) Characterizing the sub-volcano, magma chamber-derived volatile phase to test model-based predictions that this is either a single-phase gas, or two-phase brine-vapour;
- ) Exploring the sub-seafloor distribution of base and precious metals and metalloids, and the reactions that have taken place along pathways to the seafloor;
- ) Quantifying the mechanisms and extent of fluid-rock interaction, the consequences for mass transfer of metals and metalloids into the ocean, and the role of magmatically-derived carbon and sulphur species in mediating those fluxes; and
- ) Assessing the diversity, extent and metabolic pathways of microbial life in an extreme, metal-toxic and acidic volcanic environment.

Our highly ranked proposal, which will hopefully be drilled in 2018, is for a *JOIDES Resolution* expedition to drill and log a series of sites at Brothers Volcano that will provide access to critical zones dominated by magma degassing and high-temperature hydrothermal circulation, over depth ranges regarded as crucial not only in the development of multiphase mineralizing systems, but also in identifying subsurface microbially habitable environments. We have identified and prioritized seven potential drill sites based on topographic slope, magnetic delineation of fluid 'upflow' zones, and the location of hydrothermal vents that target all four known hydrothermal fields that range from gas- to seawater-dominated systems.

## Diagenesis and Rock Properties in Canning Basin Shales

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Recent renewed interest in the Canning Basin follows the identification of its high potential for shale gas. In particular, the Ordovician Goldwyer and Bongabinni Formations, which consist of open marine to inter-tidal and supratidal shale facies respectively, have been identified as potential gas sources in parts of the basin. The meso- to microstructures of these formations has been analysed using x-ray computerised tomography (CT) scanning, optical and scanning electron microscopy (SEM) in backscattered and hyperspectral cathodoluminescence modes to evaluate bedding, laminations, mineral relationships and diagenetic alteration. Additional analyses were performed using x-ray diffraction and quantitative electron microprobe analysis to determine mineralogical and geochemical signatures. Furthermore, x-ray texture goniometry (XTG) was employed to evaluate and quantify the degree of preferred orientation of the clay minerals. Finally, rock properties were calculated from measurements made during geomechanical and ultrasonic tests on the shales, determining static and dynamic elastic properties, rock strength, velocity and velocity anisotropy and these were related to the rock macro- and microfabrics.

The CT scans show that in general, the Bongabinni Formation is massive and monotonous, apart from occasional lower density laminations, whereas the Goldwyer Formation has laminations on the millimetre to centimetre scale, with narrower high density laminations and broader low density laminations. The Bongabinni Formation is dominated by illite and quartz but has been affected by early diagenetic precipitation of anhydrite and dolomite which prevents clay particle rotation and stiffens these shales. The Goldwyer Formation has more illite and quartz than the Bongabinni, along with chlorite and calcite. The SEM studies show the former unit has undergone more mechanical compaction, clay mineral diagenesis and quartz cementation during its burial history. This has resulted in a much stronger clay particle alignment in the Goldwyer, with XTG quantification showing maxima of 5.77 multiples of a random distribution (m.r.d.; where a random distribution is 1), whereas for the Bongabinni samples it is 2.44 m.r.d.

Rock strength testing showed that the Bongabinni Formation is significantly stronger than the Goldwyer Formation, with peak strengths of 25 MPa, compared to 8 MPa at the same confining pressure. Similarly, Young's modulus is also significantly higher in the former unit. The strengthening and stiffening seen are likely the result of the early diagenetic precipitation of dolomite and anhydrite in the Bongabinni Formation, which has also resulted in a lower porosity and higher elastic wave velocity in this material. However, increased particle orientation and the presence of aligned fractures in the Goldwyer Formation has probably resulted in the significant velocity anisotropy noted in this rock. In comparison, the more massive and less aligned Bongabinni Formation is almost isotropic in terms of dynamic elastic properties.

To conclude, a broad multi-disciplinary study has allowed us to elucidate the impact of diagenetic alteration on mineralogy and microstructure of two Canning Basin shales and link these changes to geomechanical and ultrasonic properties in the laboratory. The results suggest hydraulic fracturing would be more effective in the Bongabinni due to its higher strength and stiffness.

## Magnetotelluric monitoring of hydraulic fracture stimulation at the Habanero Enhanced Geothermal System, Cooper Basin, South Australia

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Magnetotelluric (MT) data were collected across the Habanero Enhanced Geothermal System project in the Cooper Basin, South Australia. A baseline regional MT survey consisting of two profiles was collected to delineate the pre-injection resistivity structure. Two dimensional inversions of the MT data reveal three main resistivity structures to a depth of 5 km. The low resistivity surface layer (about 1.5 km thick) is interpreted as poorly consolidated sediments of Lake Eyre and Eromanga Basins. Below the conductive layer, a zone with relatively high resistivity with thickness of 2 km can be correlated to consolidated Cooper Basin sediments. A high resistivity zone below depths of 3.5 km is interpreted as the hot intrusive granodiorite (granite) of the Big Lake Suite with low porosity and permeability. This deep structure is also related to the Habanero EGS reservoir.

The second MT survey was conducted during stimulation of Habanero-4 well by Geodynamics Ltd, where 36.5 ML of water with a resistivity of 13 m (at 25°C) was injected at a relatively continuous rate of between 27-53 L/s over 14 days at a depth of almost 4 km. Analysis of pre- and post-injection residual phase tensors for periods greater than 10 s indicate conductive fractures oriented in a N/NNE direction. Apparent resistivity maps also revealed that injected fluids possibly propagated towards N/NNE direction. This result is in agreement with the micro-seismic events with an area of 4 km<sup>2</sup> observed during fluid injection, as well as orientation of pre-existing N-S striking sub-horizontal fractures susceptible to slip due to stimulation. The MT responses close to injection show on average 5% decrease in apparent resistivity at periods greater than 10 s. The main reasons for observing subtle changes in resistivity at Habanero EGS is the screening effect of the conductive thick sedimentary cover (about 3.6 km thick) and the presence of pre-existing saline fluids with resistivity of 0.1 m (equivalent to salinity of 16.1 g/L at 240°C) in the natural fractures. Analysis of time-lapse models indicate an increase in total cumulative conductance of about 25 S over a depth range of 2 – 5 km in the N-S direction compared to E-W direction for MT sites close to the injection well, which likely indicate anisotropic permeability generated by hydraulic stimulation. Overall, the MT monitoring at Habanero EGS highlights the need for favorable geological settings to measure significant changes in resistivity in EGS reservoirs.

## Groundwater Resource Vulnerability Assessments in SW Pacific island Nations: Identifying Communities at Risk, and Climate Change Adaptation Strategies

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Populations in the SW Pacific region rely heavily on groundwater and, for many island nations this is the only reliable source of freshwater year-round. This vital resource is already under significant pressure from population growth and pollution, with key aquifers further threatened by the longer term effects of climate change (e.g. sea-level rise and reductions in rainfall recharge), and island subsidence. As witnessed by recent disasters in Vanuatu, Micronesia and Fiji, water resources in these island communities are also vulnerable to the sudden onset of events such as tsunamis and storm surge.

An initial regional assessment of the vulnerability of fresh groundwater systems to future climates has been carried out for 15 Pacific Island countries and territories. This study developed a groundwater vulnerability framework, assessing relative potential vulnerability of groundwater to future: (i) low-rainfall periods and (ii) mean sea-level rise for projected 30-year periods centered on 2050 and 2085. The framework rates the potential impact (sensitivity and exposure) of a climate hazard which is offset by the intrinsic ability of a groundwater system to be managed for future climate impacts.

A hydrogeologically-based typology has been developed for the study. The typology identifies five types of islands, each with similar groundwater systems—Low Carbonate, Limestone, Volcanic, Composite and Complex. These island types underpin the assessment of groundwater vulnerability.

The assessment has found that there are a large number of islands in the region with groundwater systems that are potentially vulnerable to future low-rainfall periods and projected sea-level rise. The majority of Low Carbonate islands that have been assessed have the highest rating of relative potential vulnerability to low-rainfall periods or mean sea-level rise by mid- and end-of-century. Complex islands (>2,000 km<sup>2</sup>) are the least vulnerable to low-rainfall periods or mean sea-level rise.

These results have implications for future water management and planning in the Pacific region. Moreover, parallel investigations elsewhere in the Pacific have recently shown that the combined effect of storm-induced wave-driven flooding and sea-level rise on island atolls may be more severe and happen sooner than previous estimates of inundation. However, on-going studies in the northern Pacific also demonstrate how groundwater investigations and modelling can be used to identify new resources and sustainable water management strategies while also identifying new engineering adaptation strategies.

In summary, the lack of secure water supplies threatens the long-term viability of many communities and islands in the SW Pacific. There is a pressing need to build community resilience to climate change and identify practical adaptation measures, while the provision of more secure water supplies is also required to underpin regional economic development. The paucity of relevant groundwater and other biophysical data necessitates a phased program of socio-economic and scientific investigation to provide more accurate assessments of the sustainability of current water supplies, assess risks to these vital water resources, help develop more sustainable water resource management strategies, and identify alternative water supply and adaptation options where necessary.

## Tectono-metamorphic evolution of the southern Thomson Orogen: new evidence from a multi-disciplinary study

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The geological evolution of the Thomson Orogen, and its relationship with other parts of the Tasmanides of eastern Australia, is not well understood. This is mainly due to poor exposure. The orogen is largely covered by the Eromanga and underlying sedimentary basins, which in places reach a combined thickness of more than 3.5 km. A collaborative project between Geoscience Australia, the Geological Survey of Queensland and the Geological Survey of New South Wales is using a multi-disciplinary approach to better understand the stratigraphic and tectono-metamorphic evolution of the southern Thomson Orogen, with particular focus on the region straddling the Queensland-New South Wales border where cover is thinner and mineral prospectivity is considered higher.

Available drill hole samples indicate the area as a whole is dominated by clastic sedimentary rocks, but stratigraphic age constraints are extremely limited. An extensive program of U-Pb dating is underway to help characterise the stratigraphy via detrital zircon age spectra and maximum deposition ages. Available results indicate a dominance of latest Neoproterozoic to Cambrian and late Mesoproterozoic "Grenvillian" aged zircons across the region. Maximum deposition ages, as defined by the youngest detrital zircons, tend to fall in to two groups; ~500 Ma and ~440 Ma. These detrital zircon spectra and maximum deposition ages are broadly similar to those from the northern Lachlan Orogen.

The relatively shallow cover combined with lithologies that are characterised by high-amplitude/short-wavelength signatures in aeromagnetic data, allow division of the southern Thomson Orogen into western and eastern structural domains. The western domain is characterised by a broadly northwest-southeast oriented structural grain, sub-parallel or at a low angle to the bounding Olepoloko Fault. The eastern domain is dominated by a large-scale fold structure with a northeast trending axial plane. Preliminary K-Ar geochronology results from cleavage-forming white micas ("illite") support the distinction of the two structural domains, and suggest that the dominant structural fabrics in the domains formed during different stages of Tasmanide evolution.

New U-Pb SHRIMP zircon ages from magmatic rocks suggest that the two structural domains also have different magmatic histories. The western structural domain is dominated by felsic magmatism between ~430 to ~420 Ma, whereas the eastern structural domain shows a more episodic history consisting of several magmatic events between ~455 and ~370 Ma.

In summary, our results from the southern Thomson Orogen reveal some similarities with the northern part of the central Lachlan Orogen (e.g. stratigraphic constraints and the magmatic history of the western structural domain), but also some differences (e.g. the character and timing of structural evolution). Further work investigating the nature and implications of the different domains within the context of the Tasmanides is continuing.

## The Monash Earth Sciences Garden: A new interactive teaching experience

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The Monash Earth Sciences Garden (MESG) is a new and innovative outdoors teaching space that allows undergraduates from Monash University's School of Earth, Atmosphere and Environment (SEAE) to hone their field measurement and mapping techniques, and rock and mineral recognition skills before being sent into the field. This enables students to be fieldwork-ready and thus significantly reduces time spent on these basic geological skills during external fieldwork activities where cost remains an important consideration.

The MESG, measuring 120 m by 30 m, represents a complex and unique plan that is inspired by the geology and geomorphology of Victoria, Australia. The project, located in the heart of the Science Precinct of the Clayton Campus, was designed and delivered by a small team of Earth scientists from the SEAE, in collaboration with landscape architects rush\wright.

The design incorporates over 500 different large rock samples weighing up to 14 tonnes each, representing 20 different types of sedimentary, igneous and metamorphic rocks. Nearly all rock samples were sourced from Victoria, and all quarries were identified and visited to ensure that the correct rock was being quarried, and that the best samples of rocks were chosen in terms of their fabric, structures and mineralogy.

The MESG can be viewed as a number of small study areas that independently relate particular Earth sciences concepts. For example, the central northern 'Highlands' area of the MESG comprises large blocks of Harcourt Granite, with excellent examples of enclaves and xenoliths, that have intruded an older, folded sequence resulting in contact metamorphism of mudstones to schist. This allows more detailed studies on ore geology, structural geology, engineering concepts, and metamorphic and igneous petrology to be taught. Likewise, the southeastern portion of the MESG represents the Gippsland and Otway coasts where Miocene-aged Point Addis Limestone is juxtaposed against Early Cretaceous Eumeralla Formation sandstone, allowing the concept of plate tectonics, palaeontology, planetary impact geology and climate change to be examined.

Since each rock sample has its own specific spatial location and orientation (strike and dip) in the garden, the individual rock areas can be used in an integrated manner to allow students to effectively map a 'geological province' and interpret a multi-phase, geological history narrative that spans hundreds of millions of years.

Plantings associated with the different rock areas are sympathetic to their geographical area in Victoria to reflect more of what Earth scientists see during the course of fieldwork, and, of course, to allow the study of biogeography and soil types.

As part of the SEAE Outreach Strategy for secondary schools, we have fully integrated the MESG into the 'Earth and Space Sciences' and 'Geography' subject areas of the Australian National Curriculum for Year 8–10 students

Future plans for the MESG include the addition of large Perspex soil horizons in some of the rock type areas, the construction of a weather station, and the placement of a geocache.

## **Understanding the distribution and structural setting of mineralization from principle component analysis of portable X-ray fluorescence geochemistry: new insights from an old friend.**

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Many mineral deposits that have already been discovered at the surface remain under-estimated and under-exploited because of limited understanding of their structural setting and difficulties mapping the distribution of barren cover rocks. Significant outcropping and shallow-drilled gold mineralization at the Gettysberg and Sellheim prospects, located on the NE trending, western bounding fault of the Anakie Inlier of Northern Queensland, has been known for >30 years. Exploration has focused on drilling the NE trend, but new field evidence and re-evaluation of old, un-oriented core shows that the mineralization is best developed along west to northwest trending cross faults. These structures throw barren Late Devonian Drummond Group sediments against mineralised Lower Devonian Ukalunda Formation associated with the Anakie Inlier. Both units contain strongly sericite altered medium sandstones and are difficult to distinguish in the field, which complicates surface mapping. However, our innovative principle component analysis (PCA) of portable XRF (PXRF) soil and drill chip geochemistry, unbiased by gold assays, reliably discriminates these units and zones of gold bearing rocks in 3d. These analyses and 3 D modelling are retrospectively sufficient to signal the presence of the NW trending structures, based on the character and distribution of barren and mineralized units, without in-depth structural analysis; PXRF and PCA will therefore form a pillar of our future investigations.

## Is Southern Australia bent?; recognition of a contiguous Palaeoproterozoic magmatic arc along the western margin of the Mawson Continent

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Palaeo- to Mesoproterozoic plate tectonic models of southern Australia have been hampered by the apparent lack of unequivocal evidence for subduction-related magmatism. Within the Gawler Craton, the isotopically juvenile, calc-alkaline, c. 1620–1607 Ma St Peter Suite has been suggested to represent subduction-modified crust. However, unlike Palaeoproterozoic arc systems in Laurentia and Baltica, which form quasi-linear belts of subduction-modified crust and preserve other features indicative of subduction such as back-arc basins and accreted terrains, the known extent of the St Peter Suite is ovoid in shape and the structural setting of emplacement within the Gawler Craton is enigmatic. Additionally, isotopically juvenile, calc-alkaline rocks of the Birksgate Complex in the central Musgrave Province and the Wankanki Supersuite in the western Musgrave Province have been interpreted to represent arc magmatism at c. 1590–1555 Ma and c. 1300 Ma, respectively.

New geochemical, isotopic and geochronological data from the eastern Musgrave Province in northern South Australia is pushing back the age of potential arc magmatism in the region. SHRIMP zircon geochronology of the bi-modal eastern Birksgate Complex indicates igneous crystallisation ages of c. 1665–1600 Ma with juvenile isotopic compositions ( $Nd_{1600}$  between +4 and -1.5,  $Hf_{1600}$  between +2.44 and +7.04). Similarly, new data show that geochemically similar calc-alkaline felsic magmas in the Forrest Zone of the Coompana Province, the Toolgana Supersuite, have similar isotopic compositions ( $Nd_{1600}$  between +1.5 and -0.8,  $Hf_{1600}$  between ~0 and +10) at c. 1613–1604 Ma. Based on these new constraints we propose that these elements are part of a single, contiguous c. 1650–1600 Ma magmatic-arc system. In this scenario, the St Peter-Musgrave-Toolgana arc system developed along a passive margin as a predominantly oceanic-arc outboard of the western (present location) Mawson Continent.

Some authors have speculated that its arcuate shape suggests the Gawler Craton may have undergone oroclinal bending prior to the emplacement of the undeformed Gawler Range Volcanics at c. 1585 Ma. The present day geometries of the c. 1610 Ma arc system supports this hypothesis and provides a mechanism to drive oroclinal bending within the Gawler Craton, by a change in subduction dynamics or slab roll back outboard of the central Gawler Craton core. Conceivably this also provides a plate tectonic model for the formation of the A-type, intracontinental Hiltaba Suite and Gawler Range Volcanics (GRV). Orocline development between c.1600–1590 Ma lead to over thickening of the lithosphere within the hinge of the orocline with subsequent destabilisation of the lithospheric mantle and delamination providing the thermal driver and mantle input to produce the GRV SLIP and the associated world class mineral systems.

## What lies beneath the Nullarbor Plain? Insights into the geology of the Coompana Province from deep crustal seismic reflection profile 13GA-EG1

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The Coompana Province, lying between the Gawler Craton to the east and the Madura Province to the west and straddling the border between Western and South Australia, is one of the last unknowns in Proterozoic Australia. This region is entirely covered by Neoproterozoic to Cenozoic sediments of the Officer, Denman, Bight and Eucla basins. Until recently, very little was known about the structure and lithostratigraphy, with only a few basement intersecting drill holes and limited, poor resolution geophysical imagery. New data acquisition by the GSWA and the GSSA including diamond drill holes, gravity, magnetic and radiometric data, magnetotellurics and deep crustal reflection seismic is providing new insights into the geology and geodynamics of this important region. Here we present the interpretations and implications derived from the new data.

The Jindarnga Shear zone, a west dipping crustal structure, is the boundary between the Gawler Craton to the east and the Coompana Province to the west. In the hanging wall the eastern Coompana crust is three layered, consisting of; (i) a reflective lower crust with reflectors that parallel the Moho, (ii) a reflective mid-crust with west dipping reflectors and anastomosing shear zones, and (iii) a seismically bland upper crust interpreted to be dominated by intrusives. At ~18600 cdp (common depth point) there is a rise in the Moho from ~ 44 to 39 km and the strongly reflective lower and mid-crustal layers terminate at a crustal-scale west-dipping structure, corresponding to a domain of strongly magnetic, c. 1200–1120 Ma Moodini Supersuite (interpreted) intrusions.

This structure marks a transition from a three-layered crust to a two-layered crust, with a mid to lower crustal section characterised by strong, flat-lying reflectors, and a seismically bland, intrusion-dominated upper crust. At the state border (~16200 cdp) a west-dipping structure, the Border Shear Zone, soles onto the reflective mid-crust, separating predominantly Moodini Supersuite in the footwall and c. 1610 Ma Toolgana Supersuite in the hanging wall. From the Border Shear Zone west to ~ 10100 cdp, the upper-crust is characterised by shallowly dipping, often sigmoidal reflectors separated by predominantly west dipping structures that sole onto a reflective mid-crust. This upper-crust is dominated by intrusives of the Toolgana and c. 1490 Ma Undawidgi Supersuites. At ~12020 cdp (at Forrest) is a distinct, antiformal feature that coincides with a gravity and magnetic anomaly that occurs along strike from shoshonitic Moodini Supersuite intrusions to the northeast. At ~12000 cdp there is an increase in Moho depth back to ~44 km, coinciding with the narrow end of a wedge-shaped bland region in the lower crust. The reflective mid-crust thins to the west above this wedge and both are truncated by the subvertical, crustal-scale, Mundrabilla Shear Zone, which marks the boundary between the Coompana and Madura Province to the west. The mid-crustal reflective package has complex reflectors with variably shallow dipping and anastomosing fabrics.

## Controls on the global distribution of seafloor sediments: implications for the interpretation of the deep-sea sedimentary record

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The ocean basins are the largest carbon sink on Earth and contain a rich record of our planet's tumultuous climatic history preserved as different types of deep-sea sediments, which collectively represent by far our most significant geological deposit. Knowing the controls on distribution of these sediments is critical to our understanding of global biogeochemical cycles, changes in the distribution and the elevation of land masses, sea-level changes, changes in ocean's temperature, circulation, chemistry, the occurrence of metal deposits as well as major biological perturbations. We recently created the first digital map of seafloor lithologies (Dutkiewicz et al., 2015) based on descriptions of nearly 14,500 samples from original cruise reports obtained through the Index to Marine and Lacustrine Geological Samples supplemented by descriptions acquired from non-participating agencies such as Geoscience Australia. The categorical data were interpolated using a support vector machine algorithm and can be viewed on an interactive 3D rotating globe (<http://portal.gplates.org/cesium/?view=seabed>), revealing that the distribution of modern deep-sea sediments is more complex with significant regional deviations from hitherto hand-drawn maps based on far fewer data points. Notably, the lithologies occur in drastically different proportions globally; coverage by calcareous sediment and clay is > ~30% compared to the earlier maps, and that of siliceous oozes is < ~25%, which has significant implications for the calculations of carbon stored in modern seafloor sediments. Creation of this digital map has allowed us to explore, for the first time, the connection between key oceanographic parameters (sea-surface salinity, temperature, nutrients, productivity and bathymetry) and the distribution of seafloor sediments, which represent modern material, on a global scale. Using a probabilistic Gaussian process classifier we find that the occurrence of five major lithologies in the world's ocean can be predicted on the basis of just two or three parameters, notably sea-surface salinity and sea-surface temperature. These parameters control the growth and composition of plankton and specific salinities and temperatures are also associated with the influx of non-aerosol terrigenous material into the ocean. Bathymetry is an important parameter for discriminating the occurrence of calcareous sediment, clay and coarse lithogenous sediment from each other, but it is not important for biosiliceous oozes. Consequently, radiolarian and diatom oozes are poor indicators of palaeo-depth. Contrary to a widely held view, we find that calcareous and siliceous oozes are not linked to high surface productivity. Our analysis shows that small shifts in oceanographic parameters such as salinity and temperature can have a significant effect on the composition of seafloor sediment. The linking of seafloor lithologies with oceanographic datasets provides a new framework for constraining palaeosurface ocean environments from the deep-sea sedimentary record.

Dutkiewicz, A., R. D. Müller, S. O'Callaghan, and H. Jónasson (2015), Census of seafloor sediments in the world's ocean, *Geology*, 43(9), 795-798.

## Clumped-isotope palaeothermometry from the cave systems of Riversleigh, Queensland

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Cave systems and their associated morphological structures have been investigated in palaeoenvironmental studies for decades. Stalagmite carbonate precipitates can provide detailed high resolution geochronologies and conventional oxygen-isotope records. However, there are many variables that must be considered in conventional and clumped-isotope mass spectrometry analysis and interpretation of these analyses to make a reliable speleothem-based palaeotemperature record (Affek et al., 2013; Kluge et al., 2013; Kluge and Affek, 2012; Wainer et al., 2011). Clumped isotope analysis is concerned with measuring the abundance of mass 47 (largely  $^{13}\text{C}^{18}\text{O}^{16}\text{O}$ ) in carbon dioxide reacted from a carbonate mineral with phosphoric acid. The abundance relative to the natural random stochastic distribution is temperature sensitive, up to 0.004 per mil per degree Celsius, if measured to a precision of  $\pm 0.01\text{‰}$ , implying a resolution, of about  $\pm 2\text{ }^{\circ}\text{C}$ . Accordingly, palaeotemperatures can be deduced without knowledge or assumption of the past  $^{18}\text{O}/^{16}\text{O}$  ratio (as  $^{18}\text{O}$ ) of the water.

Speleothems typically do not precipitate carbonate minerals at equilibrium conditions. Precipitation may be complicated by dynamic evaporation and degassing of  $\text{HCO}_3^-/\text{CO}_2$  systems. This complicates the identification of an exact carbonate formation temperature. This is evident by examining cave floor and stalagmite deposits, which commonly report  $_{47}$  temperatures up to  $8\text{ }^{\circ}\text{C}$  higher than the actual cave air temperature (Affek et al., 2008). Disequilibrium effects of 1.1 to  $4.5\text{‰}$  have been reported between measured temperatures and  $_{47}$ -derived cave temperatures (Daëron et al., 2011). Other speleothem deposits (formed under water) potentially precipitate calcium carbonate at equilibrium conditions with a host fluid, such as cave pearls, pool stones, calcite rafts and rim pool calcifications. These formation types may be more useful in representing equilibrium formation temperatures. This study aims to contribute to the understanding of equilibrium formation temperatures in cave deposits which currently remain relatively unexplored.

The Riversleigh Oligo-Miocene to Quaternary cave systems of north-eastern Queensland, Australia and their associated bone deposits will aid in advancing the understanding of how speleothem deposits record palaeoenvironmental temperature change. In addition to flowstone, cave pearl and calcite rafts, various macro-fossil specimens have also been discovered and form part of the megafauna assemblage of the Riversleigh fossil area. Equilibrium deposited carbonate structures produce plausible  $_{47}$  calcite formation temperatures of  $\sim 19\text{ }^{\circ}\text{C}$  from the broader Bitesantennary Area (Bitesantennary, Neville's Garden and Inabayence sites). These give an indication of mean annual air temperature of the Mid-Miocene period in northern Australia. We note the stalagmite deposits appear to produce banded temperature differences with their deposition structure. In addition we note that stalagmite precipitates exhibit higher than expected  $_{47}$  formation temperatures in the order of  $8\text{ }^{\circ}\text{C}$  higher than other surrounding equilibrium cave precipitates, confirming trends observed by Affek et al. (2008). Fine grained calcite precipitates such as cave-pears and organic-rich flowstones produce highly enriched  $_{47}$  values, corresponding to unrealistically low (even negative) calculated precipitation temperatures, confirming findings of negative reported palaeotemperatures by Kluge et al. (2014). Future analyses will determine the body temperatures of terrestrial vertebrates of the Riversleigh faunal assemblages, to aid in the palaeobiological reconstruction of their physiology and metabolism, and to provide past air temperatures.

## Gold sensing at ppb level with the optical methods

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World demand for gold is increasing and its price has risen by almost \$700 per ounce over six years (2002-2008) [1]. To meet this demand a new portable highly sensitive detection method is necessary. The current portable methods, such as X-ray fluorescence (XRF) enable detection of gold at ppm level. However, economically significant amount of gold in a rock varies between 0.5-8 ppm [2, 3].

Two optical methods were tested for their utility in the detection of low ppb level of gold: absorption and fluorescence. The absorption method makes use of the unique phenomenon observed only in the relation to metal nanoparticles, called surface plasmon resonance (SPR). For the fluorescence measurement the 4,4-difluoro-4-bora-3a, 4a-diaza-s-indacene (I-BODIPY) molecule was synthesised, which in the presence of gold is modified and becomes fluorescent. The limit of quantification (LOQ) of the two methods was studied using both non-portable high resolution spectrometer and portable set up. We also tested if using an optical fibre as a sensing chamber instead of cuvette can increase the fluorescence LOQ. The suspended core optical fibre was produced from high purity silica. In this type of the fibre, the light is guided through the core (1.5 µm) surrounded by three air holes (60 µm) which act as a sensing chamber. The fraction of light being guided in the holes which interacts with the sample was measured.

The results indicate that both methods allow achieving low detection limit with the portable set up. The LOQ depends on the size of NPs and with increasing size of NPs the LOQ decreases in absorption (492 ppb for 5 nm NPs and 184 ppb for 50 nm NPs), but increases in fluorescence (74ppb for 5 nm NPs and 1200ppb for 50 nm NPs). We have found that using an optical fibre instead of cuvette enables to decrease the fluorescence LOQ of 50 nm to 492ppb, whereas the LOQ for smaller NPs was similar as in a cuvette. Apart from higher sensitivity, using an optical fibre provides additional benefits over cuvette such as possibility of remote sensing and low volume of the sample required for the analysis (0.3µl).

Currently we are conducting the experiment with a range of rock samples. Gold in a rock is usually present in the form of microparticles or even bigger particles, whereas for the optical sensor, gold needs to be in form of nanoparticles. In addition, gold may not be present as a free nuggets, but rather bound to the mineral. Thus, it needs to be leached, released from rock and transformed into nanoparticles. First results into development of a safe method for extraction of gold from rock for optical detection will be presented.

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## **Basin evolution in the Carnarvon and Perth Basins – implications for petroleum systems**

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The North West Shelf of Australia is a prolific hydrocarbon province, but there are aspects of its petroleum systems that remain poorly understood, such as the differences in prospectivity between the Perth and Northern Carnarvon Basins and the precise source of the gas contained in Triassic reservoirs of the fluvial Mungaroo Formation that make up many of the LNG fields of the Exmouth Plateau. The underlying pro-delta Locker Shale is a recognized source rock but is buried deeply beneath several kilometres of Mungaroo Formation, implying that charge would be generated from it during the Triassic, prior to the formation of traps during Lower Jurassic extension.

There are four aspects of the tectonic evolution of northern and western Australia that may help explain these observations. Significant rifting during the Carboniferous and Permian was probably responsible for the fundamental architecture of the North West Shelf rift system, but understanding the tectonics of this period is made difficult by poor imaging of these sections on seismic data - a result at of the depth at which they occur, particularly beneath the Exmouth Plateau. However, integration of observations from onshore basins and the margins of offshore basins is helping to shed light on events during this may provide a better understanding of the tectonic setting of the large Triassic depocentre on the Exmouth Plateau in which the Locker Shale and Mungaroo Formation accumulated.

Lower to Middle Jurassic rifting is better understood, although new insights are still to be gained form the excellent imaging on 3D seismic data of the extensional structures that formed at this time. With extension and sedimentation focused on marginal basins (the Exmouth, Barrow & Dampier sub-basins), the Exmouth Plateau was sediment starved. resulting in erosion of Triassic reservoirs in the crests of extensional fault blocks, providing a further constraint on charge to some of these structures.

Upper Jurassic and Lower Cretaceous deformation is widely attributed to India-Australia separation, and although it is widespread in the Perth Basin, it is confined to the Exmouth sub-basin in the Northern Carnarvon Basin. Deformation here is unusually short lived, associated with uplift and erosion, and extensive igneous activity. A recently proposed mantle plume may explain a number of these observations, and has obvious implications for heat flow and source rock maturity – particularly for the oil prone source rocks that charge Lower Cretaceous reservoirs in the Exmouth sub-basin.

Finally, subsequent to break-up, broad, large scale folds developed over parts of the Exmouth Plateau. However, compressional reactivation of individual normal faults is mainly confined to the western margin and is Pliocene to Recent in age. The differences between the Perth and Northern Carnarvon Basins in terms of Lower Cretaceous uplift and subsequent fault reactivation may go some way to explaining the differences in petroleum productivity of these adjacent basins.

## Determining porosity-permeability relationships from core plugs for aquitard formations in the Gunnedah Basin, Australia

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Understanding vertical permeability ( $K_v$ ) heterogeneity of aquitards is vital in examining the potential risk of coal seam gas related depressurisation of groundwater resources across a range of scales. Continuous vertical profiles of permeability derived from combining geophysical wireline data and core-based porosity and  $K_v$  measurements improve representation of aquitards in groundwater flow models. Such information is pivotal for robust assessments of the degree to which depressurisation within coal seam formations may propagate to adjacent aquifers. We first developed an effective way of capturing small-scale permeability heterogeneity across key aquitards in the Gunnedah Basin in NSW by establishing porosity-permeability relationships using laboratory measurements of porosity and  $K_v$  on core samples. These relationships are subsequently used for generating high-resolution permeability profiles based on continuous porosity estimates derived from bulk density logs. In a final step the fine-scale permeability estimates will be upscaled to grid sizes typically used in regional scale cellular groundwater flow models.

A total 59 cores were recovered from different wells drilled in four selected aquitard formations in the Gunnedah Basin: Napperby (interbedded fine sandstone, claystone and siltstone), Watermark (marine siltstone, shales and sandstone), Porcupine (fining upward sequence of conglomerate and sandstone to mudstone) and Purlawaugh (fine to medium grained sandstone thinly interbedded with siltstone, mudstone and thin coal seams). Porosity-permeability relationships were determined for each aquitard using laboratory measurements of porosity ( $\leftrightarrow$ ) and permeability ( $K_v$ ) on the core plugs using a nitrogen gas based permeameter-porosimeter. The methodology is widely used in core evaluation and returns the equivalent liquid permeability (i.e. Klinkenberg corrected gas permeability). Both porosity and permeability were measured under various overburden pressures ( $P$ ), typically in the range 3.4 – 14 MPa. Initially, the dependency of porosity and permeability on confining pressure ( $P$ ), the ( $P,\leftrightarrow$ ) and ( $P,K_v$ ) relationships were established by fitting an exponential model to the data for each of the core samples. In the next step, the porosity-permeability data for all confining pressures is pooled per formation and a linear regression model fitted to the ( $\leftrightarrow\log K_v$ ) data pairs estimated. The porosity-permeability models are most accurate in the Purlawaugh and Watermark formations with coefficients of determination ( $R^2$ ) of 0.91 and 0.81, respectively. For the Porcupine and Napperby formations the  $R^2$  is approximately 0.70. The study investigates possible causes of the relatively low Porcupine and Napperby model performance in comparison with the other two formations.

The formation-specific porosity-permeability models are subsequently combined with continuous porosity profiles inferred from bulk density wireline logs at about 100 wells drilled in the Gunnedah Basin. The wireline-based porosity profiles are then converted into continuous permeability values using the previously established porosity-permeability models for the four main aquitards. An existing numerical grid pertaining to a cellular groundwater flow model is then used as the basis for upscaling the fine-scale  $K_v$  values to grid-cell equivalent values. This three-dimensional  $K_v$  dataset provides an improved representation of aquitard  $K_v$  heterogeneity for regional scale groundwater flow simulations in the Gunnedah Basin.

## Investigating the Moho beneath onshore and offshore Tasmania using the complete Bouguer anomaly

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Tasmania is divided into two main terranes including Western Tasmanian Terrane (WTT) with exposed Neoproterozoic basement and Eastern Tasmanian Terrane (ETT), dominated by Palaeozoic rocks with no Proterozoic outcrops. The WTT joined the ETT along the proposed Tamar Fracture System during the early Ordovician or Early to Middle Devonian. In contrast, offshore Tasmania comprises a number of extensional sedimentary basins associated with continental breakup. These late Mesozoic-Cenozoic age basins include the Bass, Sorell, Otway and Gippsland Basins within the study area. The Bass and Sorell Basins were initiated due to extension related to failed rifting between Australia and Antarctica during the Jurassic-Cretaceous. The Tasman Sea developed due to seafloor spreading between ~84 Ma and ~53.3 Ma.

In this study, Moho depth was investigated across major tectonic boundaries, including sediment basements, the unstretched continental crust limit (UCCL) and continent-ocean boundary (COB). A 3D gravity model was constructed to investigate the gravity-constrained Moho depth and its correlation with seismic interpretations. Over 700,000 onshore and offshore gravity observations are compiled from Geoscience Australia (GA), Mineral Resource Tasmania (MRT), the Geological Survey of Victoria (GSV) and the NOAA geophysical data viewer. Gravity corrections including latitude, free-air and Bouguer were applied. We calculated a terrane correction for a radius of 167 km to minimise the effects of the difference between the spherical cap and infinite horizontal slab to calculate the complete Bouguer anomaly.

The model comprises six layers: sediments, four units of upper and lower crust within and beyond the UCCL, and mantle. We delineated the continental shelf break as the furthest offshore extent of the UCCL. We used the AuSREM Moho depth and calculated the Airy Isostatic Moho to provide initial constraints. The Airy Isostatic Moho depth based on the Airy-Heiskanen model represents deeper onshore Moho and crustal thinning beyond the UCCL. The average assigned densities are 2.40-2.67 g cm<sup>-3</sup> for sediments, 2.57-2.80 g cm<sup>-3</sup> for crust and 3.22 g cm<sup>-3</sup> for mantle across Tasmania. We used the Paradigm Gocad Package for 3D model construction and VPmg for inversion. The study area extends from 142.46°.50" to 149.58°.11" longitude and from -38.20°.29" to -43.57°.39" latitude in the GDA94 datum. Our 3D inversions indicate that oceanic crust most likely onsets beyond the study extent.

A series of different geometry inversions were systematically evaluated by assigning a range of densities to the lower crust and carrying out a property inversion of the upper crust. The inversion indicates that the gravity Moho surface differs from the broadscale AuSREM seismic estimations of this surface. The gravity Moho estimation varies from ~33 to ~40 km depth in onshore Tasmania, up to 10 km deeper than the seismic model, and displays crustal thinning beyond the UCCL, with minimum depth of ~16 km west of the Sorell Basin. Across the Bass Strait, crustal thinning is supported by shallow Moho estimations. The gravity-constrained Moho corresponds to the Airy Isostatic surface with a relatively deep onshore Moho, thinning towards the ocean.

## **Managed aquifer recharge challenges and opportunities in northern Australia.**

**Dr Richard Evans**

*Jacobs*

Managed aquifer recharge (MAR) is a commonly used technique in many countries to artificially increase the recharge rate over the wet season and hence increase the storage of groundwater for subsequent use during the dry season. Considering northern Australia's long dry season and relatively short wet season it would be expected that MAR could play a major role in water resource planning and development. However this has not occurred to date due to several significant reasons. These factors are explained in this paper. This paper is focussed on the applications of MAR for irrigation developments. MAR applied to urban water supply development is much more economically feasible than for irrigation and hence the latter case is a greater challenge.

The fundamental geology and hydrogeology of northern Australia is a significant factor which controls the feasibility of MAR in northern Australia. The marrying of specific MAR methods (e.g. injection bores, spreading basins, recharge weirs) with geological settings is the first requirement for a successful MAR scheme. The advantages and disadvantages of narrow and fan alluvial systems, limestones and dolostones, and fractured rock aquifers (which are common in northern Australia) are closely linked to the MAR method. Storage behaviour is in turn controlled largely by the aquifer hydraulic properties and source water availability and timing. These factors all control the technical feasibility of MAR schemes. Examples of successful MAR schemes in northern Australia will be presented. Operational aspects, especially clogging, also strongly influence the longevity of specific projects.

Fundamental impediments to large scale irrigation based MAR schemes in northern Australia will be identified. These are generally not geology or hydrogeology based, but are more related to social and logistical issues. Nonetheless the primary issue is not the technical feasibility, rather it is the economic feasibility of the total irrigation development, which includes a MAR and conjunctive water use component. The economics of irrigation in northern Australia is controlled by many factors largely unrelated to the cost of MAR schemes. However when other water supply options are compared (e.g. building large dams) MAR is very attractive both economically and environmentally. Hence it is believed that MAR will have a long term future in northern Australia.

## Unravelling the enigmatic Galilee Basin, insights from geological modelling for the Galilee Bioregional Assessment

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The Galilee Basin encompasses approximately 248,000 square kilometres of central Queensland, although basin strata only outcrop along its eastern margin, coincident with the Great Dividing Range. The remainder lies buried beneath a cover of younger Eromanga Basin and Cenozoic sediments, which in places can be up to 2000m thick.

Geological modelling of the Galilee Basin undertaken as part of the Galilee Bioregional Assessment (BA) to improve the understanding of the regional distribution and variations in the Galilee geological units and to provide a framework for hydrogeological modelling. This BA will provide a baseline level of information on the ecology, hydrology, geology and hydrogeology of the Galilee subregion, with explicit assessment of the potential impacts of coal seam gas (CSG) and coal mining development on water resources. The Galilee BA area includes the whole of the Carboniferous to Triassic Galilee Basin, as well as parts of the overlying Jurassic to Cretaceous Eromanga Basin and Cenozoic sediments that occur within the Galilee BA boundary.

Using available drillhole data, geological, and seismic mapping, a series of geological surfaces were modelled for the major geological units in the Galilee Basin, including formation tops for the Moolayember Formation, Clematis Group, Rewan Group, Upper Permian coal measures, Joe Joe Group and basement for the Galilee. Basin-scale isopach maps were derived for each major stratigraphic unit, revealing new characteristics about the areal extent and stratigraphic thickness of the Galilee strata. The Upper Permian coal measures, includes the Bandanna Formation, Colinlea Sandstone and their lateral equivalent, the Betts Creek beds.

Major depo-centres in the Galilee Basin include the Koburra Trough and the Powell and Lovelle depressions. From the modelling it is evident that significant areas of erosion or non-deposition occur within the Triassic sequences, in particular along the western margin of the Galilee Basin and the Powell and Lovelle depressions. Triassic rocks are also absent across the Barcaldine Ridge, a major structural feature that separates the northern and southern parts of the Galilee Basin. The economically important upper Permian coal measures are at their thickest in parts of the Koburra Trough, and the Aramac Depression. This coincides with locations of the main CSG projects in the basin and several of the large coal mine developments.

To build a complete geological model of the Galilee BA area, the modelling for the Galilee Basin was combined with existing geological models for the Eromanga Basin. The Eromanga Basin models were compiled by Geoscience Australia as part of the *Hydrogeological Atlas of the Great Artesian Basin*. The combination of these models has outlined some areas where there is potential for direct connectivity between Upper Permian coal measures in the Galilee Basin and the Hutton Sandstone aquifer in the overlying Eromanga Basin. These include parts of the western margin of the Galilee Basin and the Barcaldine Ridge.

The Eromanga Basin stratigraphic modelling is freely available from Geoscience Australia's website. In the near future, all geological model data used for the Galilee BA will be made available through the Bioregional Assessment Information Platform.

## **Characterising the regional hydrogeology of the Galilee Basin and its relationship with aquifers in the Great Artesian Basin (Eromanga Basin)**

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*Groundwater Branch – Geoscience Australia*

Investigations into hydrogeology of the Galilee Basin and its relationship with the Great Artesian Basin were undertaken as part of the Galilee bioregional assessment (BA). This BA will provide a baseline level of information on the ecology, hydrology, geology and hydrogeology of the Galilee subregion, with explicit assessment of the potential impacts of coal seam gas (CSG) and coal mining development on water resources. The Galilee subregion incorporates the whole of the Carboniferous to Triassic Galilee Basin, as well as parts of the overlying Jurassic to Cretaceous Eromanga Basin and Cenozoic sediments that overlie the Galilee Basin.

As part of the Galilee BA, hydrostratigraphic units were defined, and their extents and thickness mapped across the subregion. For major aquifer systems, potentiometric surfaces were constructed from water level measurements and corrected to an equivalent fresh water hydraulic head. Characterisation of aquifers using existing hydrochemistry data has outlined some significant regional differences in water chemistry.

Much of the Galilee Basin is overlain by the Eromanga Basin, which includes a significant proportion of the main aquifer systems of the Great Artesian Basin (GAB). Groundwater flow systems in the Eromanga Basin include a regional water table aquifer in the Winton and Mackunda formations and the Rolling Downs Group aquitard, and the main regional GAB aquifers in the Hooray and Hutton sandstones.

Groundwater flow in the main GAB aquifers is generally to the west. Overall, westward flow is also apparent in the water table aquifer. However, here flow directions are more strongly influenced by topographic variation and the location of major drainage lines such as the Thomson River.

The main aquifers in the Galilee Basin occur in the Clematis Group and sandstones of the Upper Permian coal measures (particularly the Colinlea Sandstone). Overall the hydrochemistry for Galilee Basin aquifers is characterised as Na-Cl dominated with minor HCO<sub>3</sub>. This contrasts with hydrochemistry of the GAB aquifers, which are Na-HCO<sub>3</sub>-Cl dominated systems.

Groundwater flow in the Galilee Basin is more complex and significantly different to that of the overlying Eromanga Basin aquifers. For instance, a major feature of groundwater systems in northern part of the Galilee Basin is a regional north-trending groundwater divide, which it directs groundwater flow towards the eastern and western margins of the basin. Along the western margin of the Galilee Basin, parts of the Galilee Basin aquifers appear to be in direct contact with the overlying Hutton Sandstone aquifer, and represent areas where there could be potential for direct hydraulic connection between Galilee Basin and overlying Eromanga Basin aquifers.

Higher CSG contents in Galilee Basin coal measures appear to be confined to central sections of the Galilee basin, north of the Barcaldine Ridge and exhibit a regional east-west trend. It is postulated that the distribution of CSG is being influenced by regional structures and groundwater hydrodynamics.

## **Australia and New Zealand in IODP ocean drilling research**

**Exon, Neville**

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Australian and New Zealand scientists have been involved in scientific ocean drilling for more than 40 years, and have made vital contributions to the nearly 40 expeditions in our region, often as co-chief scientists. Our Southern Hemisphere scientific skills and data sets give us a considerable advantage in writing proposals for a global scientific program.

Our two countries joined IODP as ANZIC in 2008, and since then there have been six expeditions in the region, the most recent on Australia's northwestern margin in late 2015. Our scientists have been involved in 37 expeditions from 2008 to 2015. Most were two-month expeditions on the non-riser American-funded vessel *JOIDES Resolution*, but some were on the deep-drilling, riser-equipped Japanese vessel *Chikyu*, and some on alternative platforms.

A new phase of IODP, the International Ocean Discovery Program, began in October 2013 and has funding through until 2020. ANZIC continues as an entity, and nearly all possible Australian and New Zealand research institutions are involved. This phase is addressing the fields of climate and ocean change; biosphere frontiers including the sensitivity of marine organisms to environmental change; the nature of sub-seafloor microbial communities; the deep processes of the Earth; and the processes and hazards that affect humanity.

The *JOIDES Resolution* is operating north of Australia in 2016 and most of 2017, and on the Naturaliste Plateau in late 2017. The vessel will then travel eastward into the Southwest Pacific Ocean and will be there and on the Antarctic margin in most of 2018. The *Chikyu* and alternative platforms may also come into our region within the next few years.

Four mature proposals for *JOIDES Resolution* - in the Southwest Pacific including the Antarctic margin - are with IODP and two of these have been approved. Two highly rated proposals are to use *Chikyu* to drill and monitor the Hikurangi subduction zone east of New Zealand, and to drill the Cretaceous sequence of the Lord Howe Rise. A European seabed drilling system is scheduled to drill the Cenozoic sequences on the Antarctic margin south of Australia in early 2018.

Increasing numbers of our scientists should get involved in ocean geoscience and microbiology using IODP as a tool. As we know, ocean tectonics controls the distribution and physical nature of our continents, and ocean processes drive our weather patterns and rainfall. IODP is helping to explain how the Earth has worked in the past and how it works now, and can provide insights into how it may work in the future. Local and foreign scientists get involved in planning IODP expeditions, gathering data to underpin such expeditions, and writing proposals for research drilling around the world and in our region. This is the world's largest geoscience research project and it brings huge scientific benefits, especially to those directly involved.

## **Regional to deposit scale geochemical and spectral footprints of the ~1.6 Ga thermal event in the eastern Gawler Craton – a case study from the Punt Hill region, South Australia**

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<sup>1</sup>*Geological Survey of South Australia – Department of State Development, Adelaide, Australia*

South Australia hosts one of the world's great iron oxide copper gold (IOCG) terranes. Termed the Olympic Cu-Au Province (Skirrow et al. 2007), this belt is renowned as the host to Olympic Dam, the type example of breccia-hosted, hematite-rich IOCG deposits (Groves et al. 2003). The same thermal event resulted in variants of this deposit class throughout the Olympic Province and includes skarn-dominated mineralisation where these fluids interacted with calcareous lithologies.

The South Australian Geological Survey in collaboration with the Deep Exploration Technologies Cooperative Research Centre (DET CRC) have undertaken a program of systematically acquiring co-located geochemical, spectral and petrophysical data on historic drill cores in order to characterise proximal to distal footprints of dominantly IOCG-type deposits in the eastern Gawler Craton, South Australia. Results of this study from Cu-Au prospects in the Punt Hill region are presented and provide an example of how integrating diverse data can be used to map mineral systems and recognise exploration vectors.

A critical aspect of this study involved collecting multiple streams of data from a regional and prospect-scale distribution of drill holes. Spectral scans of drill core were made using the semi-automated hyperspectral logging tool, HyLogger™. Samples were analysed for 65 elements by ICP as well as F by specific ion electrode. Drill hole sampling was accompanied by measurements of magnetic susceptibility and specific gravity.

Spectral, geochemical and petrophysical data were used to characterise dominant alteration assemblages. Once samples were classified, geochemical associations with each assemblage were determined. These were used to determine critical elements and improve interpretation of trace element distribution in the broader mineral system.

Alteration in the Punt Hill region was dominated by prograde and retrograde skarn assemblages. Cu mineralisation is most strongly associated with alteration assemblages dominated by talc, amphibole, chlorite, garnet and pyroxene. Trace elements associated with mineralisation include Au, Ag, As, Bi, Cd, Ce, Cu, La, Mo, Ni, Pb, Sb, Se, U, W, Zn. Assemblages and associated trace elements for distal parts of the system were determined and the distribution of these elements used to map the broader footprints of the mineral system. These data support km-scale fluid flow along a corridor that hosts the Punt Hill prospects.

Spectral mapping of white mica chemistry indicated that Cu mineralisation was associated with an AlOH absorption feature with wavelengths of 2207-2218 nm and provide the potential as a vector to mineralisation in the district.

Where drill holes are sampled on the appropriate scale, this method of data integration and analysis provides a powerful tool to understand the extent and processes active within a mineral system.

## **Mineral systems of the southern margin of the Gawler Range Volcanics - Outcomes of the Mineral Systems Drilling Program, South Australia**

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An extraordinary outpouring of magmatism occurred during the early Mesoproterozoic within the Gawler Craton. This event formed a felsic large igneous province comprising the Gawler Range Volcanics (GRV) and associated Hiltaba Suite intrusions and was responsible for circulation of extensive hydrothermal fluids and the formation of iron oxide-Cu-Au deposits such as Olympic Dam, Prominent Hill amongst others. Although the eastern margin of the GRV are known to contain such IOCG deposits, the mineral prospectivity of the southern margin of the GRV is less well understood.

In collaboration with the Deep Exploration Technologies Cooperative Research Centre and exploration companies - Minotaur Exploration and Kingston Resources, the Geological Survey of South Australia (GSSA) drilled a series of deep holes (Mineral Systems Drilling Program - MSDP) to test and investigate the potential for a range of shallow- to mid-level deposit styles such as epithermal (low, intermediate and high sulphidation such as at Parkinson Dam, Menninnie Dam and Paris respectively), skarn (e.g. Wilcherry Hill) and IOCG mineralisation. Along with geological mapping and targeted geophysical studies, the drill program also aimed to improve the understanding of the structural architecture of the southern margin of the GRV.

Drilling in the Spencer and Olympic domains intersected thick basaltic flows in the lower GRV previously undocumented for the region. These can be traced under cover over a strike length of 100km and broadly parallel the Roopena Fault Zone, supporting the notion that the fault underwent extension synchronous with volcanism. Reinterpretation of aeromagnetic data along the Roopena Fault Zone highlights a series of dilational zones which have the potential to host epithermal mineralisation associated with extensional deformation.

Within the southwestern GRV, drilling has identified features such as colloform-textured quartz-pyrite veins and broad and variably intense sericite alteration within a fault zone that overlies a splay of the Yarlbrinda Shear Zone. This style of hydrothermal alteration is consistent with epithermal fluid flow during fault movement. Regional fluid flow modelling (Potma and Zhang, 2006) and geological observation in the region suggests that reactive host rocks are key trap sites for hot and potentially metal endowed fluids. Where fluid/rock interactions are increased, such as in breccia zones, the host rock itself may be an important additional source of metal. Such interactions are evident along large parts of the southern margin of the GRV, particularly at the contact between calcareous units of the Paleoproterozoic Hutchinson Group and the lower GRV (e.g. Paris field and Menninnie Dam deposit). The MSDP has extended concepts developed in the region, to areas not previously tested and into areas where the mineral system is more likely to have been preserved. The drilling results support concepts that structural corridors within, as well as along the margins of, the GRV are prospective for epithermal mineralisation.

## Precambrian Organic matter and Thermal Maturity of the Beetaloo Basin, Northern Territory, Australia

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The Beetaloo Basin is a sub-basin of the greater McArthur Basin. The basin fill comprises marine and fluvial sediments deposited in the Proterozoic to Mesozoic periods. High quality marine source rocks that host a significant unconventional hydrocarbon resource have been identified within the Meso-Proterozoic Velkerri and Kyalla formations; organic matter in the source rocks is derived from bacteria and filamentous organisms such as blue green algae (Cyanobacteria). Organic geochemistry, petrography and basin modelling were conducted over 12 wells to determine the type, abundance, maturity of source rocks and their hydrocarbon generative potential. TOC for the samples analysed ranges from <1% to ~10% with the main organic matter types being alginite, bituminite and bitumen. HI ranges between ~5 and ~800 mgHC/gTOC where the variations are related to organic matter composition as well as the extent of maturation and hydrocarbons generated. Increasing maturity and secondary hydrocarbon cracking appear to develop micron-size secondary porosity within bitumen.

Assessing thermal maturity for Precambrian source rocks is problematic as they predate the appearance of higher plant organic matter specifically vitrinite. Therefore, maturity assessments were conducted based on a range of parameters that are sensitive to increases in temperature at various stages of thermal maturation. The parameters evaluated in this study include reflectance of alginite, associated bituminite and bitumen as well as Tmax from pyrolysis, elemental composition of organic matter and ratios of aromatic hydrocarbons extracted from organic matter. For the majority of wells studied alginite reflectance and Methylphenanthrene Index (MPI-1) linearly increase with depth suggesting that deep burial is the main cause of thermal maturation. However, transient heat effects from igneous intrusions and hydrothermal fluids appear to have locally affected thermal maturity.

Thermal history modelling is challenging due to the uncertainties associated with age dating of Proterozoic sediments and timing of burial and tectonic events. Apatite Fission Track Analysis (AFTA) suggest multiple episodes of burial and uplift with maximum burial occurring during the Cambrian-Carboniferous period; any heating associated with deep burial or elevated heating on any Proterozoic unconformities is of lower magnitude. During basin modelling both Palaeozoic and Proterozoic maximum burial scenarios were tested. The modelling suggest that in some parts of the basin >2 km of Proterozoic and Palaeozoic section as well as up to ~800 m of Mesozoic section may have been eroded during basin uplift.

Organic matter maturation kinetics determined for Middle Velkerri samples predict hydrocarbon generation at a narrow temperature range of ~120 to 160°C. The source rocks are capable of generating low volatile black oil with low sulphur contents. Basin modelling suggests that the upper part of the Kyalla Formation is mature for oil generation in most parts of the studied area, and that the Velkerri Formation is mature for oil generation on the Walton High and along margins of the basin. The Velkerri Formation becomes gas mature to over-mature towards deepest parts of the basin. The thermal maturity parameters investigated suggest that the beginning of gas generation window is approached at depths between ~1 and 1.5 km.

## Climate variability in southern Australia during the last glacial-interglacial transition: a multi-proxy (micro-XRF and stable isotope) record from Lake Surprise

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The Last Glacial Maximum (LGM) is characterised by asynchronous climate change in the high northern and southern latitudes. Peak cooling and the subsequent deglaciation was accompanied by shifts in synoptic-scale meteorological phenomena, however the nature of these changes and their effects on climate in the mid-latitudes is currently unclear. The expression of LGM and deglacial climate change on land in the southern mid-latitudes is particularly poorly constrained.

A new high-resolution, well-dated bulk sediment  $^{13}\text{C}_{\text{org}}$  record from Lake Surprise in south-eastern Australia provides a record of past moisture availability, and allows robust comparison of marine and terrestrial climate change during the period from 30,000 – 10,000 cal yr BP. The  $^{13}\text{C}_{\text{org}}$  record is accompanied by a continuous record of major-element geochemistry (scanning XRF data) which provides additional insight into aeolian and alluvial processes affecting the lake environment. The Lake Surprise  $^{13}\text{C}_{\text{org}}$  record exhibits large variations of up to 10‰, and indicates a generally dry LGM spanning approximately 21,000–17,000 cal yr BP, with the pre-LGM period punctuated by distinct periods of increased rainfall. An interpreted climate amelioration at ~17,000–16,000 cal yr BP is followed by greatly reduced variation in the  $^{13}\text{C}_{\text{org}}$  record, indicating a rapid post-LGM stabilisation of the environment.

The Lake Surprise record highlights teleconnections between the mid- and high southern latitudes; this is the first record from the mid-latitudes of the Southern Hemisphere to demonstrate a clear link between ocean and terrestrial climate change via shifts in the strength or position of the Southern Westerly Winds during the LGM and deglacial period. We therefore contribute to a better understanding of ocean and atmospheric climate drivers during global climate change, and the response of terrestrial climate systems in the southern mid-latitudes.

## Calcium isotope constraints on marine carbon cycle, and seawater carbonate chemistry: Examples from modern and Paleozoic marine carbonates

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The global bio-geochemical cycles of carbon and calcium in the Earth's surface environments are tightly linked through the processes such as (i) silicate/carbonate weathering, (ii) riverine transport, (iii) inorganic and biogenic calcification, and (iv) the deposition of sedimentary carbonates in the ocean. Here we will illustrate how stable calcium isotopes (i.e.,  $\Omega^{44}\text{Ca}$  proxy) could be used to further constrain the cycling and geochemical pathways of carbon in the marine environments, with implications for the reconstructions of past rates of  $\text{CaCO}_3$  deposition in the ocean, and possible changes in marine carbonate chemistry (i.e.,  $\text{CaCO}_3$  saturation state of seawater).

The potential of marine  $\Omega^{44}\text{Ca}$  proxy for paleo-studies will be illustrated on marine carbonates deposited in the late Silurian (~420 Ma ago) in the Prague Basin that records a globally recognized positive carbon isotope excursion (CIE) reaching a magnitude of about +10‰, which makes this CIE the largest positive  $\Omega^3\text{C}$  excursion of the entire Phanerozoic. Although the cause of this CIE is not yet known, the large amplitude and global coverage poses a significant challenge to the traditional interpretive framework that considers weathering and burial of organic and inorganic carbon in the context of a global ocean C cycle. This has led to an exploration of alternative mechanisms for creating large CIEs that include effects of a local-scale C cycling and/or syn-depositional/diagenetic overprinting. In this study, we use Ca isotopes to further test plausible explanations and hypotheses proposed to explain the origin of this CIE, with implications for our understanding of the marine carbon cycle and its  $\Omega^3\text{C}$  record in marine carbonate archives.

Due to a general decoupling of Ca and C cycles during the production and deposition of organic matter, the  $\Omega^{44}\text{Ca}$  proxy should not be responsive to phenomena such as enhanced weathering and burial of organic carbon in the ocean, yet in contrast Ca isotopes are expected to be fairly sensitive to effects of local Ca cycling and/or changes in the marine  $\text{CaCO}_3$  precipitation rates. Our  $\Omega^3\text{C}$  and  $\Omega^{44}\text{Ca}$  records of late Silurian carbonates from Prague Basin, shows a typical positive late Silurian (i.e., mid-Ludfordian) CIE with a peak-maximum of about +10‰, and 'normal' pre- and post-excursion baseline values close to 0‰. The post-excursion decline in  $\Omega^3\text{C}$  (from ~9 to 0‰) is coupled with a large coeval and systematic increase in  $\Omega^{44}\text{Ca}$  from ~0.3 to ~0.9‰, but there is no similarly correlated change during the onset of the CIE. Due to different residence times of Ca and C in the oceans, such tight correlation between  $\Omega^{44}\text{Ca}$  and  $\Omega^3\text{C}$  proxies is not expected for 'open ocean' settings. Importantly, our results revealed a statistically significant correlation between  $\Omega^{44}\text{Ca}$  and Sr concentration data throughout the entire profile ( $R^2 = 0.49$ ,  $p < 0.05$ ,  $n = 37$ ). The slope of this correlation (= -0.00095) is identical to that from the 'kinetically' controlled laboratory precipitation experiments for calcite. Hence, our results point to an overall 'kinetic' control of the observed  $\Omega^{44}\text{Ca}$  variations, which is likely related to either temporal changes in the saturation state of  $\text{CaCO}_3$  in local (global?) seawater in the Prague Basin, or possibly due to biologically-mediated variations in precipitation rate linked to changes in carbonate producer communities.

## **Constraining Gondwana break-up and associated rift-shoulder exhumation of the Ghanese continental margin using fission track thermochronology**

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Cretaceous Rifting between Western Africa and Brazil preceded the opening of the southern Atlantic Ocean in the framework of Gondwana break-up. As a result, the continental margins were subjected to large-scale faulting and associated denudation/exhumation. In the case of the Ghana margin in western Africa, basement denudation occurred as a response to intra-continental transform faulting between West Africa and Brazil. Previous studies on the transform margin indicate multiple events of denudation related with faulting and landslides produced by increases in bathymetric step between the continental margin (bordered by the Ghanian shelf) and the oceanic crust to the east (Bouillin et al., 1997; Hayford et al., 2008). Basement denudation as a response to this tectonic process is significant and estimated to be ~5km in total.

This study provides further constraints on the denudation history using apatite fission track thermochronology on samples taken along a north-south transect in northwestern Ghana, perpendicular to the main trend of the transform margin. Our new results test the hypothesis of rifting and break-up around ~130 Ma in this region and provide further constraints on the thermo-tectonic evolution of the Ghanese margin in general.

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## Iron and REE-bearing mineral assemblages in the rocks hosting the Olympic Dam and Wirrda Well IOCG deposits

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The Proterozoic Olympic Domain in South Australia is amongst the world's premier iron oxide-copper-gold-uranium-rare earth element (IOCG) provinces. While a range of source rocks have been proposed for the metals present in these systems, in most cases, the primary source of the metals and the importance of their content in host lithologies remains poorly constrained.

We present the preliminary results of a study of minerals from South Australian felsic igneous rocks carried out in an effort to determine if granites and rhyolites can provide enough iron and other components to form the Olympic Dam deposit. We examine enclaves and segregations (mineral clusters) from relatively unaltered to mineralisation peripheral rocks from both the Olympic Dam-hosting Roxby Downs Granite (c. 1.59 Ga) and Wirrda Well-hosting formation of the Donington Suite (c. 1.85 Ga), alongside a sample suite from the exceptionally extensive Eucarro Rhyolite (c. 1.59 Ga). In these sample suites the mineral clusters comprise iron and titanium oxides, titanite, apatite, zircon, fluorite and REE-bearing phases, amongst other minerals. Similar mineral assemblages are common in intrusive bodies worldwide, especially in ostensibly dry, high temperature systems sharing other general 'anorogenic-type' characteristics.

In the granites studied, Fe and a range of other elements have been liberated from primary magnetite, Ti-magnetite, ilmenite, titanite, biotite and the amphiboles. In more altered rocks, these minerals were replaced by variably Fe-enriched chlorite or biotite, with Ti-oxide often delineating replaced grains in extensive disseminations. At all localities studied, Ti-oxide needles in calcite and fluorite, and the conspicuous absence of Ti-phases in some partially altered ilmenite and titanite crystals show that conditions were at some point suitable for Ti mobilisation. Titanite is particularly noteworthy as some grains contain abundant LREE-rich britholite formed during the progressive breakdown of the host titanite crystal. LREE-rich, metal- and Y-bearing monazite-, synchysite-, bastnäsite- and britholite-group minerals are also found as fine-grained disseminations in the granites' major minerals, and throughout the lava's groundmass along with very fine Fe-oxides. Titanite and the Fe- and Ti-bearing oxides in both granites and lava often incorporate, and are intergrown with, several to more than twenty, predominantly euhedral, to severely embayed, variably metamict and zoned zircons (10–300µm diameter, modes around ~50µm and ~100µm). Many zircons appear altered and contain Fe, Al, Ca, Y, F and Hf in inclusions, with a portion of these elements likely lattice-bound. Zircons often have thorite inclusions and xenotime rims, and textural and chemical evidence indicates possible metasomatic zircon formation.

The findings of this study of IOCG host rocks shows that Fe, HFSE and REE sequestered in primary major and accessory minerals throughout magmatic crystallisation have been released by recrystallisation and/or alteration during thermal and fluid flow events around Olympic Dam and Wirrda Well, and even in the Eucarro Rhyolite lava. We suggest that Fe, HFSE and REE from these deposits' host rocks were mobile in, and entrained by, hydrothermal fluids related to the multiple mineralising events, before being eventually deposited in the mineralisation complexes in response to changing physiochemical conditions.

## Gaining new high-resolution palaeoclimate information from Australia's water-limited environments: Dating the “un-dateable” of cores

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The water-limited environments prevalent across much of Australia's tropical zone have been a challenge for palaeoenvironmental research in this region resulting in a lack of suitable archives. However, peatlands associated with perennial inland springs and forming unusual mounds are found throughout Australia's arid and tropical regions (Whinham and Hope, 2005; Boyd, 1990a; Ponder, 1986). These peat mounds preserve a wealth of proxies for palaeoenvironmental research including pollen, charcoal, diatoms, non-pollen palynomorphs, plant macrofossils, humic acids, geochemical tracers and dust (eg. Field et al., in preparation; McGowan et al., 2012; Boyd, 1990b; Owen et al., 2004; Scott, 1982; Backwell et al., 2014).

Despite the obvious potential of these springs for providing high resolution palaeoenvironmental records where conventional sites such as lakes and wetlands are scarce, the vast majority of records from peat mounds have been frustrated by confusing radiocarbon chronologies. Age reversals and erroneously young dates are common where suspected root contamination causes serious complications (eg. Field et al., in preparation; McGowan et al., 2012; Wyrwoll et al., 1986; Scott et al., 2003; Backwell et al., 2014; Macphail et al., 1999; Boyd, 1990b; Scott and Vogel, 1983). A concerted effort by Scott and Nyakale (2002) to remove rootlets prior to dating resulted in a much tighter chronology, apparently confirming roots as a source of contamination. It therefore appears that building reliable radiocarbon chronologies is a challenge for mound spring peat records.

Here we report on the development of new palaeoenvironmental records for the Kimberley region from mound springs. These records will help to shed new light on northwest Australian summer monsoon activity throughout the late Quaternary. However, these records are dependent on reliable chronologies. In an attempt to overcome the dating difficulties previously experienced in such settings a variety of techniques have been applied to four Kimberley mound spring cores. Techniques included <sup>14</sup>C, <sup>210</sup>Pb, Pu and OSL analysis. Radiocarbon results from pollen concentrate and bulk sediment showed age reversals and erroneously young dates, whilst dates from rootlets at the same depths returned significantly younger ages suggesting root contamination as a potential error source. Whilst the peats contained insufficient quartz for OSL dates, the method was applied to calculate dose rates indicating whether the sediments are in stratigraphic order and to eliminate the possibility of overturning as a source of the age reversals. Hand-picked charcoal was then radiocarbon dated in an attempt to eliminate roots. This presentation will report on the results of these new charcoal ages and whether they are able to provide a more reliable chronology for spring sediments than other fractions (pollen, bulk sediment) used in similar studies.

In order to further constrain chronologies <sup>210</sup>Pb analysis was attempted. Root mats at two springs made them unsuitable, however the two without root mats suffered further complications by unsupported <sup>210</sup>Pb activity being masked by supported <sup>210</sup>Pb. Analysis of spring water has been able to determine whether this is due to high uranium concentrations in the groundwater. Pu analysis was also attempted to validate the <sup>210</sup>Pb chronologies and provide additional tie-points.

## **Surface displacements from InSAR in the Perth Basin, Western Australia**

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Vertical land motion (mostly subsidence) has been identified in the Perth Basin from two continuous GPS (CGPS) stations since the mid 1990s. However, the spatial and temporal variation of the subsidence is not well known due to a dearth of dedicated geodetic observations of sufficient precision. We have therefore established a holistic geodetic monitoring system in the Perth Basin incorporating repeat levelling and interferometric synthetic aperture radar (InSAR) with the existing (and new) CGPS stations. InSAR scenes from DLR's (German Space Agency's) TerraSAR-X (TSX) satellite mission have been acquired at 11-day intervals since October 2012. The first two years of TSX scenes were funded by AuScope's Australian Geophysical Observing System (AGOS).

We have now processed three integer years of the TSX time series (October 2012 – October 2015) using the small baseline and persistent scatterers techniques (PS). The PS analysis indicates a narrow subsiding coastal strip running north and south from Hillarys Boat Harbour (~31.83S, 115.74E), relative to inland areas of the Perth metropolitan area. The differential displacement rate can reach -5 mm/yr, although there do appear to be some additional seasonal and non-linear trends. The subsidence has been assumed to be caused by groundwater extraction.

Further subsidence appears to be occurring in the eastern region of the Perth Basin, although this is made more difficult to detect by a partial loss of coherence in the TSX phase information, and moreso because seasonal variation with magnitude of up to 10 mm is also present. The latter has been identified by repeat levelling and now appears in the three-year TSX time series for points in this area. It is assumed that this is primarily caused by seasonal expansion of Guildford Clay found in this area as it becomes wet in winter and dries in summer, but seasonal changes in deeper groundwater may also contribute to this signal.

## **Woolshed Creek Fossil Site – Canberra’s heritage from long, long ago.**

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The capital of Australia is sometimes referred to as a “City in the Landscape” after the design concepts of Walter Burley Griffin and Marion Mahony Griffin were accepted to blend the urban environment of the nation’s capital into the hills and ridges along the Molonglo River. The evolution of these hills and ridges started over 450 million years ago when the Canberra region was located on the edge of the Gondwana Supercontinent. At that time it is estimated that 80% of all Silurian (419-443 million years ago) invertebrate species were brachiopods. The fossilised remains of one particular species can now be seen at the heritage listed Woolshed Creek fossil site near Canberra Airport. This site has been recently rehabilitated and made accessible to the public after the major construction associated with the nearby arterial road, the Majura Parkway.

The site was first discovered by the Rev. William B. Clarke in 1844. Clarke (1798–1878) studied at Cambridge University and was a highly regarded geologist and clergyman before he emigrated to Australia in 1839. At Cambridge he was mentored by the renowned geologist Professor Adam Sedgwick. Clarke’s passion was geology and biology and he roamed across much of southeast Australia making valuable observations and records. He is often referred to as the “Father of Australian Geology”. Clarke had many contacts in London and Cambridge and he sent rock and fossil samples back to UK where they were compared with others from around the world. He was elected a Fellow of the Royal Society in London in 1876. To commemorate his work the Clarke Medal is awarded each year by the Royal Society of New South Wales, alternating between the fields of geology, zoology and botany.

The brachiopod fossils from Woolshed Creek were recognised by Clarke as belonging to the Silurian geological period, an exciting discovery at the time, indicating for the first time that rocks of this age were present in Australia. A small area of fossiliferous mudstone within the Canberra Formation crops out in the bed of Woolshed Creek. The dominant fossils are brachiopods, principally the species *Atrypa dunroonensis*, named in 1920 after the nearby Dunroon estate. Clarke published his conclusion on fossil age in 1848. This was the first published identification of Silurian fossils in Australia, and much later led to an area along Woolshed Creek, including the original outcrop, being registered as a Geological Heritage Site. Clarke’s fossil collections were subsequently examined by palaeontologist L.G. de Koninck of Leuven University (Belgium), and published by him in 1876-7. The importance of the site is not just in its scientific and palaeontological value, but also because of its contribution to the 19<sup>th</sup> century networking of geoscientists around the world that enabled the construction of the geological time scales used by the modern geological sciences.

## Predicting lower mantle heterogeneity from 4-D Earth models

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The Earth's lower mantle is characterized by two large-low-shear velocity provinces (LLSVPs), approximately ~15000 km in diameter and 500-1000 km high, located under Africa and the Pacific Ocean. The spatial stability and chemical nature of these LLSVPs are debated. Here, we compare the lower mantle structure predicted by forward global mantle flow models constrained by tectonic reconstructions (Bower et al., 2015) to tomography models. In the dynamic models, spanning 230 million years, slabs subducting deep into the mantle deform an initially uniform basal layer containing 2% of the volume of the mantle. Basal density, convective vigour (Rayleigh number  $Ra$ ), mantle viscosity, absolute plate motions, and relative plate motions are varied in a series of model cases. We use tomographic filtering (Ritsema et al., 2007) in order to directly compare the high-resolution mantle structure predicted by the dynamic models to S-wave tomography model S40RTS (Ritsema et al., 2010). We also compare the predicted mantle structure to waveform tomographic models (Mégnin and Romanowicz, 2000; French and Romanowicz, 2014). Finally, we use cluster analysis to classify a set of equally-spaced points (average separation ~0.45°) on the Earth's surface into two groups of points with similar variations in present-day temperature between 1000-2800 km depth, for each model case. Below ~2400 km depth, this procedure reveals a high-temperature cluster in which mantle temperature is significantly larger than ambient and a low-temperature cluster in which mantle temperature is lower than ambient. The spatial extent of the high-temperature cluster is in first-order agreement with the outlines of the African and Pacific LLSVPs revealed by a similar cluster analysis of five tomography models (Lekic et al., 2012). Model success is quantified by computing the accuracy and sensitivity of the predicted temperature clusters in predicting the low-velocity cluster obtained from tomography (Lekic et al., 2012). In these cases, the accuracy varies between 0.61-0.80, where a value of 0.5 represents the random case, and the sensitivity ranges between 0.18-0.83. The largest accuracies and sensitivities are obtained for models with  $Ra = 5 \times 10^7$ , no asthenosphere (or an asthenosphere restricted to the oceanic domain), and a basal layer ~ 4% denser than ambient mantle. Increasing convective vigour ( $Ra = 5 \times 10^8$ ) or decreasing the density of the basal layer decreases both the accuracy and sensitivity of the predicted lower mantle structure.

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## **The geodynamics of past sea level changes**

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I will discuss why geodynamic models are required to establish the chronology of past long-term (10-20Myr) global sea level changes. Sea level change is a cross-discipline, cross-scale (spatial and temporal) theme that has the potential to bring together many aspects of the research undertaken by our community, spanning for example from water recycling at subduction zones to climate change.

## Globally light Fe-isotopic composition of oceanic arc basalts implies highly depleted mantle wedge compositions: Is oceanic subduction initiated against low density, refractory, peridotite zones in the upper mantle?

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We present new Fe-isotope data on > 60 primitive basalt samples from throughout the currently active global network of arcs, and use this data to investigate whether there is systematic variation in Fe isotopic compositions that may reflect either the composition of the mantle wedge, or variation in oxidation potentially due to differing slab fluid flux to different arc's mantle wedges. Such fundamental differences between the melting conditions of different sub-arc mantle wedges may reflect critical tectonic factors such as the rate of subduction and the age of the subducting plate [1].

Global arc magmas have elevated  $\text{Fe}^{3+}/\phi\text{Fe}$  values in the range >0.1 to 0.5, compared to MORB with values in the range 0.1-0.2. [3,4], while studies of peridotite from sub-arc mantle wedges [5] have also revealed systematically elevated oxidation states compared to none arc mantle samples, some argue that arc magmas become more oxidised than MORB only after their extraction from the mantle wedge[3,6].

Our  $\Omega^{57}\text{Fe}$  data span a wide range from -0.2 to +0.2 ( $\pm 0.04$ ), greater than MORB ( $^{57}\text{Fe} = 0.11\% \pm 0.01\%$ ) and with a lower mean value ( $^{57}\text{Fe} = 0.04 \pm 0.10\%$ ).  $\text{Fe}^{3+}/\phi\text{Fe}$  are higher than MORB and lie in the range 0.2 to 0.5. Some key relations in our data set include; positive correlations between  $\Omega^{57}\text{Fe}$  and Pb- or Sr-isotope ratios, and with  $\text{Fe}^{3+}/\phi\text{Fe}$ . There is also a weak correlation between  $\Omega^{57}\text{Fe}$  and age of subducting crust (positive). Many suites show a trend of slight increase in  $\Omega^{57}\text{Fe}$  with decreasing MgO or Mg#, this presumed the result of fractionation. The 0.4% span in  $^{57}\text{Fe}$  in arc basalts to andesites, combined with the fact that our modelling shows that crystal fractionation and feasible variation in partial melting or indeed variation in oxidation state of Fe are not likely to generate a variation of more than 0.1% in  $^{57}\text{Fe}$ , implies that this substantial range reflects a significant component of source variation. Critically, the pervasively light composition of projected arc parental basaltic magmas relative to MORBs suggests that these sources are often very significantly more refractory peridotite than at mid-ocean ridges. Modelling shows that this degree of depletion requires multiple episodes of melt extraction, perhaps implying this mantle was already depleted prior to becoming trapped to form the mantle wedge of oceanic arcs. Perhaps "rafts" of buoyant refractory peridotite in the upper asthenosphere become the localised sources for oceanic subduction initiation?

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## Exploration for iron oxide-copper-gold deposits using monazite chemistry

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Light rare earth elements (LREE) are commonly enriched within iron oxide-copper-gold (IOCG) deposits hosted in the Gawler Craton, South Australia. The characteristically elevated LREE signature can be used as a geochemical vector towards potential IOCG mineralisation. The LREEs are host within a number of minerals including monazite ((Ce,La,Th)PO<sub>4</sub>), which is a resistate phase that does not undergo significant chemical alteration during processes of physical transport and weathering.

LREE-enriched monazite is preserved within basement rocks within and proximal to the Prominent Hill IOCG deposit in the northern Gawler Craton. These basement rocks have been redeposited in the cover sequence during processes of physical transportation and dispersion associated with Permian glacial activity subsequent to the mineralising event. The basement rocks are now preserved within glacial diamictite at the base of the cover sequence. The monazite within the mineralised zone has a characteristic geochemical signature that is also preserved within monazite grains contained within mineralised and unmineralised basement clasts in the cover sequence glacial diamictite. The monazite grains are characteristically enriched in La and Ce, and depleted in Y and Th relative to the background chemistry of monazite from elsewhere in the Gawler Craton (e.g. shear zone-hosted and metamorphic monazite).

We have derived a chemical criteria for exploration using monazite in the cover sequence diamictite. Monazite with concentrations of La + Ce >63wt% and Y and Th <1wt% is similar to monazite derived from the Prominent Hill mineralisation, and is therefore 'compelling' data. Monazite grains yielding concentrations of 57.5wt% < La + Ce <63wt% are considered 'interesting'. Compositions of La + Ca < 57.5wt% are considered 'background'. This chemical signature can also be recognised in whole rock geochemical data. Exploration criteria for whole rock data is that (La+Ce):Y and (La+Ce):Th ratios greater than 30:1 and 32:1 respectively are considered 'compelling'. (La+Ce):Y between 10:1 and 30:1 and (La+Ce):Th ratios between 16:1 and 32:1 are considered 'interesting'. (La+Ce):Y and (La+Ce):Th ratios less than 10:1 and 16:1 respectively are considered 'background'.

Within the Prominent Hill region, the scale of the geochemical footprint associated with anomalous whole rock geochemical data is 2-3 times the size of the orebody itself. The scale of the footprint is controlled by the dispersion of LREE-enriched monazite due to glacial processes and palaeotopography. This chemical criteria is a useful vectoring tool towards Prominent Hill-style IOCG mineralisation, and may also be applicable to exploration for other IOCG deposits within the Gawler Craton and further afield.

## **Exploration under cover: learning to use the overburden**

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Discoveries of economically viable ore systems have been declining as a result of having to explore deeper terranes as undiscovered mineralisation is mostly hosted within basement rocks that are buried by younger cover sequences. Recently, cover sequences are being recognised as potential media that can be easily sampled and that is useful in mineral exploration, particular where geochemistry is linked with palaeotopography and landscape evolution. However, many unknowns remain in using the cover for mineral exploration, including how geochemical footprints of various deposit types are expressed in different cover sequence media and the mechanisms of element transportation and dispersion (e.g. mechanical versus chemical). In order to utilise the cover to our best advantage in mineral exploration there is a strong requirement that we understand the fundamentals of these unknowns.

## **Exhumation of the Tso Morari metamorphic core complex in an intra-oceanic setting prior to the India-Asia collision**

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Here we consider the tectonic evolution of the Tso Morari schist dome, reporting: i) map scale observations concerning the kinematics and sense of shear in the mantling carapace shear zones to this North Himalayan metamorphic core complex; ii) data from bulk rock geochemical analysis of the mafic rocks that demonstrate the eclogites that now exhibit ultra-high-pressure parageneses were once ocean island basalts; and iii)  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronological data that date the operation of the major crustal shear zones that were responsible for the exhumation of these eclogite-facies high pressure rocks. These observations have implications for the large scale tectonic evolution of the India-Asia collision. The large-scale structure implies a minimum of two north-facing subduction zones, while geochemistry requires accretion of the Tso Morari rocks in an intra-oceanic setting. The enigmatic occurrence of the core complexes known as the North Himalayan gneiss and schist domes then becomes evident, since lithosphere-scale extension can be explained only if compression during the accretion event led to the formation of back-thrusts that evolved into south-facing subduction zones. As in other extensional terranes that form above retreating subduction zones in convergent settings, bivergent detachment faults may have been created, as follows: i) a south-dipping system that exhumed the Ladakh Batholith from beneath the adjacent Indus molasse basin to the south; and ii) a north-dipping system that enabled exhumation of the Tso Morari schist dome, from beneath the Nidar ophiolite, and the overlying molasses to the north. Exhumation of these high pressure rocks involved at least two distinct episodes, with the direction of extension swinging from orogen-parallel to orogen-normal, possibly in consequence of the evolution of a 3D subduction geometry (?). An arcuate south-dipping slab may have first rolled back towards the north-west, and then continued rolling back northward. Roll-back of south-facing subduction zones provides a geodynamic explanation for the multiple Eocene–Oligocene and Oligo–Miocene magmatic and thermal pulses experienced by these rocks, and the multiple extensional episodes that led to widespread development of metamorphic core complexes in several distinct episodes at these times in the north west Himalaya.

## **Highly retentive core domains in K-feldspar preserve argon ages from high temperature stages of granite exhumation**

**Marnie Forster (1) and Gordon Lister (2)**

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Retentive core domains are characterized by diffusion parameters that imply K-feldspar should be able to retain argon even at temperatures near or above the granite solidus. In this case it should be possible to date granite emplacement using argon geochronology, and the same answer should be obtained as by using other methods. We present one case study where this is the case, from the elevated Capoas granite stock on Palawan, in the Philippines, and another where it is not, from the South Cyclades Shear Zone, on Ios, Greece. We attempt to determine the factors such as the role of fluid ingress in triggering the in situ recrystallization that can eliminate and/or modify the core domains, leading to relatively youthful ages. Thermochronology is still possible, because less retentive diffusion domains exist, but different methods need to be applied to interpret the data.

The work also demonstrates that K-feldspar can be sufficiently retentive as to allow direct dating of processes that reduce the dimensions of diffusion domains, e.g., cataclased and/or recrystallized K-feldspar in fault rock and/or mylonite.

These are important developments in the methodology of  $40\text{Ar}/39\text{Ar}$  geochronology, but to further advance we need to clarify the nature of these highly retentive core domains. In particular, we need better understand how they are modified by microstructural processes during deformation and metamorphism. We need also to assess the role of any crystal structural changes during step-heating in vacuo.

## Investigation of the Coompana negative magnetic anomaly in southwestern South Australia

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The basement rocks beneath cover of the Eucla Basin in southwestern South Australia contain a substantial igneous component as revealed by the geophysical character of the region and existing drill hole constraints, which have intersected mafic volcanics and granites beneath the Officer and Eucla basins. Of particular interest are a number of large anomalies defined by their prominent and characteristic magnetic field expressions of dominant reverse remanent magnetisation. A recent 200m spaced aeromagnetic survey by the Geological Survey of South Australia has provided substantial improvement in definition of these anomalies. The circular 2000 nT amplitude, 50 kilometre diameter Coompana magnetic anomaly is the most prominent, with several superimposed and surrounding anomalies likely due to shallower sources. Drilling in the vicinity of these satellite anomalies has intersected mafic volcanics at depths of 300 to 400 metres. Recent geochronology indicates that these mafic volcanics are Neoproterozoic (c. 860 ma) in age, and likely correlated with widespread mafic magmatism at this time across southern and central Australia (e.g. the Gairdner and Amata dolerite suites). It is unclear if these volcanics are associated with the anomalies, or form a younger cover sequence over older basement units.

Sparse regional gravity data reveals a negative gravity anomaly coincident with the main Coompana magnetic anomaly, implying that the deep body might be of acidic to intermediate composition, and although at the limits of its resolution, also suggests that at least some of the shallow magnetic sources have local positive gravity expressions (consistent with higher density mafic material). The similar magnetisation directions of the deep and shallow sources, in conjunction with the implications of the gravity data, suggests that this is a large heterogeneous and possibly fractionated system, with encouraging possibilities for hosting various mineral systems.

Recent advances in interpretation of magnetic field expressions of remanent magnetisation, together with the improved resolution of the new GSSA survey, has provided new insights into the sources of these remarkable anomalies. Estimation of the direction of magnetisation was required to solve the spatial distribution of that magnetisation, in terms of horizontal position, shape, orientation and depth. Magnetisation directions were recovered from semi-automated methods, including Helbig Analysis, as well as by staged inversions.

## Cape Grim, NW Tasmania – a world class example of submarine basaltic intraplate volcanism

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Cape Grim in far north western Tasmania, Australia, was the site of intraplate basaltic volcanism during the Cenozoic. The basalts have are typically olivine-phyric with a groundmass that includes plagioclase and pyroxene. The succession is exceptionally well preserved and exposed in rock platforms and steep coastal cliffs. A detailed field mapping and sampling project has been recently completed. The purpose of the project was to determine the facies architecture of the sequence and to interpret the source, processes, environment, duration and age of volcanism at Cape Grim.

Previously interpreted as primarily a subaerial sequence erupted over 40 myrs, field work has revealed that the succession comprises pillow lavas, sills, lobate lavas, volcanic breccia and tuff. The environment of deposition of all units was submarine and they were emplaced in relatively rapid succession. It is a rare example of a submarine basaltic succession exposed on land.

The oldest unit, the Woolnorth Tuff (WT) lies unconformably on the Neoproterozoic rocks of the Rocky Cape Group. The WT is composed almost entirely of devitrified basaltic glass shards and olivine crystal fragments, and sedimentary structures are consistent with deposition in a sub-aqueous environment. The WT is overlain by the Slaughter Bluff Volcanic Breccia (SBVB) at Cape Grim. The SBVB is dominated by a 15-25 m thick diffusely bedded pillow fragment breccia. The bedding dips to the southwest suggesting a source offshore to the northwest.

North of Cape Grim, the Little Trefoil Basalts (LTB) intrude as sills into the Woolnorth Tuff. Deformation of bedding and intermingling of the WT and the LTB at contacts indicate that the WT was unconsolidated at the time of basalt intrusion. To the south of Cape Grim, the WT is overlain and intruded by the Studland Bay Basalts (SBB). The SBB consists of pillow lavas, lava lobes and sills, pillow breccia and volcanic conglomerate. Contacts of the basalt sills with the WT suggest that the WT was unconsolidated at time of intrusion.

Overlying the WT at the same southern locations are lobate basalt lavas which are overlain by 10-30m thick mounds of basaltic pillow lavas followed by 50 m-thick succession of diffusely bedded, matrix dominated pillow fragment breccia and basalt breccia. Bedding orientations generally dip to the south-southwest suggesting an inland northeastern source.

Cenozoic basaltic volcanism in Tasmania is understood to have occurred between 22 and 8 Ma on the basis of a limited number of K/Ar dates (Sutherland & Wellman 1986, Baillie 1986). The younger ages (8 Ma and 13 Ma) obtained in northwestern Tasmania overlap with the Older Volcanics of Victoria but predate the Newer Volcanics. Ar/Ar dating of the Cape Grim succession, underway as part of this project, will allow us to more accurately place Cape Grim volcanism in the context of Cenozoic volcanism in Tasmania and Australia.

## **Geochronological constraints from the Coompana Province, with implications for geological relationships with the Gawler Craton, Musgrave Province and Madura Province**

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The Coompana Province is one of the most poorly understood pieces of crystalline basement geology in the Australian continent. It lies entirely concealed beneath a variable thickness of Neoproterozoic to Cenozoic sedimentary rocks, and is situated between the Gawler Craton to the east, the Musgrave Province to the north, and the Madura and Albany-Fraser Provinces to the west. A recently-acquired reflection seismic transect (13GA-EG1) provides an east-west cross-section through the southern part of the Coompana Province, and yields new insights into the thickness, seismic character and gross structural geometry within the Coompana Province. To assist geological interpretation of the 13GA-EG1 seismic line, new SHRIMP U-Pb zircon ages have been acquired from samples from the limited drill-holes that intersect the Coompana Province.

New results from several granitic and gneissic rocks from the Coompana Province yield magmatic and/or high-grade metamorphic ages in the interval 1100 – 1200 Ma. Magmatic or high-grade metamorphic ages in this interval have not been identified in the Gawler Craton, in which the last major magmatic and metamorphic event took place at ~1590 – 1570 Ma. The Gawler Craton was largely unaffected by ~1100 – 1200 Ma events, as evidenced by the preservation of pre-1400 Ma  $^{40}\text{Ar}/^{39}\text{Ar}$  cooling ages. In contrast, magmatic and metamorphic ages of 1100 – 1200 Ma are characteristic of the Musgrave Province (Pitjantjatjara Supersuite) and Madura Province (Moodini Supersuite).

The new results from the Coompana Province have also yielded magmatic or inherited zircon ages at ~1500 Ma and ~1640 Ma. Once again, these ages are not characteristic of the Gawler Craton and no pre-1700 Ma inherited zircon has been identified in Coompana Province magmatic rocks, as might be expected if the province was underlain by older, Gawler Craton-like crust.

The emerging picture from this study and recent work from the Madura Province and the Forrest Zone of the western Coompana Province is that the Coompana Province has a geological history that is quite distinct from, and generally younger than, the Gawler Craton to its east, but that is very similar to the Musgrave and Madura Provinces to the north and west.

The contact between the Coompana Province and the Gawler Craton is interpreted in the 13GA-EG1 seismic line as a prominent west-dipping crustal-scale structure, termed the Jindarnga Shear Zone. The nature and timing of this boundary remain relatively poorly constrained, but the seismic and geochronological evidence suggests that it represents the western edge of the Gawler Craton, marking the western limit of an older, more isotopically evolved and multiply re-worked craton to the east, from a younger, more isotopically primitive crust that separates the South Australian Craton from the West Australian Craton.

## **Smart aquifer characterization and mapping with machine-learning and evolutionary techniques**

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Traditional methods used for aquifer characterization and mapping are prohibitively time consuming, costly, and provide data at limited spatial and temporal resolution. This presentation reviews some recent applications of machine-learning (ML) and evolutionary techniques for comparatively efficient conceptualization, estimation, prediction, and forecasting of groundwater system components. As with traditional modeling, the application of soft-computing techniques is problem specific. An important attribute of these techniques is that they are amenable to the fusion of (and discovery in) disparate, sparse, scale-dependent, and uncertain relations characteristic of hydrogeophysical data. In the case of one unsupervised ML technique, called the self-organizing map (SOM), the vector basis and lack of distinction among variable types provides flexibility in the simultaneous estimation of values for multiple dependent aquifer variables. Another important attribute is that these methods can be readily integrated with numerical and statistical methods providing a hybrid model solution. In turn, the output from one hybrid model can serve as input to other hybrid models providing a cascading mechanism for solutions. In this presentation, a cascading hybrid solution is used to illustrate some of the current possibilities and challenges in aquifer characterization and mapping of a surficial aquifer in northwestern Nebraska, USA. Examples of possibilities include the estimation and scaling of hydrostratigraphic units, providing information for groundwater model conceptualization and optimal starting values and geostatistical constraints for development and calibration of a future groundwater model. Some challenges are in the timely processing of electromagnetic sounding data, performance testing, and uncertainty quantification. Timely processing could better be achieved by parallelization of the modified-SOM code for practical application to continuous data streams and computing cross-validation of models. Following such a development, the proposed methodology could benefit by introducing uncertainty in the estimates of 1D resistivity profiles, fractional lithology, hydraulic properties, and hydrochemistry. Further, the application of reduced order methods would be beneficial for optimal selection of borehole lithologies and sounding profile data for targeted Bayesian inversions. The application of quantile modeling to Bayesian results would provide the necessary information to train of a series of ML networks for calculating a prescribed level of uncertainty in model variables.

## New Pathways for Isotopic Fractionation during Iron Redox Cycling

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Iron redox cycling is ubiquitous in sedimentary and aqueous environments and may be recorded in the iron isotope composition of minerals and fluids. However, proper interpretation of measured isotope values is often difficult because of large uncertainties in the equilibrium isotope fractionation factors for iron oxides relative to fluids and other minerals. The recent discovery that structural Fe(III) in iron oxide minerals can completely and rapidly exchange with dissolved Fe(II) in aqueous solution (i.e., Fe(II) catalyses iron oxide recrystallisation) makes the direct measurement of equilibrium iron isotope fractionation factors for aqueous Fe(II)-mineral pairs a new possibility at low temperature (22 degrees C). Here, we use the three-isotope method ( $^{54}\text{Fe}$ - $^{56}\text{Fe}$ - $^{57}\text{Fe}$ ) to explore isotopic exchange and fractionation between  $^{57}\text{Fe}$ -enriched aqueous Fe(II) and natural-abundance hematite. We find that aqueous Fe(II) readily exchanges with hematite, as evidenced by increasing and decreasing  $^{57}\text{Fe}/^{56}\text{Fe}$  ratios in hematite and aqueous Fe(II) respectively, and that the rate and extent of such exchange depends on hematite grain size. Hematite materials having the smallest mean particle size (~10 nm) completely and rapidly exchange their structural iron atoms with aqueous Fe(II) whereas hematite having a larger mean particle size (~100 nm) exhibits lesser amounts of exchange that is similar to the amount of surface iron atoms. Mass-dependent iron isotope fractionation between aqueous Fe(II) and hematite, assessed by monitoring  $^{56}\text{Fe}/^{54}\text{Fe}$  ratios, also varies with hematite particle size; slow isotopic exchange reactions involving large grain sizes appear to approach equilibrium whereas rapid exchange occurring between Fe(II) and small hematite particles are apparently affected by a kinetic fractionation. We infer the aqueous Fe(II)-hematite equilibrium iron isotope fractionation factor at 22 degrees C to be  $-3.07 \pm 0.22 \text{ ‰}$  (2 $\sigma$ ) in  $\Delta^{56}\text{Fe}$ . By combining fractionation factors for other Fe(II)-mineral pairs (e.g.,  $\text{Fe(II)}_{\text{aq}}\text{-magnetite}$ ), these values are useful tools for assessing isotopic (dis)equilibrium of adjacent mineral grains in the rock record. Furthermore, our work helps constrain the initial processes that impart, or post-depositional diagenetic processes that alter, the isotopic composition of iron-bearing minerals.

## Rutile thermometry from ultrahigh temperature metamorphic rocks – what do the temperatures mean?

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Rutile is a common mineral in many crustal rocks. In the past decade, the Zr content of rutile has been widely used as a thermometer in metamorphic rocks. Zr-in-rutile thermometry records high (>800 °C) metamorphic temperatures and is therefore an extremely useful avenue for identifying records of ultrahigh temperature (UHT; >900–1000 °C) crustal metamorphism. The use of rutile thermometry will be increasingly used into the future owing to the common occurrence of rutile in rocks. However, it is not fully understood what the full (published) datasets of rutile thermometry mean in terms of rutile growth and/or breakdown and/or rutile's ability to retain Zr upon cooling.

Curiously, datasets of Zr-in-rutile thermometry from UHT rocks include much lower temperatures, of the order of ~700 °C. These datasets do not feature a continuous transition from UHT to lower temperatures, but instead define distinct, separate, temperature populations. The reason for this distribution has not yet been tested.

We have studied a number of rutile-bearing samples from known UHT terranes: the Napier Complex (Antarctica), Eastern Ghats Province (India), Southern Granulite Terrane (India) and Prydz bay (Antarctica), in order to characterise: 1) the microstructural location of rutile in the rocks; and 2) the distribution of Zr in rutile in the different microstructural settings, and consequently the Zr-in-rutile temperature of these rutile grains. The results of Zr-in-rutile thermometry will be coupled with calculated phase diagrams for a number of samples in order to try to understand where rutile may have developed along the  $P-T$  path. Preliminary results show some intriguing patterns, namely that Zr-in-rutile temperatures lower than 900 °C are more common than temperatures >900 °C. Full microstructural characterisation of the rutile grains is still underway, as is further Zr-in-rutile analysis.

## 10 million years of subsidence on the Northwest Shelf of Australia: initial results from International Ocean Discovery Program Expedition 356

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The Northwest Shelf of Australia is an ideal location to constrain the spatial and temporal patterns of vertical motions caused by the interaction between plate motion and convection within the Earth's mantle, known as dynamic topography as it is positioned on the fastest moving continent since the Eocene, on the edge of the degree two geoid anomaly and is known to have experienced significance anomalous subsidence in the last 10 million years. International Ocean Discovery Program Expedition 356 has drilled a transect and recovered Miocene to Recent strata at seven sites along a transect from 29°S to 18°S. The upper 200-1000m of strata in the Perth, Carnarvon and Roebuck Basins were continuously cored for the first time. The purpose was to obtain a well-constrained stratigraphic framework for generating high-resolution subsidence curves for the last 10 million years. Preliminary shipboard analyses revealed significant palaeobathymetric variations from terrestrial to upper bathyal palaeodepths suggesting a complex subsidence history for the region. Ongoing post-cruise analyses are combining age models and palaeobathymetric data from each site with both laboratory and wireline logging physical properties measurements of lithology-dependent properties such as density and porosity. Combining these borehole data with seismic interpretations will allow accurate subsidence estimates over 10° of latitude. Resolving whether northern Australia is moving with/over a time-transient or long-term stationary downwelling within the mantle will vastly improve our understanding of deep-Earth dynamics and their impacts on surficial processes.

## International Ocean Discovery Program Expedition 356: a Miocene-Pliocene record of reefs, oceans and climate off Northwest Australia

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International Ocean Discovery Program Expedition 356 cored six primary sites along a latitudinal transect from 29°-18°S off northwest Australia to obtain a 5 m.y. record of the evolution of the Indonesian Throughflow (ITF), Indo-Pacific Warm Pool and regional climate. The coring strategy was designed to reveal a detailed history of ITF variability and its relationship to climate. Six sites were drilled from south to north: U1459, U1460, U1461, U1462, U1463 and U1464.

Sites U1459 and U1460, in the Perth Basin, yielded a Miocene to Quaternary upper-slope to outer-shelf carbonate section that will allow investigations of the relative roles of the Leeuwin Current (and the ITF) on the initiation and evolution of reef development on the Rottnest Shelf and Carnarvon Ramp system. The clay mineralogy and pollen record of the thick (270 m) high-recovery, Pleistocene section at Site U1460 is likely to yield a 2 m.y. orbital-scale climate record of the winter-dominated rainfall regime. When combined with similar records from the high-recovery Pliocene record at site U1459, this will greatly increase understanding of how Australia's subtropical to warm temperate climate responded to Pliocene warmth through to the Middle Pleistocene Transition and onset of icehouse conditions.

Sites U1461 and U1462, in the Northern Carnarvon Basin, are near a series of drowned reefs at ~22°S. Both sites yielded well-constrained ages and well logs that permit both calibration of regional seismic profiles and dating of reflectors beneath these reefs, thereby constraining reef onset. Marine ooids present in the Pleistocene strata of Sites U1461 and U1462 indicate that shallow-water, carbonate-supersaturated, arid, tropical conditions prevailed. Further analyses will constrain the age of these key tropical indices and enhance understanding of the onset of aridity and reef development in northwestern Australia. Site U1461 yielded the thickest sequence of Pliocene to Pleistocene strata on this expedition (1000 m). The excellent recovery and very good preservation of the calcareous microfossils within these strata mean that the recovered record is potentially one of the best sampled paleoceanographic and climate archives along the western continental margin of Australia.

Another archive with excellently preserved calcareous microfossils was cored at Site U1463. The very good preservation of foraminifera in the Pleistocene and Pliocene strata of this site is likely to facilitate orbital-scale paleoceanographic and palaeoclimate reconstructions using inorganic (elemental/isotopic) and organic geochemical analyses to yield an unparalleled 5 m.y. record of oceanic conditions immediately downstream from the ITF. The only comparable records to the Expedition 356 Sites in the Indian Ocean are the deep oceanic archives from DSDP Site 214 and ODP Site 763A.

Site U1464 in the Roebuck Basin is up-dip from a drowned shoal. Drilling revealed a detailed bio-chronostatigraphic framework enabling dating of the initiation and demise of this "failed" Rowley Shoal. The presence of anhydrite in the Miocene strata at U1464 suggests drier conditions prevailed before the Australian monsoon intensified during the Pliocene.

## Speciation and nanoscale ordering in pyrrhotites: a case study from the Panzhihua deposit, SW China

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Pyrrhotite group minerals are dominant over pyrite in magmatic ores, where they are associated with Ni- and Co-sulphides of economic interest. Pyrrhotites are non-stoichiometric phases with general formula  $\text{Fe}_{1-x}\text{S}$  ( $x = 0\text{--}0.125$ ). Non-stoichiometry relates to Fe-vacancies leading to superstructures of various types, causing drastic changes in magnetic and surface properties. Structural differences impact on flotation behaviour [1].

Pyrrhotite structures derive from the hexagonal close-packed NiAs structure. Troilite ( $\text{FeS}$ , 2C-pyrrhotite) is rare in ores but common in meteorites since sub-solidus re-equilibration is observed  $<300^\circ\text{C}$ . At such conditions, 4C-pyrrhotite ( $\text{Fe}_7\text{S}_8$ ) and NC-pyrrhotite (between  $\text{FeS}$  and  $\text{Fe}_7\text{S}_8$ ) dominate. Prefixes indicate the superstructure lattice repeats along the axis of layer stacking relative to c-axis periodicity in the NiAs substructure; 4C- and NC-pyrrhotite correspond to ‘monoclinic’ and ‘hexagonal’ pyrrhotite, respectively. NC-type pyrrhotites are a structurally-diverse group with widely variable Nc values, including both periodic ( $\text{Fe}_9\text{S}_{10}$  [5C],  $\text{Fe}_{10}\text{S}_{11}$  [5.5C] and  $\text{Fe}_{11}\text{S}_{12}$  [6C]) and non-periodic NC-pyrrhotites. Structural disorder in NC-pyrrhotites relates to both superstructuring and anti-phase domain boundaries (APB, [2]). Such models may carry petrogenetic implications when placed in an appropriate geological context.

We present data on pyrrhotites in Fe-Ti-V-(Co-Ni) ores from melagabbro, Lower Zone, Panzhihua layered intrusion, Emeishan LIP, SW China. Pyrrhotites are subordinate to Fe-Ti-oxides, and host cobaltpentlandite. Fluid-assisted alteration is observed, including replacement of olivine, clinopyroxene and plagioclase, and secondary Fe-oxides at boundaries between primary Fe-Ti-oxides and sulphides.

At the  $\mu\text{-scale}$ , pyrrhotite comprises two intergrown phases distinguishable on back-scatter electron images. The darker phase ( $\text{Fe}_9\text{S}_{10}$ , 5C-pyrrhotite) is concentrated towards the margin of the brighter ( $\text{FeS}$ , troilite) but also forms lamellae ranging in size from nm to a few  $\mu\text{m}$  within matrix troilite. *In-situ* micro-X-ray diffraction shows two hexagonal phases, with peak intensities matching troilite and NC-pyrrhotite. Raman spectra show identical bands but subtle intensity differences. To better understand speciation and order-disorder state of the intergrowths, nanoscale characterisation was undertaken via Transmission Electron Microscopy (TEM), including High-Angular Annular Dark Field (HAADF) Scanning TEM imaging on foils prepared *in-situ* by Focused Ion Beam-SEM. Electron diffraction shows coherent lattice-scale intergrowths between dominant 2C and 5C (dark lamellae) on the  $[0\text{-}11]_{2\text{C}}$  and  $[2\text{-}10]_{5\text{C}}$  zone axes, respectively. Although satellite intensity and arrangement along the  $c^*$  axis in 5C vary within a lamellae or from one lamella to another, they indicate 3-fold superstructuring along  $a^*$  in 2C, ordered over intervals of hundreds of nm. Ultra-high resolution FEI Titan Themis TEM (Adelaide Microscopy) delivered atomic-scale HAADF-STEM imaging showing extensive disordering within the dark lamellae (5C). The latter consists of 1- and 2-nm-wide darker (Fe-deficient, vacancy ordered) strips with highly-irregular distribution throughout an ordered 2C matrix, and with indistinguishable boundaries towards the outside matrix. In detail, the structural motif within the double strips shows  $\frac{1}{2}$  offsets (APB) with one another but coherency towards the 2C motif. Preliminary results show that the degree of ordering changes from  $\mu\text{-}$  to nm-scale within pyrrhotites, attributable, at Panzhihua, to solid-state re-equilibration during hydrothermal overprinting.

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## What Lies Beneath: Secrets of Myanmar's Tethyan Margin

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Myanmar lies at a crucial geological juncture where the main Tethyan collision zone swings south around the Eastern Himalayan Syntaxis into Southeast Asia, with the consequence that the region has experienced an increasingly oblique history of collisional geometry over the recent period of orogeny. Myanmar is also one of the World's more prospective terrains in terms of its minerals endowment. An understanding of its mineral potential can only be fully realized with an understanding of its tectonic history, but Myanmar remains poorly explored and geologically enigmatic, in part due to its relative political and scientific isolation over the past half century. Therefore there remains considerable uncertainty around the configuration, nature and timing of major Tethyan-related tectonic events within, and consequently the crustal architecture beneath, Myanmar, which renders discussions on Myanmar's metallogenesis somewhat equivocal.

Two major magmatic belts run N-S through Myanmar and are responsible for a significant proportion of its minerals endowment. The Wuntho-Popa Arc is a continental magmatic arc with evidence of Late-Cretaceous, Eocene and Miocene episodes of magmatism. It hosts Cu-Au porphyry and epithermal mineralization styles, including the Monywa Cu mine. The Western Belt, or Mogok-Mandalay-Mergui (MMM) Belt, contains a series of granites trending from Late Triassic I-types, through Cretaceous-Eocene S-types to Oligocene-Miocene leucogranites associated with high-T metamorphism of the Mogok Metamorphic Belt. In its southern extension this belt hosts world-class Sn-W deposits associated with the S-type granites. However, the relationship of (a) the Arc to the MMM Belt, and (b) the southerly Early Cenozoic magmatism to the northerly Late Cenozoic metamorphism and magmatism within the MMM Belt is all of some debate.

Given the limited exposure, isotope geochemistry is one of the few viable ways of resolving the question of Myanmar's crustal architecture. We present new zircon U-Pb, Lu-Hf and O isotope data from both belts with the goal of unpicking the various crustal blocks, in order to shed some light on this key but poorly-understood part of the Eastern Tethyan region.

## **Redox gradients, and ore footprints: Mineralogical variability and geochemical insights into the Cloncurry District mineral system**

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The Uncover Cloncurry project aims to examine the petrophysics, mineralogy and geochemistry of approximately 20 deposits/prospects in the Cloncurry district, Eastern Mount Isa Inlier, Australia. The district includes iron oxide-copper-gold (IOCG), iron sulfide copper-gold, sedimentary exhalative, structurally controlled hydrothermal, and skarn styles of mineralisation. One of the aims of this project is to provide a fully-integrated, internally-consistent dataset of petrophysical, mineralogical and geochemical data. This is achieved using micro-X-ray fluorescence ( $\mu$ XRF), rapid-scanning electron microscopy (SEM), micro-computed tomography ( $\mu$ CT), and conventional geochemistry. By analysing the same sample (i.e. the same 25 mm round) for petrophysical data (e.g. density, magnetic susceptibility, and remanent magnetisation), modal mineralogy and textural information (determined by SEM) and 3-D distribution, abundance and grain-size data of minerals (determined by  $\mu$ CT). A larger scale of geochemical and mineralogical data is provided by  $\mu$ XRF mapping, where the geochemistry of samples up to ~10 cm by ~20 cm can be mapped quantitatively prior to 25 mm rounds being drilled; while offcuts of samples are sent for conventional geochemistry. To date, a TESCAN integrated mineral analyser (TIMA) was utilised to collect automatically-assigned modal mineralogy and textural information from over 440 samples from 20 deposits, and  $\mu$ CT data has been collected on 60 samples from 13 deposits. Both of these datasets will continue to expand as the project advances. We assess these results in terms of alteration paragenesis and examine relationships between mantle fluids, redox state, geophysical expression and structural localisation.

Scale-integration of geochemical and geophysical data provides a unique opportunity to explore geochemical and mineralogical gradients within these mineral systems. For example, at the Ernest Henry IOCG deposit, a 550 m section of drill core that traverses near-perpendicular to the mineralised pipe-like ore-body was analysed at a spatial resolution of ~12 m. The modal mineralogy data show a muscovite and garnet halo around the ore-body at a 50 – 100 m-scale. The hanging wall of the ore-body is dominated by pyrite with chalcopyrite being the dominant sulphide within the ore-body itself; pyrrhotite is minor, with magnetite the dominant magnetic phase. These observations highlight the transition from a relatively oxidised halo to a reduced core within Ernest Henry, and emphasise the strong control of redox on the geophysical expression of this deposit. In addition, the data provide joint geophysical and geochemical vectors in a near-mine setting to aid in target identification and avoid false positives.

## Snowball Earth ocean chemistry driven by extensive ridge volcanism during Rodinia breakup

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During Neoproterozoic Snowball Earth glaciations, the oceans gained massive amounts of alkalinity, culminating in the widespread deposition of massive cap carbonates upon deglaciation. Changes in terrestrial runoff associated with both breakup of the Rodinia supercontinent and deglaciation can explain some, but not all of the requisite changes in ocean chemistry. We propose an alternative (but complimentary) “shallow ridge hypothesis”, in which extensive submarine volcanism along shallow ridges formed during supercontinent breakup results in the formation of large volumes of glassy hyaloclastite, which readily alters to palagonite. Here we estimate fluxes of calcium, magnesium, phosphorus, silica and bicarbonate associated with these shallow ridge processes, and argue that extensive submarine volcanism during the breakup of Rodinia made an important contribution to changes in ocean chemistry during Snowball Earth glaciations. We use Monte Carlo simulations to show that widespread hyaloclastite alteration under near-global sea ice cover could lead to  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  supersaturation over the course of the glaciation that is sufficient to explain the volume of cap carbonates deposited. Furthermore, our conservative estimates of phosphorus release are sufficient to explain the observed P:Fe ratios in sedimentary iron formations from this time. This large phosphorus release may have fuelled primary productivity, which in turn would have contributed to atmospheric  $\text{O}_2$  rises that followed Snowball Earth episodes. Thus we infer that shallow ridge volcanism associated with the Proto-Pacific and Iapetus rifts played a significant role in the oxidation of the Ediacaran ocean, thereby stimulating the emergence of multicellular life.

Further reading:

Gernon, T.M., Hincks, T.K., Tyrrell, T., Rohling, E.J. & Palmer, M.R., 2016. Snowball Earth ocean chemistry driven by extensive ridge volcanism during Rodinia breakup. *Nature Geoscience* 9, p. 242–248; doi: 10.1038/ngeo2632.

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## Interpretation of magnetic and gravity data of the Madura and Coompana Provinces along the deep crustal seismic survey 13GA–EG1

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Neoproterozoic to Cenozoic sedimentary rocks below the Nullarbor Plain cover basement components that hold the key to understanding how the Archean building blocks in South Australia and Western Australia are connected. Recently acquired geophysical data and stratigraphic drill cores provide fundamental information that allow the area between the Archean Yilgarn Craton in the west and the Gawler Craton in the east to be divided into distinct Proterozoic tectonic units: the Albany-Fraser Orogen, the Madura Province, and the Coompana Province. Here we present a first interpretation of gravity and magnetic data collected along the deep crustal seismic survey 13GA–EG1, with a focus on the Madura and Coompana Provinces.

The northeast trending Rodona Shear Zone that separates the Albany-Fraser Orogen from the Madura Province is imaged on the deep crustal seismic line 12GA-AF3, the westward continuation of 13GA-EG1. The Rodona Shear Zone is divided into a set of western and eastern segments that in the vicinity of line 12GA-AF3 bound a magnetic high. Susceptibility models suggest the highly magnetic unit within the Rodona Shear Zone dips to the east. The Madura and Coompana Provinces contain several distinct features, including large-scale shear zones imaged by discrete linear highs or demagnetization lows. Potential field data have been inverted over these features to produce susceptibility and density models that constrain the geometry of these features at depth. The Madura Province section of 13GA–EG1 is characterised by large amplitude variations in magnetic susceptibility and an eastwards increasing gravity signature. Both magnetics and gravity show a sharp drop in values, possibly due to local fracturing and demagnetization, at the N–S oriented Mundrabilla Shear Zone which separates the Madura Province from the Coompana Province. In models produced from both magnetic and gravity inversion the Mundrabilla Shear Zone is imaged as a subvertical structure, consistent with interpretations from the 13GA–EG1 deep seismic reflection line.

The Forrest Zone (western Coompana Province) is characterised by relatively low amplitude smooth magnetic anomalies and does not show peaks as strong as the provinces on either side. The eastern boundary of the Coompana Province is defined by the west-dipping Jindarnga Shear Zone, separating overall lower gravity Coompana Province from the higher gravity domains of the Gawler Craton. Within the Gawler Craton, the Nawa, Fowler and Christie domains show a strong long wavelength gravity high which extends northeastwards in an arc around the gravity low of the Nuyts and Wilgena domains, which form a semi-circular region dominated by magmatic rocks with high magnetic signature and relatively low densities.

Multi-scale edge detection (worms) of the gravity and magnetic fields outline features that correlate well with structures interpreted from 13GA–EG1. In the west these features include the Rodona, Boonderoo and Serpent Shear Zones, and sections of the Mundrabilla Shear Zone; in the east the Jindarnga, the Karari, and the Tallacootra Shear Zones also show associated worms. Our work shows that interpreting potential field data in conjunction with deep crustal seismic profiles is essential to enable a 3D understanding of basement rocks under cover.

## **Paleoproterozoic subduction zones and their role in craton assembly in Western Australia**

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The Paleoproterozoic era witnessed the assembly of the world's major continents by amalgamation of numerous Archean nuclei, through extensive continental collision or subduction processes. In Western Australia, the Capricorn Orogen records two collisional orogenic events, the 2215–2145 Ma Ophthalmian and 2005–1950 Ma Glenburgh Orogenies, responsible for the amalgamation of the Pilbara and Yilgarn Cratons to form the West Australian Craton. An Archean to Paleoproterozoic crustal element, the Glenburgh Terrane of the Gascoyne Province, forms an exotic microcontinent between these two Archean units. These three crustal blocks were assembled along two major crustal suture zones. The lithospheric architecture across these sutures is of particular interest in studying not only their spatial connection to world-class mineral deposits, but also the characteristics of early Wilson cycles in the Paleoproterozoic. In 2015, a 100-km long high resolution (2 to 8 km station spacing) passive-source seismic array was deployed across the Pilbara Craton — Glenburgh Terrane boundary. Conventional Earthquake seismology imaging techniques, including ambient noise tomography, receiver function stacking and body wave tomography are applied to the one year continuous recordings. Preliminary results show that drastic structural differences across the suture zone are present in the crust, consistent with observations from surface geology, active source profiling, magnetotelluric and gravity modelling studies. These structural heterogeneities may also extend into the lithosphere. Combining a variety of surface geological information, these deep-seated seismic structures are interpreted to be related to collisional processes during the Ophthalmian Orogeny, even though the region may have been affected by over a billion years of subsequent intracratonic crustal reworking.

## Geologically Recent Volcanoes and Recent Earthquakes in the Newer Volcanic Province of SE Australia

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There are more than 400 volcanic eruption sites in the Newer Volcanic Province of southwest Victoria and far southeast of South Australia, a region covering about 400 km east-west and 200 km north-south. The oldest erupted about 4 million years ago, and although there have been no eruptions since European settlement in 1834, the oral history of the aboriginal people who arrived about 50,000 years ago refers to active volcanoes, but without any indication of date. Volcano types include scoria cones, maars, and extensive areas of lava flows on the plains.

Australia includes no active plate boundaries so seismicity is low, but relatively fast movement of the plate to the north (~70 mm/year), and very active plate boundaries to the north and east result in high intraplate stress and above average seismicity for a stable continental region. In the region including the Newer Volcanic Province and the surrounding area, the average recurrence interval of earthquakes exceeding magnitude 5.0 is about 20 years, and exceeding magnitude 6.0 is about 200 years. Seismograph coverage was initially limited, and only 164 larger events were located to 1975, many using intensity reports so are quite imprecise. About 2000 earthquakes, mainly small, have been located from 1976 to 2015, with significant improvements in seismograph density and thus earthquake location accuracy over the past 20 years, particularly in the east of the region.

Most of the larger earthquakes with magnitudes from 5.0 to over 6.5 were located south of the main volcanic region, along the coast or offshore.

When the spatial distributions of earthquake epicentres and volcanic eruption locations are compared, it is found that few earthquakes occur in the volcanic regions, and few volcanoes occur in the earthquake regions. Some of the volcanic regions do correlate with above average heat flow measurements. It is possible that the lack of earthquake activity in the volcanic regions is due to higher temperatures limiting the accumulation of strain, and providing deformation by plastic flow. In the extreme, if magma were still present this would significantly limit accumulation of tectonic strain energy and reduce the occurrence of earthquakes.

At this stage the study is two-dimensional, considering surface volcanoes and earthquake epicentres only, due to the limited precision of earthquake depths especially towards the west. Correcting depth errors would produce some movement of epicentre locations. This could be avoided by using a high-density seismograph network, and thus allow a three-dimensional view of the tectonic processes, both earthquake and volcano.

## **Data from the Deep: The critical dependence of deep exploration on deep sampling and other statements of the obvious**

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Trends in mineral exploration over the past decade (increased proportion of expenditure on brownfields and bulk commodities; increased proportion of small discoveries; diminishing tier 1 and 2 discoveries) are partly a reflection of our inability to grasp the challenge of exploration under deep cover. There is little evidence to suggest that this represents a failure of the will (exploration expenditure has reached all-time highs over the same period) or the imagination (viable exploration hypotheses and compelling targets abound). Rather, the evidence supports a simple but profound explanation – that we lack the technology to efficiently explore in this challenging environment. Critical to this argument is the well-documented relationship between mineral exploration drilling and rates of discovery. No matter how elegant and reasoned your exploration model, no matter how compelling your geophysical target, there will be no discovery without the ability to take samples and measurements from down where it matters. The high cost / high risk nature of deep drilling has resulted in only sparse sampling of Australia's prospective under cover mineral provinces, with little capacity to measure and map mineral systems or vector toward ore within them. Using our growing knowledge of mineral system footprints and by analogy with well-sampled, shallowly-buried mineral systems we can gain an appreciation for the density of sampling required to dramatically improve the risk profile of exploration in these provinces. The amount of drilling required is substantial, but feasible! The key is to develop new, low cost technologies for drilling and sampling and to deploy those technologies as mapping tools (multiple holes with vectoring potential), rather than as one-off tests of specific targets. As the density of sampling grows so too will our understanding of the search space, allowing continuous tweaking of the technology, refinement of our exploration models and increasing probability of discovery.

## Late Proterozoic to Paleozoic thermal history of the lower Adelaidean sequences at Arkaroola. Where the heck is Delamere?

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We present the results of field mapping and structural analysis combined with monazite and Ar/Ar geochronology from the lowermost Adelaidean supracrustal rocks exposed to the immediate north of Arkaroola in the northern Flinders Ranges. Metasedimentary and volcanic rocks of the Arkaroola Subgroup and Emeroo Subgroup overlie Mesoproterozoic basement of the Mt Painter Inlier and are exposed in a complex map pattern influenced by multiple episodes of rift-related faulting during the Neoproterozoic and overprinted by Paleozoic folding and fabric development. An early period of ductile deformation is represented in the metasedimentary rocks as structural fabrics defined by biotite and muscovite that are invariably near parallel to bedding. This fabric is preserved within quartz-rich microlithons and within millimetre to centimetre-scale andalusite and cordierite porphyroblasts, consistent with a low-pressure amphibolite facies thermal overprint. The porphyroblasts are overprinted by a pervasive biotite and muscovite schistosity (S2) that is parallel to regional scale folds with ~NE-SW trending axial traces. This fabric is in turn overprinted and folded by localised third generation structures, most notably within 10s of meters of fault zones. Monazite separates from two samples of porphyroblastic Woodnamoka Phyllite display complex internal zonation and yielded a range of Late Proterozoic ages, with two clusters of concordant data at ~705 and 645 Ma. These ages lie within the period of deposition of the overlying Adelaidean sequences (~760 to 580Ma). Although one possibility is that the monazites are authigenic, our preferred interpretation, based on the recognition of biotite inclusions within monazite, is that they are metamorphic. If this is true, the earliest stages of metamorphism and deformation in the northern Flinders Ranges are basin related rather than orogenic. Ar/Ar analyses from three samples of strongly (S2) foliated metasediment from the Woodnamoka Phyllite and one sample from an S2 parallel biotite-rich shear zone within the Wooltana volcanics yielded biotite and muscovite plateau ages of between 430 and 390Ma. These dates add to growing evidence that the Arkaroola area experienced a significant period of cooling in the Silurian to early Devonian. Our favoured interpretation is that this period of cooling is related to regional faulting, folding and differential exhumation of basement and lower Adelaidean rocks which was broadly coincident with the Alice Springs Orogeny. Despite our attempts to find it, there is little evidence for the Delamerian Orogeny (ca. 515 to 485 Ma) in the study area.

## Mesozoic to Cenozoic Uplift and Exhumation of the far Eastern Tianshan

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The topography of southern Central Asia is dominated by the vast intracontinental Tianshan mountain belt, extending from near the Aral Sea in Uzbekistan to the Gobi Desert in far western China. The Chinese Tianshan orogenic collage was generated as a result of Palaeozoic accretionary orogenesis, terminating in the late Permian – early Triassic with the collision between the Siberia-Kazakhstan active margin and the Tarim craton. Like many parts of the Central Asian Orogenic Belt (CAOB), the Tianshan subsequently experienced significant punctuated intracontinental reactivation and exhumation throughout the Mesozoic and Cenozoic in response to a variety of plate margin forces. While the exhumation history of the central Tianshan is fairly well documented, its easternmost extent has not been systematically studied to date. This study aims to investigate the thermal history of the easternmost ranges of the Tianshan, the Harlik and Balikun Ranges.

Low-temperature thermochronology provides a means to pinpoint the response of the CAOB to tectonic events that transpired at the Eurasian plate margins. In particular, the effects of the most recent event, the India-Eurasia collision, is revealed. The progressive eastward reactivation of the Tianshan ranges, originating from the vicinity of the western syntaxis of the India-Eurasia collision, is an important trend in the ongoing Central Asian intracontinental orogeny. Studying both the distal extremities of the Tianshan and the regions most proximal to the syntaxis make it possible to develop a more comprehensive understanding of the modern evolution of the Tianshan.

This presentation is focussed on the far eastern extremity of the Tianshan, and presents data from nineteen granitic samples collected from the Harlik and Balikun Ranges along and across major structural features. Samples were analysed using multi-method thermochronology (apatite U-Pb, apatite fission track, apatite and zircon (U-Th-Sm)/He), identifying fault reactivation and differential exhumation. Here we report evidence for major reactivation during the Oligocene and Miocene, which is consistent with previous results from throughout the Tianshan and Central Asia, in addition to earlier reactivation during the Mesozoic. These results contrast sharply with those found in the Beishan, which lies to the immediate south east of the eastern Tianshan and has a similar tectonic history, but shows no sign of significant Cenozoic exhumation.

This study is part of a larger effort to understand the propagation of strain and the patterns of reactivation throughout Central Asia during the Mesozoic and Cenozoic, and more broadly the relationship between plate margin forces and the corresponding phases of intracontinental deformation.

## Applications of isotope systems of alkaline earth metals for the reconstruction of paleo-depositional environments in Proterozoic basins: Examples from the McArthur Basin (Australia) and Onega Basin (Fennoscandia)

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The McArthur Basin in northern Australia comprises thick Paleoproterozoic and Mesoproterozoic successions that have been subdivided into a number of sedimentary packages. Proven source rocks in the youngest, dominantly siliciclastic Wilton package experienced a relatively low degree of post-depositional alteration and contain prospective Proterozoic hydrocarbon resources. The stratigraphically older Glyde and Favenc packages contain numerous occurrences of sedimentary carbonates dominated by *platform stromatolitic dolostones* (e.g., in McArthur, Balma, Vizard and Nathan groups), originally formed in various shallow-marine and coastal 'sabkha-playa' depositional environments.

The aim of this work is to constrain the isotope variability of alkaline earth metals (specifically Ca, Sr and Mg) in these platform carbonates, specifically dolomites from Glyde Package (i.e., Barney Creek Formation) for the purposes of *intra-basinal correlation* based on the isotope chemostratigraphy. Specifically, this study will investigate the isotope composition of major and minor elements in dolostones ( $\text{CaMg}(\text{CO}_3)_2$ ), including isotope proxies such as  $\Omega^{44}\text{Ca}$ ,  $\Omega^{26}\text{Mg}$ ,  $\Omega^{3}\text{C}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$ ; and will further test the sensitivity of these proxies to paleo-depositional environments, facies changes, and the effects of post-depositional alteration (i.e., meteoric diagenesis and dolomitisation).

The acquired isotope data from the McArthur Basin will be compared with available 'alkaline earth metal' isotope data collected from similarly aged (i.e., Paleoproterozoic) dolostones deposited in the Onega Basin in Fennoscandia, which were also formed in shallow-water sabka-playa settings. Results from the Onega Basin show that these proxies (especially  $\Omega^{44}\text{Ca}$ ,  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $\Omega^{3}\text{C}$ ) are highly sensitive and indicative of different paleo-depositional environments. Specifically, dolostones from supratidal (playa) settings yielded lighter  $\Omega^{44}\text{Ca}$ , heavier  $\Omega^{3}\text{C}$ , and more radiogenic  $^{87}\text{Sr}/^{86}\text{Sr}$  compared to samples from intertidal (sabkha) settings. These facies-dependent differences in alkaline earth metal isotopes observed in the shallow-water carbonate record of Proterozoic basins are likely inherited from the effects of local-scale elemental cycling in these semi-restricted depositional environments. This is due to processes such as (i) a mixing of local seawater (evaporated brine) with freshwater sources, and (ii) the concomitant precipitation and deposition of carbonate (i.e., calcite, aragonite, dolomite) and evaporite (e.g., gypsum, anhydrite) minerals.

## **Low temperature thermochronology of the Turkana Depression and dynamic topography of the East African Rift System**

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The East African Rift System (EARS) is the pre-eminent example on Earth today of a major continental rift zone, and has played a key role in the evolution of ideas about how continental crust responds to extension. Indeed, much of our understanding of the early stages of continental breakup in plate tectonic theory derives from observations made in the EARS. One of the most obvious features of the EARS is that rifting is localized within two separate, more extensive regions of major crustal uplift centred on the Ethiopian Dome in the north and East African Dome, or Plateau, in the south. The Ethiopian Dome is traversed by a single major rift zone, whereas rifting in the East African Dome is divided into two branches, the western and eastern (or Kenyan) rifts, with the eastern branch traversing a subsidiary, volcanically-active Kenyan Dome.

Defining the gap between the two major uplifted regions is a broad belt of relatively subdued topography and much lower average elevation known as the Turkana Depression (TD), running from the Kenyan coastal plain in the southeast to the broad South Sudan plain in the northwest. The mid-point between the Ethiopian and East African Domes is in the region of Lake Turkana in northern Kenya. Here the pattern of rifting is more complex, covers a broader area, and shows evidence of activity over a longer period (Cretaceous to Recent) compared to the narrow, Miocene-Recent rift zones crossing the domes to north and south.

Apatite fission track thermochronology from exposed basement of the Neoproterozoic Mozambique Belt across northern Kenya shows the area to be dominated by a major late Cretaceous to early Paleogene cooling event. This regionally pervasive event has previously been documented in a broad zone from southeastern to central northern Kenya and has now also been found across basement rocks in northwestern Kenya. Thermal modelling indicates this ~70-40 Ma cooling event was caused by some 2-4 km of basement denudation over a broad NW-SE trending belt at least 200 km wide. This denudation is associated with the dominant period of basin fill within the neighbouring Cretaceous-Paleogene Anza Rift to the east.

Widespread basement denudation along the TD margins suggests that the observed crustal thinning to only ~20km in this area is inherited from the Cretaceous rift system, which also probably connected across northwestern Kenya into the system of coeval basins in South Sudan. Due to this modified structure, the lithosphere beneath the TD produced a more limited dynamic response to the arrival of mantle upwelling now observed along the length of the modern EARS, compared to much thicker lithosphere to the north and south. The localisation of dynamic topography within the Ethiopian and East African Domes may therefore be due more to the inherited lithospheric structure between them than to partitioning of upwelling into separate plumes beneath the domes. The more complex and longer-lived rifting observed in the broad extended zone across the TD can also be regarded as an interference pattern between the Cretaceous and modern rifts.

## Late Proterozoic - Phanerozoic intracontinental reactivation and differential exhumation of the eastern Musgrave Province: insights from low-temperature thermochronology

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The eastern Musgrave Province records a complex thermotectonic history including multiple reactivations during the Proterozoic and Phanerozoic. This study aims to place temporal constraints on these reactivation events and to assess the differential exhumation recorded across the main structural architecture of the study area.

Multi-method thermochronological results were obtained for granitoid samples collected along a roughly north-south transect through the eastern Musgrave Province. With the aid of time-temperature modelling, four distinct thermal events were identified that affected the study area throughout the late Proterozoic and Phanerozoic. Late Neoproterozoic cooling was observed, which is thought to be related to the Petermann Orogeny. Subsequent cooling events at ~450–400 Ma (Silurian – Devonian) and ~310–290 Ma (Late Carboniferous) are thought to reflect exhumation associated with two phases of the Alice Springs Orogeny, the latter exhuming the sampled eastern Musgrave plutons towards shallow crustal depths. An additional poorly constrained Triassic – early Jurassic thermal event was observed throughout the study area, which is thought to be related to elevated geothermal gradients at that time.

The high sample density across the structural architecture of the study area revealed differential preservation of the thermal record. It was found that more shallowly exhumed levels were preserved in the centre while deeper exhumation occurred towards the margins of the sampled transect, matching an inverted graben tectonic model. This correlates well with the subsurface record of the Eringa Trough in the west Pedirka Basin, where a >1.5km thick sequence of Carboniferous - Permian sedimentary rocks was inverted along reactivated normal faults that match up with the structural history of the eastern Musgraves basement described in this study. The results demonstrate that low temperature thermochronology can be used to assess differential exposure and crustal depth across faulted terranes and to elucidate the associated preservation potential of mineral deposits. It also demonstrates the power of linking basement deformation to that preserved in the overlying basins.

## Gold Deposits in Metamorphic Rocks: why are we getting more confused?

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Orogenic gold deposits represent the main source of gold in deformed Phanerozoic metasedimentary or Precambrian metavolcanic terranes, typically having formed 20-200 million years after their host rock terranes. These deposits are typically characterized by (1) post-peak metamorphic timing; (2) changing far-field stresses in a dominantly subduction/active margin setting; in (3) metamorphosed fore-arc or back-arc locations; (4) a broad thermal equilibrium with country rocks, as indicated by alteration assemblages and lack of telescoped zonation; (5) hydrothermal addition of K, S, CO<sub>2</sub>, H<sub>2</sub>O, Si, and Au with variable additions of As, B, Bi, Na, Sb, Te, and W; and (6) supralithostatic low-salinity H<sub>2</sub>O-CO<sub>2</sub>-CH<sub>4</sub>-N<sub>2</sub>-H<sub>2</sub>S ore fluids.

Although these features have been accepted for decades, there has been increased recent controversy over genesis of these deposits. Historically, orogenic gold deposits were high-grade, with gold-bearing quartz-carbonate veins mined underground at 5 to >10 g/t. At higher gold prices, many deposits have produced much lower-grade open-pit ore from hydrothermally-altered rock that would have previously been considered waste, or just distal geochemical anomalies (i.e., <1 g/t). Consequently, interpretation of what is an orogenic gold deposit and what is not has become more difficult. Furthermore, greater complexities tend to be associated with older deposits, such as the spatial overlap of orogenic gold with other deposit types, metamorphism of some giant orogenic gold deposits, and more episodic ore deposition. This likely reflects differences in the Earth's thermal budget and tectonic processes between the Phanerozoic and Archean.

Whereas our ability to measure many parameters of the ore-forming fluid for orogenic gold continues to improve, and a relatively consistent fluid chemistry continues to be recognized, the interpretation of these data remains equivocal. A magmatic-hydrothermal model, although recently coming back into favor, is incompatible with geological and geochronological data from many regions. Similarly, large gold endowments in numerous juvenile oceanic terranes, indicate an enriched SCLM cannot be the direct gold source. A crustal or subduction-zone metamorphic model remains the most viable ore-genesis model that can be applied globally, with sulfur and gold released from prograde metamorphism of pyrite at depth. In Phanerozoic terranes, metasedimentary rock sequences are potentially an important fluid and metal source, whereas in Archean greenstone belts, the metavolcanic rocks are the only potential source given stratigraphic/structural considerations. The giant Cretaceous orogenic gold deposits in Archean terranes of the North China block indicate that, in some examples, the subducting slab is the only reasonable source for metals and sulfur from metamorphism of pyrite.

Accepting of a universal metamorphic model for orogenic gold adds constraints for targeting. For example, most orebodies will (1) be related to pre-existing crustal-scale fault systems cutting volcanosedimentary crust; (2) show broadly identical mineralogy and alteration assemblages; (3) have, if present at all, proximal igneous intrusions that will solely represent zones of pre-gold rheologically favorable rock for the location of ore-bearing structures; and (4) be preferentially located in greenschist-facies domains, particularly in Phanerozoic terranes, although several recent Archean discoveries are in amphibolite-facies terranes.

## Leveraging AuScope technology to define distal footprints of mineral ore systems

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The Discovering Australia's Mineral Resources Program of CSIRO is conducting a regional study to define distal footprints of covered ore systems in the Capricorn Orogen – an underexplored area of known mineral potential that lies between Pilbara and Yilgarn Cratons in Western Australia, both known as prolific metallogenic provinces. With most of that area being covered by weathered material, much of its mineral wealth remains yet to be found. The data integration theme of the project aims at enabling heterogeneous datasets of regional geophysical interpretations to be combined with hydrogeochemical, regolith, and resistate mineral studies around known deposits allowing geoscientists to gain insight into the key indicators of mineralisation.

The project analyses a large number of heterogeneous datasets collected from various sources, e.g., field sampling, laboratories, historical data, that are often presented from different perspectives. Data interoperability, in particular standardised data ingest and classification, is a critical factor in enabling comprehensive and interdisciplinary data analysis. The Spatial Information Services Stack (SISS) was developed in AuScope to facilitate interoperability of geospatial data. SISS uses standard Open Geospatial Consortium (OGC) web services for interoperable data access from third-party client applications, such as the AuScope portal, ArcGIS clients, etc. It should be noted that in projects of this scale data interoperability challenges are not all of a technical nature, social aspects have to be considered, too.

The choice of standard and open source technology to support the backbone of the data integration theme of the project lowered technological barriers to implementation and uptake. Initially, the Capricorn Distal Footprints project implemented the OGC compliant Web Feature Service and Web Map Service components of SISS for interoperable data access. Later the use of the SISS stack was extended to include the Persistent Identifier Service. This service is used to manage registrations of sample materials with the International Geo Sample Number (IGSN) system. The use of identifiers for sample materials is critically important for responsible curation of the diverse sample materials generated in the project. The unambiguous identification of samples by IGSN also contributes to the goal of enabling synoptic integration of heterogeneous geochemical datasets for regional-scale exploration.

The data interoperability achieved in the project forms the basis for the application of more advanced data analytics. With the project data accessible through standard interfaces, it can now be used in numerical codes in Virtual Research Environments, like the AuScope Virtual Lab. Leveraging more advanced numerical methods over larger volumes of data compiled in the project reveals new opportunities for further insights into the geology and resources potential of the Capricorn region.

The AuScope-developed Spatial Information Services Stack has proven to be a reliable set of technology. In the Capricorn Distal Footprints project, it acts as a science enabler providing a unified data interface and allowing researchers to interact with the data using third-party tools and applications they are familiar with. SISS provides a full spectrum of interrelated components that can be used as building blocks serving the specific needs for data integration in the project.

## A possible characterisation routine involving HyLogging, XRD and LIBS for rapid core library mineral analysis

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Reflective spectroscopy allows rapid identification of minerals and their variations by measuring their fundamental vibrational characteristics that are unique to each mineral. HyLogging non-destructively and rapidly scans the surface of the core for its detailed mineralogy at 125 samples/m or 150-200m/day), using three spectrometers covering visible-near and shortwave infrared (380-2500nm) and thermal infrared (6000-14500nm) regions of the electromagnetic spectrum and delivers depth referenced mineralogical information with high-resolution images. Laser Induced Breakdown Spectroscopy (LIBS) is a rapid elemental analysis technology that maps the elemental composition by ablating a small volume of the sample surface using a concentrated laser pulse, thus creating a high-temperature micro plasma containing free electrons, excited atoms and ions. The radiation emitted to reach the ground state is characteristic of individual elements contained in the sample, which may then be combined to qualitatively and quantitatively identify the mineral composition. This can also be validated using X-ray diffraction (XRD), which is a well-established tool to study the unit cell parameters of a crystalline material and its phase identification. This technique requires sample destruction but gives the bulk composition of the sample, unlike the former two methods that determine only the surface representation of minerals.

This study tests a practical core-library based workflow strategy for mapping and validating the mineralogy quickly, without involving much preparatory and laboratory work. First-pass HyLogging is followed by second-pass domaining and mineralogical modelling to derive sample points (fillets) for clarification of mineral assemblages. A third-pass of hand-held LIBS analysis provides selective elemental distribution and chemical trends, representative of the target minerals modelled before. These mineral assemblages are then validated using on-site benchtop XRD measurement as a fourth-pass, which provides the detailed mineralogy of the filleted drill core samples and their unit-cell phase identification.

The Cannington region was chosen for its economic interest and diverse mineralogy and known similarity to the Ag-rich Broken Hill type mineralisation. It is situated in the Eastern succession of the Mount Isa inlier, northwest Queensland. The deposit is hosted by banded migmatitic quartzofeldspathic gneiss, which grades into unusually garnet-rich (30-60%) interbanded sillimanite-garnet schists and garnetiferous quartzites, similar to that of the Broken Hill deposit.

Representative sample ‘fillets’ were sliced from the middle of the Cannington CUD5198 drill core, based on the initial HyLogger scanning. The minerals identified in these fillets were supported by XRD validation with 85% confidence of the main mineral groups. The 15% variance observed is due to the fact that HyLogger maps only the minerals it sees on the core surface while XRD represents the bulk mineralogy of the sample. Elemental mapping by LIBS on the same surfaces also effectively support the minerals identified. This study suggests that when these three techniques are used in concert, they could represent a rapid and cost-effective work-flow of mineral identification beneficial to the minerals industry, thus avoiding complex analysis procedures and long wait times. Identifying the right sampling surface with uniform mineral representation is the main challenge in this procedure and extreme care is required during sampling for the best results.

## **Infrared analysis of drill cores from the Paris Silver Prospect, South Australia**

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The Paris silver deposit is located in the southern Gawler Craton in South Australia, and has recently been upgraded to a JORC compliant inferred resource estimate containing 33Moz of silver. Selected drill cores along a central section from the PARIS deposit, held by Investigator Resources Ltd., were sent to the HyLogger™ 3.3 at the Glenside Drill Core Storage Facility, for spectral analysis in March 2015. Mineralisation is largely hosted in a brecciated and clay altered sequence which is an elongate body with some graphitic intersections, extending for approximately 1.5km. The results returned an upper quartz and kaolinite rich altered body and a lower, carbonate, the Katunga Dolomite (Hutchinson Group) with minor tremolite and diopside. Graphitic intersections were associated with iron oxides, talc and chlorite. Felsic rich veins interrupt the dolomite and have been interpreted as structurally controlled intrusive dykes or sills into the Katunga Dolomite. Spectral analysis and logging were used in conjunction with traditional logging techniques to analyse the mineral system footprint for the inferred resource. Three dimensional modelling, using GoCAD modelling software, was then used to create a mineralogical cross section of the cores along section 7.

## A new chronology and probabilistic assessment of sea-level variability over five glacial cycles

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Reconstructions of global ice volume through the Quaternary provide a crucial context for understanding climatic and environmental changes at the regional, hemispheric, and global scale. On these timescales, changes in sea level give an indication of the global glaciation state. However, while several well-dated sea-level records exist for periods within the last glacial cycle (ca 0-130 ka BP), older time intervals are much less represented. For example, available reconstructions of sea level prior to the last interglacial tend to be discontinuous or of low resolution, and contain large sea-level uncertainties. To address these issues, we have developed a robust, radiometrically constrained timescale for continuous and centennial-resolution records of sea level and rates of sea-level change, over the last five glacial cycles (~500,000 years). Our method is based on synchronisation of Red Sea dust and relative sea-level (RSL) records to speleothem  $\Delta^{18}\text{O}$  records from Soreq cave (Israel) and Sanbao Cave (China). We have also used Bayesian, Monte Carlo-style, and new change-point analyses to assess chronological and sea-level uncertainties, which has resulted in the first probabilistic records of sea level and sea-level change rates for periods before the last interglacial. To illustrate an implication of our new sea-level records, we have explored i) the relationship between natural (pre-anthropogenic forcing) sea-level rise rates and 'glaciation state', and ii) the deglaciation response time of global ice sheets. Our results suggest that maximum sea-level rise rates remained below 2 m per century following periods with up to twice present-day ice volumes, while substantially higher rise rates were attained for greater ice volumes. The data also show that deglaciation response times can vary from centuries to several millennia.

## Hydrogeochemistry in Australia: Challenges and Possibilities

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Groundwater can be a useful sampling medium for geological investigation and mineral exploration: its composition is highly sensitive to its origin and interaction with minerals in the subsurface, and it responds to faults and other geological structures. Thus, there is considerable scope for groundwater adding value to mineral exploration where prospective rocks are covered along basin margins.

We are encouraging uptake of the technology, through development of robust and cost-effective methodology, and from site studies. Field guides, notebooks, and field apps are now available. Issues such as bailing vs pumping have been tested, and metrics for contamination and determination of its effects on varying elements have been developed. Vast amounts of groundwater data are publicly available (e.g., <http://portal.auscope.org/portal/gmap.html>).

Mineral systems concentrate various elements at various scales and in particular zones. For groundwater, this is further complicated by the differing mobilities of various elements depending on the environment. In acidic groundwater environments, for instance, base metals (e.g., Cu, Zn) are highly mobile, although the background concentrations also can be high due to acid attack on the country rocks. In neutral groundwater environments, base metals commonly have low mobilities but oxy-anions (e.g., Mo, W, As) can give larger and more consistent haloes. In some terrains, particularly in southern Australia, the upper 20 m of the water column can be 3 pH units lower than deeper groundwater. In such a situation, combining results from shallow and deep groundwaters will give erroneous spatial patterns.

Interpreting hydrogeochemical data at a Continental scale has required resolving issues related to differing analytical quality, and sometimes differing sampling and analytical methods. Results provide support for lithochemical discrimination of the Australian continent, and allow assessment of the utility of these methods for varying terrains, e.g., from very acid/saline in southern Australia, through mostly fresh and neutral in the western two thirds of the continent, to sulfate-poor in the artesian-dominated systems of northeastern Australia. In each case, differing element suites and indices should be used for exploration.

At the Terrain scale, specific groundwater indices delineate large scale lithological groups, and major mineral camps. Such a broad-scale approach may miss camp scale-variation but does delineate major features, such as the Agnew and Granny Smith Gold camps in WA. Other large systems, such as iron oxide copper-gold (IOCG) or copper porphyries may also be observable. At the Prospect scale, indicator elements (e.g., Au, Ni, Cu, Zn, W, As) are commonly valuable, with Indices developed for specific commodities (e.g., AuMin or NiS). Combined with geophysics, this may assist in selecting drilling targets.

Hydrogeochemistry, combined with a robust understanding of environmental factors, rock weathering and good quality analytical chemistry, can positively assist exploration at varying scales. Continuing research and interaction with explorers should contribute to the next phase of economic mineral deposit discovery in Australia.

### Acknowledgements

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## Uranium-series dating of bracketing mineral accretions associated with Kimberley rock art

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Uranium-series radiogenic dating methods have been successfully applied for the first time to layered mineral accretions that are commonly associated with rock art sites in the Kimberley region of Western Australia. Particularly promising results have been obtained from an important coastal site characterised by extensive rock engravings ('pecked' cupules) on cave walls. Considered one of the oldest art styles, 'rock markings' such as these cupules offer an insight into how the first Australians interacted with and transformed their environments and are found across the world with specific historical and social meanings. The cupules were not made for utilitarian purposes such as grinding foodstuffs and instead represent a visual residue of multi-sensorial interactions people have with places.

This study focuses on millimetre to centimetre thick mineral accretions into which the cupules have been ground as well as others accumulating within the cupule hollows, providing a rare and important opportunity to provide bracketing ages for the rock art. Extensive mineralogical and geochemical analyses have identified a recurring suite of dominantly sulphate, oxalate and phosphate minerals, with other minor phases, that comprise many of the accretions forming in rock shelters across the Kimberley. In particular, magnesium phosphate minerals such as newberryite are found to host sufficient uranium for the application of uranium series dating methods. The identification of micron-scale layering within the internal stratigraphy of these accretions using LA-ICP-MS and SEM-EDS analysis, enables targeted, high-resolution micro-sampling of the uranium rich layers. The application of uranium-series dating to these layers is particularly important as co-genetic samples from multiple samples within individual growth layers, and sequential layers across the accretion's internal stratigraphy, both allow testing for closed system behaviour with respect to uranium and thorium to be demonstrated, an issue which has hampered many previous radiogenic dating studies.

This study demonstrates the importance of detailed inorganic and organic geochemical characterisation of both the sample and its associated rock shelter in the production of reliable and reproducible ages via uranium-series dating of rock art associated materials. The method has the potential to provide significant numbers of dates bracketing rock art ages across a region that currently has very little high quality geochronological information.

## Escript – Open-Source Tool for Numerical Modeling of Earth’s Processes

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The idea for design of the programming tool escript is to provide scientists with an easy to use software environment in which complex mathematical models can be quickly implemented and tested. Models are developed using the programming language python. Python is easy to learn even for programming novices, and now widely available on all compute platforms. The key concept in escript is the capability to solve partial differential equations (PDEs). It provides a PDE solver of a general form that can be specialized for user-specified application scenarios. The PDEs can be linked to build coupled models where escript automatically inserts the necessary data conversions. Solutions of PDEs are performed using finite element methods (FEMs) on structured or unstructured meshes. The user's python scripts refer to defining the PDEs and solution method only while the underlying data structures used in C++ are not exposed. This level of abstraction creates highly portable model descriptions, which can run on desktop computers as well as parallel supercomputer without changes. Platform dependencies such as data distribution are hidden from the user and handled by the escript libraries. Application areas for escript include Earth mantle convection, geophysical inversion, earthquakes, fracture propagation, porous media flow, plate subduction zones, erosion, wave propagation and tsunamis. We will discuss two applications in more details:

The first application case is in modeling rock fracturing to help improve current fracture simulators applied in oil and gas reservoirs. Fracturing are modelled using the concept of damage. In damage mechanics the elastic moduli of the rock degrade gradually as damage progresses and fracture propagation is identified as the evolution of damaged elements. Damage is initiated when failure criteria are reached. Pre-existing natural fractures can be prescribed initially as damaged elements. Tensile damage is considered to be the direct cause of crack initiation and fracture-growth is tracked by identifying elements whose ultimate tensile strain has been reached. Loading tests of uniaxial compression of a pre-flawed cylindrical sample have been performed. Rock heterogeneity responsible for localized failure is simulated using an initial Weibull distribution for the elastic moduli. This process has been implemented in escript. With appropriate parameter calibration uniaxial compression experiments can be modeled even beyond sample failure.

The second application case is the inversion of gravity anomaly data. The objective is to reconstruct the density distribution in the subsurface from surface gravity surface measurements. While common inversion approaches discretize the underlying PDE for the gravity field first and then apply an optimization method to the discrete problem. A more consistent approach would be to obtain the solution for the unknown density distribution by modeling a set of coupled PDEs. The problem can easily be implemented using escript. The software has been applied to the inversion of the gravity anomaly of the Australian continent with 250Million unknowns using over 22000 cores on the Pawsey Supercomputer in WA. The results are accessible at <https://github.com/al8ken/FEILDAustralia>.

Information on escript including downloads can be found at <https://launchpad.net/escript-finley>. The development and maintenance of escript is funded through AuScope NCRIS.

## Large-Scale 3D Resistivity Inversion of Subsurface Injection Monitoring Data using the Adjoint State Method

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Electrical Resistivity Tomography (ERT) is widely used as a geophysical tool to image the subsurface. The idea is to inject a current into the ground and measure the produced potentials away from the injecting electrode(s). Inversion of the spacial variation of the potential measurements is used to recover electrical resistivity in the subsurface. This in turn is interpreted as proxy to other targets including water content, salinity, contamination or cavities. Traditionally ERT data are collected on the surface along a line of electrodes which allow for two-dimensional inversions only. There is a growing trend to arrange electrodes as a two-dimensional array not only on the surface but also down boreholes opening the door for a truly three-dimensional inversion. However three-dimensional inversion is computationally intensive and requires the use of parallel computers. Approaches currently being used reach limitations when it comes to solving large-scale 3D problems.

We present a new inversion approach which is more suitable for parallel computation. In contrast to conventional methods which apply spatial discretization to the electric potential equation before optimization, our method solves the optimization problem prior to applying any spatial discretization. In addition to the forward problem predicting the measurement from the injected current, the so-called adjoint problem also needs to be solved. For this problem a virtual current is injected through the measurement electrodes and responses at the injection electrodes are obtained. The magnitude of the injected virtual current is proportional to the misfit at the measurement electrodes. The new approach has the advantage that the solution process of the optimization problem remains independent to the meshes used for discretization and allows for mesh adaptation during inversion. In addition, existing parallelization algorithms for the finite element method (or other discretization methods) that have already been optimized can be directly applied as solvers for the inversion problem.

ERT has been identified as a potentially suitable geophysical method to monitor the flow of an injected fluid (e.g CO<sub>2</sub>) in the subsurface. We apply our new inversion method to synthetic survey data created by the resistivity profile representing the characteristics of subsurface injections. We use over 1Million cells in three-dimensions for the inversion. Our numerical tests show that to obtain good inversion results the number of sources is of less importance than their correct vertical positioning relative to the area affected by the fluid flow caused by fluid injection.

The inversion has been implemented using escript, see <https://launchpad.net/escript-finley> for details. The development and maintenance of escript is funded through AuScope NCRIS.

## The History and Heritage Value of the Mineral Collection of the South Australian Museum

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The mineral collection of the South Australian Museum currently numbers 34300 registered specimens, the bulk of which are stored in the Science Centre behind the Museum's North Terrace galleries. The Museum collections date back to 1856 and included mineral specimens among the very early acquisitions. Although an Honorary Curator of Minerals was not appointed until 1882, the importance of maintaining a mineral collection was recognised early in the Museum's history mainly as a tool for mineralogical education with a direct application to growing the state's mineral wealth.

The collection grew in the 20<sup>th</sup> Century under the curatorship of T.C. Cloud (1882-1906) and Douglas Mawson (1907-1953) mainly through the acquisition of a series of important Australian collections and some exchanges with UK and US mineral suppliers. This enriched the collection in both systematic species and locality specimens together with large suites of outstanding specimens from Australian localities. In particular Broken Hill, Moonta-Wallaroo, Burra Burra, Kalgoorlie (Golden Mile) and Mount Painter are well represented in these early 20<sup>th</sup> Century acquisitions. The suite of copper (and associated) minerals in the collection from Burra Burra and Moonta-Wallaroo districts are the world's finest from these localities. A second period of collection growth accompanied the introduction of the Taxation Incentive for the Arts scheme under the curatorship of Allan Pring (1984-2015), during which the collection was enriched in suites of specimens from the Olympic Dam and Iron Monarch deposits as well as worldwide classic minerals and cut gems (particularly Australian opal). The S.A. Mines Department collection of approximately 6000 specimens was transferred to the S.A. Museum in 1996 and included important reference specimens from the state's early mines.

As well as being exceptional specimens in their own right many of the early acquisitions in the collection are important historical objects, such as the suite of Burra Burra specimens donated by S.A. premier and Burra Burra mine director Sir Henry Ayres in 1881. An important function of the collection from both a scientific and a heritage point of view is the preservation of mineral species, paragenetic suites and associations from mines that have now been worked out or are otherwise inaccessible for further collecting, and ore deposit mineralogy is a key research focus at the Museum. As an example, the Oroya Shoot, which was the source of rich Au-Ag-Hg tellurides in the Golden Mile of Kalgoorlie is now completely mined out. Researchers interested in further studying the mineralogy or geochemistry of this important mineralisation style now rely on well documented specimens in museum collections. Other examples include the diverse suite of phosphate minerals from the now depleted Iron Monarch iron ore mine in the Middleback Ranges and the rich oxide and supergene zones of many base metal mines (e.g. Burra Burra, Moonta-Wallaroo, Broken Hill). Closer to home, the encroachment of the Adelaide suburbs and the requirement to rehabilitate defunct quarries means that many localities for superb, large quartz crystals are now completely inaccessible. The preservation of an outstanding suite of these crystals in the S.A. Museum collection means that they will be available for generations to admire.

## Deep stratigraphic drilling for tectonics, climate and ancient life on the Lord Howe Rise continental ribbon

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The Lord Howe Rise is a ribbon of submerged and extended continental crust that separated from Australia during the Late Cretaceous. The Lord Howe Rise is concealed beneath the Tasman Sea in water depths of 1000–3000 m, so current knowledge of Lord Howe Rise geology is based on sparse shallow (<600 m below-seafloor) DSDP drilling into Cenozoic pelagic sediments, isolated dredge samples and regional-scale marine and satellite geophysical data.

Existing data provide a broad understanding of the Lord Howe Rise's crustal structure, sedimentary basin architecture and resource potential. However, building knowledge of Lord Howe Rise geology, and the geological evolution of the southwest Pacific more broadly, requires drilling into rocks that record the >100-million-year geological, tectonic and climatic history of the region. To this end, Geoscience Australia and JAMSTEC are leading an international effort to drill a deep stratigraphic hole into a Lord Howe Rise rift basin that will core Cretaceous and older sediments and potentially basement rocks. This deep riser drilling will extend to a depth of up to 3500 m below the seafloor. Two shallow, non-riser holes may also be drilled up to ~500 m below the seafloor into basement horst blocks.

A proposal for drilling using the JAMSTEC drilling vessel CHIKYU was submitted to the International Ocean Discovery Program (IODP) in October 2015 (Proposal 871-CPP) and has received general support from the IODP Science Evaluation Panel. The objectives of the IODP deep stratigraphic drilling are to: 1) define the role and importance of continental crustal ribbons, like the Lord Howe Rise, in plate tectonic cycles and continental evolution; 2) recover new high-latitude biomarker and micropaleontology data in the southwest Pacific to better constrain Cretaceous paleoclimate and linked changes in ocean biogeochemistry; and 3) test fundamental evolutionary concepts for sub-seafloor microbial life over a 100-million-year timeframe.

If funded, the deep stratigraphic drilling is planned for late 2018 or early 2019. Preparations for drilling include a seismic survey conducted in the first half of 2016 that acquired 2D seismic reflection and refraction data along an east–west transect across the Lord Howe Rise to map regional crustal structure and 2D seismic reflection data at the sites being considered for drilling. A second survey in 2017 will acquire the geotechnical data necessary to successfully drill a deep stratigraphic well. This detailed site survey will acquire high-resolution seabed and shallow sub-seafloor data, shallow sediment cores (<60 m below-seafloor) and underwater video.

## Murraba Basin, Western Australia: revised Neoproterozoic stratigraphy and evidence for Ediacaran–early Cambrian tectonism beneath the Canning Basin

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The predominantly Neoproterozoic Murraba Basin straddles the WA-NT border, overlying crystalline basement of the Arunta and Tanami regions, and the older Birrindudu Basin, but predating the Paleozoic–Mesozoic Canning Basin. Most of the Murraba Basin is mapped as Redcliff Pound Group comprising basal siliciclastic units, the Munyu (south), Lewis Range (north) and Muriel Range (northeast in NT) Sandstones, previously inferred to be conformably overlain by the Murraba Formation and Erica Sandstone, in ascending order. The local Hidden Basin beds were inferred to be younger. Although considered a component of the Centralian Superbasin, correlation with even the nearest contemporary basins previously proved difficult. The apparent absence of Cryogenian glacial units led to the Redcliff Pound Group being assigned to pre-glacial Supersequence 1 of the Centralian Superbasin, although the carbonate-evaporite facies characterizing the bulk of that supersequence elsewhere was also apparently absent.

A recent reconnaissance survey of the southern Murraba Basin indicates that the Redcliff Pound Group contains a much more complete Centralian Superbasin succession than previously thought. All four Neoproterozoic supersequences recognised elsewhere are likely present; however, carbonates of upper Supersequence 1 and a possible glacial to inter-glacial succession of Supersequence 2 are very poorly exposed or concealed in an interval between the basal siliciclastic units and the much younger Murraba Formation. The Hidden Basin beds are now considered older, possibly a component of the Paleo–Mesoproterozoic Birrindudu Basin.

The Murraba Formation and Erica Sandstone package is now assigned to Supersequences 3 and 4 of Ediacaran to probably early Cambrian age (supported by inter-basin correlations and biostratigraphy). The base of the Murraba Formation is interpreted as a major unconformity. The ensuing shallow marine succession contains abundant chert-rich conglomerate and granule beds that are likely derived from erosion of silicified and chert-bearing carbonate of Supersequence 1. The uplift implied is likely coincident with the Miles Orogeny (c. 650–600 Ma), previously recognised only in the Paterson Orogen on the other side of the Canning Basin. Extension of at least lower components of the Centralian Superbasin and subsequent tectonism beneath the central Canning Basin is supported by the maximum deposition age of  $870 \pm 22$  Ma from detrital zircons in metasedimentary basement in petroleum well Acacia 2.

A sudden up-section change from shallow marine shelf to immature red deltaic sandstone implies a renewed phase of tectonism, taken as the base of Supersequence 4. This event was likely coeval with the Petermann (580–520 Ma), Paterson and King Leopold Orogenies, recognised in the Musgrave/southern Amadeus Basin, Paterson and southern Kimberley regions, respectively. Paleocurrents from cross-bedded channel sandstone consistently indicate transport from the west, implying the locus of tectonism was in the area now concealed by the Canning Basin. At least some of the deformation of the Murraba Basin succession by east–west compression likely occurred at this time. Eolian sandstone in the upper Erica Sandstone may extend into the lower Cambrian, coeval with widespread eolian deposition immediately prior to eruption of the Kalkarindji Large Igneous Province in adjacent areas at c. 510 Ma.

## Low-Temperature Thermal Histories of the Northern and Eastern Gawler Craton

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The thermal evolution of a region can be revealed using a combination of low-temperature thermochronological techniques which can then potentially illuminate the palaeo-stresses, namely exhumation, of an intra-continental setting. Fission track studies conducted on apatite, and titanite and U-Th-Sm/He analyses conducted on apatite, and zircon from four regions within the northern and eastern Gawler Craton revealed the low-temperature thermal histories of these regions. These regions, the Peake and Denison Ranges, central Gawler Craton, northern Gawler Craton, and buried Stuart Shelf, all revealed complex and long-lived thermal histories. Yet, thermal events during Cambrian – Ordovician, Carboniferous, and Early Jurassic are witnessed in all regions with some samples also suggesting localised Cretaceous cooling. These periods of thermal activity are recording far-field stresses caused by orogenies such as the Delamerian and Alice Springs orogenies, or far-field stresses caused by the break up of Australia and Antarctica. Within the buried basement of the Stuart Shelf an older thermal event was identified and thought to be related a late Mesoproterozoic thermal event. We explore the possibility that the data are revealing phases of reactivation of the extensive shear zone networks in the region and/or the incision of major canyon systems (Reddy et al., 2015). The data presented here also suggest that despite the Gawler Craton having experienced its last major tectonothermal event in the early Mesoproterozoic (Hand et al., 2007), it appears to have far from tectonically inactive through the Neoproterozoic and Phanerozoic. The central to northern Gawler Craton is the catchment of the transcontinental Late Cretaceous Ceduna River (MacDonald et al., 2013; Lloyd et al., 2015) and a site of considerable controversy about the cause of the rejuvenation of the river system to deposit the upper lobe in the Bight Basin (MacDonald et al., 2013) yet previously, very little data was present within these regions, therefore, these datasets aid in revealing the chronological history relating to this transcontinental river system.

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## Estimating grain density with the HyLogger™

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Grain density is a measure of the density of the grains (and cement if applicable) of a rock and excludes the effect of the volume of pore spaces from calculations. It is governed by the concentration of the minerals present and by the densities of these minerals. Grain density is commonly measured by Archimedes' method which can be time consuming and may limit the number of measurements collected. A proposed alternative method is to derive grain density estimates from the mineral outputs from HyLogger™ datasets. The mineral outputs derived from the HyLogger Thermal InfraRed (TIR) wavelength range combined with published mineral densities, produce an estimate of grain density for a given drill core interval by:

$$\text{grain} = 1 \cdot C_1 + 2 \cdot C_2 + \dots + n \cdot C_n$$

where  $C_{\#}$  and  $C_{\#}$  are the density and concentration of each individual mineral type present in the sample respectively.

The grain density of 340 samples was measured using Archimedes' method and compared with the estimated grain density derived from the HyLogger mineral outputs for the same intervals. Grain density results by the two methods correlated to within 0.15 g/cm<sup>3</sup> of each other for 85% of the sample set. Investigation of the outlier values highlighted a group with gypsum coatings resulting from drill core decomposition. Most other outliers are from 'tight' (low pore connectivity) fine-grained sediments that belong to a single stratigraphic unit. A subset of 275 samples was created by excluding the stratigraphic units that contained these outliers. All of the grain densities determined by the two methods for the samples in the subset correlated to within 0.34 g/cm<sup>3</sup>, with 95% of the samples correlating to better than 0.15 g/cm<sup>3</sup>.

Sandstone and dolerite have HyLogger-derived grain density estimates that correlate well with the measured Archimedes' results. Other lithologies including fine-grained sedimentary rocks such as shale and mudstone did not correlate as well. Errors in grain density estimates may be introduced to Archimedes' measurements by incomplete penetration of pores by fluid during submersion or to HyLogger-derived grain density estimates through inaccurate estimation of mineral proportions. This warrants further investigation.

HyLogger-derived grain density estimates can be calculated on small, continuous intervals in drillcore. On suitable lithologies, this could enable grain density heterogeneity to be recognised on smaller scales than would usually be practical by Archimedes' method. Sample bias in Archimedes' measurements could be recognised from reviewing HyLogger-derived grain density heterogeneity adjacent to sample locations.

Results from this case study show that estimating grain density from the mineral outputs derived from HyLogger gives a reasonable proxy for lithologies such as sandstones and dolerites. It may be a useful technique for showing grain density heterogeneity and may be applied to National Virtual Core Library (NVCL) drillcore.

## The mission-specific platform (MSP) concept: a new dimension in scientific ocean drilling

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ECORD funds and implements mission-specific platform (MSP) operations for IODP as an independent platform provider. The development of the MSP concept allowed the ocean research community to work in technically challenging conditions where the US drillship *JOIDES Resolution* and the Japanese drilling vessel *Chikyu* are unable to operate, such as those located under ice-covered seas, in shallow water, in environmentally sensitive areas or in certain hard-to-drill lithologies such as carbonate reefs and loose sediments. MSPs, that are contracted on a case-by-case basis, have therefore added a new dimension to ocean drilling.

The ECORD Science Operator (ESO) consortium has successfully implemented five MSP expeditions for the Integrated Ocean Drilling Program to the Arctic (2004), Tahiti (2005), New Jersey (2009), the Great Barrier Reef (2010), and the Baltic Sea (2013). These projects had multiple scientific objectives, including the recovery of records of climate and sea-level change, and the recovery of previously unknown buried microbiological communities.

ECORD aims to deliver one MSP expedition per year on average for the International Ocean Discovery Program. The MSP concept has evolved to use alternative coring technologies, as determined by scientific priorities and operational efficiency, in addition to wireline coring that is traditionally used for scientific drilling. One example is the use of robotic sea floor drills to collect high quality core at multiple locations. Such drills have several advantages, including better core recovery in hard rocks and operating costs that are much lower than those related to standard coring deployed by a drill ship. Likewise, long piston coring is another method to acquire high-quality cores along transects that can now be accommodated by IODP MSP expeditions. In parallel, the ECORD operational funding scheme has also evolved to add external co-funding and in-kind contributions to support MSP expeditions.

A five-year, i.e. 2014-2018, operational plan for MSP expeditions has been defined by the ECORD Facility Board for the first phase of the International Ocean Discovery Program. It includes four expeditions addressing a wealth of science themes (geomicrobiology, tectono-magmatic processes, effects of large impacts on Earth's environment, paleoceanography, climate and ice histories) and involving a variety of drilling systems:

- ) The MSP expedition 357-Atlantis Massif Serpentization and Life (Nov.-Dec. 2015) which was focused on the role of serpentinization in driving hydrothermal systems, sustaining microbiological communities, and sequestering carbon in ultramafic rock;
- ) The MSP expedition 364-Chicxulub Impact Crater (Apr.-May 2016), to study especially the impact dynamics mechanism, its effect on the deep biosphere, and its energy and mass extraction;
- ) Two other expeditions that will be implemented in 2018, the "ECORD Polar Year" with the objectives to reconstruct long-term Cenozoic climate history of Antarctica (IODP Proposal #813-Antarctic Cenozoic Paleoenvironment) and of the central Arctic Ocean (IODP Proposal #708-Central Arctic Paleoceanography).

## Extending metamorphic models for the development of Proterozoic Australia

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Much of Palaeoproterozoic Australia is characterised by cycles of basin development and high thermal gradient metamorphism. This is particularly the case in the North Australian Craton (NAC), but is also evident in the Gawler and Curnamona regions of the South Australian Craton. While there is little doubt that the basin forming events reflect extension, the metamorphic history is generally interpreted in terms of accretion and collision. For example, metamorphic rocks in the southern NAC are interpreted to record crustal thickening, although the explicit evidence for crustal thickening is equivocal. Exemplifying this is the 1730–1690 Ma Strangways Metamorphic Complex, where crustal thickening is generally inferred because metamorphism occurred at pressures of around 8 kbar. Neither these pressures nor the localised nature of the terrane are evidence for crustal thickening. Additionally, the metamorphic evolution is punctuated by the emplacement of abundant mafic dykes, suggestive of lithospheric extension rather than thickening.

In southern Australia the widespread Kimban event has been traditionally interpreted to record collision between parts of the Gawler Craton. The reasons behind such an interpretation are nebulous. There is localised high-pressure metamorphism within discrete shear zones, but the bulk of the metamorphic record is low- to medium-pressure with locally rapid changes in metamorphic grade that more commonly characterise extensional systems. Indeed one of the major tectonic records of the Kimban time is the development of the rift-driven Willyama Supergroup, which initiated at around 1710 Ma and continued to develop through the Kimban evolution to post-1690 Ma. It was associated with A-type and metasedimentary-derived granites as well as mafic magmas.

The slightly later c. 1640 Ma Liebig Event has been interpreted to record the collision/accretion of an exotic terrain with the NAC, but has an equivocal metamorphic character. In places metamorphism attained pressures of 8-9 kbar. At face value these could be interpreted as evidence for thickening, particularly in the absence of a structural record due to later overprinting. However, this metamorphism is spatially and temporally coincident with mafic magmatism, and the prograde evolution involved the formation of high thermal gradient mineral assemblages. This is not what would typically be expected for metamorphism driven by crustal thickening.

Rather than recording contraction, we suggest that metamorphic systems such as the Strangways Metamorphic Complex, Kimban and Liebig events developed in extensional settings that contributed to building a wide thin Proterozoic rock system. Areas of greater extension record metamorphism temporally linked to the partial to extraction of continental ribbons. One such extracted ribbon may be the Neoarchean core of the Gawler Craton which conceivably once formed part of a “craton” that incorporated the basement of the Pine Creek Orogen in Northern Australia. Extensional breakup of this Neoarchean system left in its wake a long-lived history of basin development and high thermal gradient metamorphism. We therefore suggest the oft-noted absence of typical metamorphic records for collision is evidence that collisional events did not control the Palaeoproterozoic evolution of Australia, and that structural evidence for shortening represents comparatively minor modifications of overall extensional systems.

## A shale Detachment in Thailand: Evidence of Brittle Deformation from Structural Observations and Laboratory Analysis

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A detachment can be defined as a horizon or zone, centimetres to kilometres in thickness, which mechanically decouples deforming rocks or sediments from underlying, non-deforming sequences. Detachment horizons accommodate thin-skinned deformation in fold and thrust belts across a variety of tectonic settings, the detachments themselves being most commonly composed of salt or shale. Shale detachments have been previously described as largely ductile in their mechanism of deformation, however, increasing resolution of seismic imaging and understanding of these zones suggest brittle, fault-dominated deformation may have a significant role in their behaviour and the deformation of overlying fold and thrust belts. Dependence on seismic imaging and other indirect and low-resolution study methods has resulted from the lack of outcropping shale detachment zones, both active and ancient, for detailed study. Existing outcrop-based studies and work in this study exhibit complex and important structures which occur at a sub-seismic scale, highlighting the uncertainty in characterising shale detachments using seismic data alone. Recent investigation demonstrates the structural style and deformational mechanisms of an exceptionally well-exposed upper-level shale detachment zone in the Sap Bon Formation of the Khao Khwang Fold and Thrust Belt, Central Thailand. We use detailed structural analysis to investigate the deformational mechanisms of this ancient, exhumed detachment zone, as an analogue to active modern-day examples. Through detailed field mapping we present multiple cross-sections through the detachment zone and characterize the deformational style and complex structural geometries present. Within the detachment zone deformational complexity and density of faults increases with proximity to a floor thrust, and this relationship is associated with higher TOC values. Cm-scale 'shale shear zones' accommodate significant shortening and form a three-dimensionally complex system of anastomosing faults bounding competent lenses of rock. These shear zones exhibit higher strain than surrounding rock, and have developed as a result of competency contrasts in the protolith shale, as packages of rock deforming at different strain rates create strain-rate discontinuities; these incompatibilities are then accommodated by shear failure. Carbon and oxygen stable isotope analysis of calcite mineralisation in a pervasive fault-fracture mesh is used to investigate the relative temperature of syn-deformational fluid flow, while illite crystallinity is investigated and applied as a tool to track strain variation in fine-grained rocks. We present a model for the evolution of the fault zone which constitutes an upper-level detachment, and the potential influences on the development of complex fault damage zones in shale detachments.

## The Australian Structural Permeability Map

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There are two fundamental requirements for successful geothermal development: elevated temperatures at accessible depths, and a reservoir from which fluids can be extracted. The Australian geothermal sector has successfully targeted shallow heat, however, due in part to the inherent complexity of targeting permeability, obtaining adequate flow rates for commercial production has been problematic. Deep sedimentary aquifers are unlikely to be viable geothermal resources due to the effects of diagenetic mineral growth on rock permeability. Therefore, it is likely structural permeability targets, exploiting natural or induced fracture networks will provide the primary means for fluid flow in geothermal, as well as unconventional gas, reservoirs. Recent research has focused on the pattern and generation of crustal stresses across Australia, while less is known about the resultant networks of faults, joints, and veins that can constitute interconnected sub-surface permeability pathways. The ability of a fracture to transmit fluid is controlled by the orientation and magnitude of the in-situ stress field that acts on the fracture walls, rock strength, and pore pressure, as well as fracture properties such as aperture, orientation, and roughness. As a result, understanding the distribution, orientation and character of fractures is key to predicting structural permeability. This project focuses on extensive mapping of fractures over a number of scales in four key Australian Basins (Cooper, Otway, Surat and Perth) with the potential to host geothermal resources. Seismic attribute analysis is used in concert with image logs from petroleum wells, and field mapping to identify fracture networks that are usually not resolved in traditional seismic interpretation. Initial work with these techniques has led to new developments in our ability to image subsurface faults and fractures at a variety of scales from independent datasets. We establish a strong relationship between features identified using seismic attribute analysis and interpreted natural fractures. However, care must be taken to use these methods in a case-by-case basis, as controls on fracture distribution and orientation can vary significantly with both regional and local influences. Structural features present within the study areas exert distinct control over fracture orientation, while areas devoid of dominants structural trend tend to exhibit fractures approximately parallel to maximum horizontal stress. These results outline an effective method by which structural permeability can be assessed with existing petroleum datasets. However, unlike the broad stress field, mapping fracture distribution and orientation within the Australian continent is complicated by regional and local structural variation.

## Deep Controls on the Morphology of Surface Volcanic Hotspot Tracks

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Large Igneous Provinces (LIPs) erupting since 200 Ma may have originated from plumes that emerged from the edges of the Large Low Shear Velocity Provinces (LLSVPs) in the deep lower mantle. We present global convection models constrained by subduction history over the last 230 Myr, where plumes emerge preferentially from the edges of thermochemical structures that resemble present-day LLSVPs beneath Africa and the Pacific Ocean. We show that plume eruption locations in models with a chemically anomalous lower mantle are highly correlated to reconstructed LIP eruption sites. The flow models show the formation of a network of embayments separated by steep ridges in the deep lower mantle and that plumes are anchored to the peaks of these ridges. The network of ridges acts as a floating anchor, adjusting to subduction-induced flow through time. Our results suggest that LLSVP regions can be mobile, in contrast to being stable over hundreds of millions of years, as implied by the correlation of the edges of LLSVPs and reconstructed volcanic features. We show that fast moving oceanic plates bounded by a set of dynamic subduction zones can lead to a sustained and coherent flow in the deep lower mantle. LLSVP regions in the vicinity of such coherent lower mantle flows can undergo rapid deformation. Consequently, lateral motion of mantle plumes anchored to rapidly deforming LLSVP regions can result in sharp geometric features in their surface hotspot tracks. Asymmetric deformation of the Pacific LLSVP over the last 140 Myr may explain the morphological diversity of surface hotspot tracks associated with deep mantle plumes in the Pacific.

## **Edge-convection as the cause of Cenozoic intraplate volcanism in eastern Australia: evidence from thermal isostasy**

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Competing hypotheses for the origins of Cenozoic intraplate volcanism along the eastern and southeastern margin of Australia include (singular or multiple) mantle plumes, edge-driven convection, asthenospheric shear, and lithospheric detachment at the continental margin. The scale, magnitude, and geometry of a thermal anomaly associated each of these hypotheses can be expected to differ. Surface heat flow variations occur along this boundary, but higher regional heat flow adjacent to and west of the volcanism mask any coastal anomaly. Because surface heat flow represents a combination of sub-lithospheric heating and radiogenic heat produced internal to the lithosphere, it can be difficult to determine the origin of thermal anomalies from the raw data. In this study, we develop a method for partitioning the contributions from sub-lithospheric and radiogenic heat flow employing a thermo-isostatic analysis. Our models estimate a sub-lithospheric heat flow anomaly ~300 km wide along the eastern and southeastern margin with a magnitude of 35 to 50 mW m<sup>-2</sup>, approximately 10 to 15 mW m<sup>-2</sup> above surrounding regions. The positioning of this anomaly correlates extremely well with areas of Cenozoic volcanism and thin lithospheric thickness estimates derived from seismic tomography. However, the anomaly shows no apparent variations in magnitude that are expected from the proposed plume track(s). Poor resolution models of asthenospheric shear make it difficult to reasonably assess its viability as the cause of Cenozoic volcanism; although, it seems unlikely a higher resolution shearing model would provide a better result given the geometry of the lithosphere in relation to mantle flow. Edge-driven convection represents the most likely explanation for this pattern of sub-lithospheric heat flow given the relatively consistent width, magnitude and proximity to the continental edge. This study highlights the utility of thermo-isostatic analyses to reveal processes driving the evolution of the lithosphere.

## **Vertical heat production distributions: Global and Australian perspectives from geochemical databases and thermal isostasy**

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In this study, we present a new way to estimate the vertical distribution of heat production based on a combination of thermo-isostatic analysis and empirically derived estimates of heat production from seismic velocity. Heat production is a difficult parameter to estimate because many geophysical parameters are insensitive to its magnitude directly. Heat production distributions influence temperature, but temperatures can be difficult to accurately extrapolate to depth from surface observations and geophysical parameters sensitive to temperature are the most reliable within the mantle where compositional variations are small. Elevation on the other hand, responds to thermal buoyancy and is easy to measure. Elevation variations largely reflect differences in the integrated thermal state of the lithosphere once we account for compositional buoyancy. To correct for crustal composition, crustal columns are normalized for deviations in crustal density and crustal thickness from a reference model via a simple isostatic correction.

By combining compositionally corrected elevation with surface heat flow observations, we can estimate the integrated crustal heat generation using simple thermal models. We estimate a radiogenic heat flow through the Australian lithosphere approximately 2.5 times higher than the global average for much of the eastern half of the continent. Furthermore, we suggest that elevated heat production is also likely responsible for most of the heat flow variations across the continent. An independent assessment of K, U, and Th concentrations from global geochemical databases also yield an estimated 3 times higher heat production for the Australian lithosphere, regardless of composition. Using heat production estimates from global geochemical databases, we derive an empirical relationship with seismic velocity to estimate the vertical variations in heat production across the continent. Combining these two independent methods, we are able to significantly improve our ability to estimate heat production, and therefore, temperature throughout the lithosphere. Additionally, this method gives us the ability to predict surface heat flow in regions without heat flow determinations and improve geodynamic models reliant upon temperature.

## Uncovering the petrophysical properties, mineralogy and geophysical expression of the Mount Colin and Kalman Cu-Au deposits, Cloncurry, QLD.

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The aim of the Uncover Cloncurry project is to provide petrophysical, geochemical and geophysical insights that will assist future exploration, under cover, on the fringes of the Mount Isa Inlier. Part of the project, discussed here, is focussed on detailed evaluations of a range of different deposit types with variable host lithologies, mineral assemblages, structural controls and geophysical expression. In this study we examine the petrophysics of the Mount Colin and Kalman deposits, both located west of Cloncurry, and explore some of the relationships between mineralogy, geochemistry and geophysical properties. Measurements of density (ρ), magnetic susceptibility (K) and remanent magnetisation (J) were made using a Metler Toledo MS204TS analytical scale, an Agico MFK1 kappabridge magnetometer and a CSIRO custom-made 2-axis flux gate spinner magnetometer respectively.

Mount Colin is a Cu-Au skarn sitting within a sillimanite facies sequence, but the deposit displays greenschist facies retrograde mineralogy. It is hosted within the eastern limb of the Mary Kathleen syncline, is oriented N-S and is bounded to the north and south by the Cameron and Fountain Range Faults. The deposit has low susceptibility, commonly < 0.0015 SI, reflecting its magnetite-poor mineralogy. NRM measured in the Mount Colin deposit is generally weak, with NRM commonly < 0.05 A/m. Where NRM is < 0.05 A/m two distinct linear trends can be observed between NRM and magnetic susceptibility, one indicative of pyrrhotite enrichment and the other indicative of magnetite enrichment. Tescan Integrated Mineral Analyser (TIMA) geochemical analyses illustrate that pyrrhotite occurs as thin stringers (<0.02mm), within the larger chalcopyrite grains. This grain architecture is favourable for stable remanent magnetisation and corresponds to the highest Q ratios measured (up to 14). The remanent magnetisation directions were oriented steeply downward in the SE, further expressed by a subtle negative magnetic anomaly. The magnetite present is limited to one sample, and displayed a drilling induced overprint, indicating unstable remanence.

Kalman, which sits 62km SE of Mount Isa, contains Mo-Re-Cu-Au mineralisation identified as intrusion-related hydrothermal in style. It is located along the Pilgrim Fault Zone and is hosted within the Corella Formation, which has been locally metamorphosed to amphibolite facies. Mineralisation is located adjacent to the intersection of sub-parallel 060° trending fractures and two N-S trending brittle-ductile deformation zones within the Pilgrim Fault Zone. The susceptibility of samples from Kalman is either strong (0.04-0.1 SI; associated with magnetite in mafic host rocks) or very weak (<0.038 SI; calc-silicate host rocks and ore zone). The ore zones in general are only very weakly magnetic, as the iron is contained in pyrite and chalcopyrite (as indicated by TIMA imagery) rather than within magnetite or pyrrhotite. However, specimens KMN015 and KMN028 are heavily sulphide enriched, as confirmed by their densities of 3.2g/cc and 4.0g/cc.

NRM measurements from Kalman are generally weak, with most specimens having negligible values and erratic directions. However, after low temperature demagnetisation, Mt-rich specimen returned 40%-80% lower intensities, and drilling parallel directions, thus indicating soft magnetisation in the magnetite. Not surprisingly then, the magnetic anomaly at Kalman does not coincide with mineralisation but with a relatively thick, sub-vertical mafic horizon

## Creating regional gravity images in South Australia

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A fundamental technique in geological exploration is the interpretation of gravity images. Images of sampled gravity data are generally created through a process called gridding. In South Australia over 1000 gravity surveys exist in the public domain. Creating a single coherent image of all surveys is an ongoing challenge. Individual surveys may contain errors due to gravity meter calibration, different elevation measurement techniques, user error, and processing errors. Adjacent surveys are likely to have been acquired under different conditions, resulting in over 1000 gravity surveys that do not merge with their neighbouring surveys; rather like a jigsaw puzzle where the shapes match but the pictures on individual pieces don't match. As well as the differences in individual survey data, there are also issues in the gridding algorithm itself. Generally, gridding algorithms assume that samples are equally spaced. At the state-wide scale this assumption is incorrect, as sample spacing can vary from 2 metres to 7 kilometres (in South Australia). This inconsistency creates artefacts in the final images that are geologically irrelevant, but can be mistaken for geological information.

We have experimented with two different techniques to create a regional gravity grid in South Australia. Common to both techniques is an initial 'tidy-up' of the spatial points: removing points within a certain distance to each other, and removing select points from overlapping surveys. Grid quality was visually assessed using derived products such as a first vertical derivative or residual image.

The first technique attempts to level the individual surveys – that is undertake a DC shift in values – to best match adjacent surveys. The result is further gridding artefacts: visible boundaries between the surveys and apparent features following the configuration of the gravity stations that could be (incorrectly) interpreted as linear geological features. The second technique involved resolving near-coincident station points that caused the minimum curvature algorithm to produce steep gradients within the interpolation that were clearly incorrect, and then iterating between passes of minimum curvature gridding and visual verification and removal of station points that clearly exhibited calibration or drift issues. This produced a final result that exhibited negligible effects of variable station density or minimum curvature artefacts.

All resulting grids displayed station location artefacts, which became apparent when viewing a first vertical derivative. The artefacts produced by the second technique were not as sharp as those produced using the first technique and the processing methodology of the second technique has reduced the number of artefacts produced by station configuration, overlapping and in-filled surveys making it geologically plausible.

## National Exploration Undercover School (NExUS)

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We present details of a new Minerals Tertiary Education Council (MTEC) initiative known as the National Exploration Undercover School (NExUS) to provide world-class training in mineral exploration. The program will start at the end of November 2016, and will be run over a three-week period. NExUS is centred around addressing the four key themes identified by UNCOVER as being the major knowledge areas to improve the success rate of tier 1 and 2 mineral system discoveries, particularly for areas of cover. Under each theme, the advanced discipline skills identified by MTEC are examined to highlight how they relate to the UNCOVER priority themes. The primary outcome of the program is that students understand the challenges and opportunities of mineral exploration in Australia into the future, and have knowledge of the tools required to address these problems.

The program will be a mixture of classroom, laboratory and drill core activities in the first week. NExUS will be run at the new South Australia Drill Core Reference Library at the re-developed Tonsley site in the southern suburbs of Adelaide. The Drill Core Reference Library includes a small conference room and a visualisation suite that will provide students with state-of-the-art facilities and hands-on experience. The second week will be held at Strathalbyn in the Adelaide Hills, and focuses on practical mineral exploration with the Deep Exploration Technologies CRC at Brukunga and in partnership with Hillgrove Resources at the Kanmantoo Copper Mine and nearby exploration targets. The final week will be based on Yorke Peninsula with Rex Minerals at the Hillside deposit, and other under cover targets. The aim will be to develop ongoing geophysical and geochemical sampling programs that will add from one year to the next.

Students from any University in Australia will need to apply for entry, with supporting evidence of interest in mineral exploration, and with references. Numbers will be limited to 30 placements in the first instance and thus attendance at NExUS will be competitive and prestigious. Applicants can be in the final year of BSc undergraduate study, at Honours level or at PhD and Masters levels; professionals in mineral exploration are also encouraged to apply. The program is not formally assessed, but feedback will be provided to both the students and their host University.

## Tabberabberan extended: Middle to Late Devonian contraction in the eastern Tasmanides

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The mid Devonian Tabberabberan Orogeny has long been recognised as characteristic of the Lachlan Orogen, affecting several domains across much of its width. Shortening, producing folds and associated thrust/reverse faults, is recognised in Silurian to Devonian successions including the Melbourne Zone and also has overprinted earlier structures in some domains. Timing constraints indicate some domains were affected around 400 Ma (Cobar Basin, Currowong Syncline) whereas elsewhere constraints are less definitive and shortening is more broadly late Early to Middle Devonian.

A tectonic event of similar age is recognised for the southern New England Orogen positioned immediately to the east. An older assemblage of Early to Middle Devonian age, widely regarded as oceanic and allochthonous, is separated by a basin margin unconformity from a younger assemblage of Late Devonian-Carboniferous age. Biostratigraphic control places the unconformity as Frasnian.

The Mossman Orogen of the northern Tasmanides also experienced Devonian contraction, which intensely deformed its outboard parts consisting largely of turbidites and regarded as a subduction complex. Deformation involved folding with axial plane cleavage development and thrust faulting. Greenschist metamorphism is ubiquitous. In its northern, Hodgkinson Province, syntectonic granites of the Mount Formantine suite intruding deformed turbidites have recently been redated as Frasnian (376 and 379 Ma). The age of the deformed turbidites from detrital zircon for its southern Broken River Province, combined with biostratigraphic control for unconformably overlying and undeformed Clarke River Basin strata constrain the timing of deformation as post Eifelian (391 Ma) and pre middle Tournaisian. The inboard part of the Broken River Province contains a thick sequence of richly fossiliferous shallow marine to terrestrial strata of Devonian and Carboniferous age. Devonian tectonism involved only open folding and a slight angular unconformity of Frasnian age is recognised. Based on these relationships, orogenic deformation affected the Mossman Orogen in the Frasnian (about 376 Ma).

The northern New England Orogen also experienced a Late Devonian event. A regional unconformity separates sedimentary assemblages as young as late Givetian from those of Frasnian age. The older assemblage is viewed as oceanic and allochthonous. Its strata have been weakly folded prior to development of the unconformity. It is intruded by the Mount Morgan Tonalite which is truncated by the unconformity, and dated at 378 Ma. On this basis, the weak deformation can be assigned as Frasnian (~ 375 Ma) and coeval with shortening in the Mossman Orogen.

Inliers of Devonian rocks, and those of the Burdekin and Adavale basins show that Devonian tectonism in general did not affect rocks of the Thomson Orogen to the west of the Mossman and northern New England systems. However open folding of this generation is indicated for Early Devonian strata of the Ukalunda Shelf on its eastern margin, unconformably beneath Late Devonian cover.

Late Early to early Late Devonian tectonism was common to the eastern Tasmanides. It registers a shared episode of orogenesis to which the name Tabberabberan is best applied.

## **Geological Heritage in South Australia**

**Hiern, Noel**

*Geological Society of Australia, SA Division Geological Heritage Committee*

Systematic recording of the State's geological heritage began in 1966 when the South Australian Division of the Geological Society of Australia appointed a Sub-committee to 'promote the preservation of geologically significant areas in this state, especially those important for teaching and research, and to prepare files recording data about these places' (Branch 1977).

Aided by grants totalling about \$80,000 from the National Estate Grants Program until it was terminated in June 2000, by August 2002 the Sub-committee had compiled nine Parts of 'Geological Monuments in South Australia' describing over 400 sites with significant geological and palaeontological features. In March 2008, *Geological Monuments in South Australia, Parts 1–9*, was published as a DVD (Hiern & Cowley 2008).

Initially there was no need for a mechanism to select geological heritage sites for inclusion in the GSA record because there were many well known places of acknowledged scientific value which could be designated by the Sub-committee with the modest funds available from the grants. Selection of the Lake Eyre Basin, which spans a large area with a widespread structurally simple stratigraphic sequence, provided an opportunity to devise an objective assessment system based on the degree to which various key attributes are displayed. (Hiern & Krieg 2012).

Using a model suggested by the Sub-committee, the late Graham Krieg recognised 96 potential heritage sites in the area and devised a system to assess these in terms of the presence or otherwise of seven criteria he considered to be essential attributes for heritage status. Each site was then ranked on a merit scale of 5 points for an outstanding display of each attribute present, down through excellent, good, fair to 1 point for poor.

After each site was assigned a score of the percentage of the maximum merit points available from the criteria identified to be present, Krieg found a clear separation of 24 sites having a score of 67% or greater, with the remainder falling considerably below this. These 24 high scoring sites, together with 3 below the 67% score but with special landscape and tourist attractions, were selected for designation as geological heritage sites and described in detail in Part 9 of the *Geological Monuments in South Australia*.

## Tessellations – a new tool for interpreting numerical drill hole data

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A plethora of new and improved sensors for measuring drill hole samples and down-hole logs are producing increasing quantities of data for characterising subsurface geology. This new data is replacing the traditional visual log produced by the geologist at the drill rig. However, we are lacking tools for the geologist to interpret this wealth of data. New data interpretation tools need to be automated or semi-automated to reduce time and subjectivity of interpretation; however, they must also allow the geologist to control the output so that it is suitable for its intended purpose and can incorporate expert knowledge. This presentation is an overview of a newly developed method for automated spatial domaining of 1D data, called a tessellation.

The tessellation incorporates mathematical methods that can be used to identify geological boundaries from a 1D data series. These boundaries can be plotted at a range of scales using a scale-space plot, allowing the geologist to simultaneously identify large and small scale geological features. Furthermore, the plot can be filtered to remove noise and unwanted weak variation. Filtering is also useful for spatially lumping geological units for simplified 3D geological modelling (i.e. upscaling). In order to facilitate classification of geological units using multiple variables, the tessellation of each variable can be combined at specific scales. Methods have also been developed to identify the nature of boundaries, whether they are sharp or gradational, and the location of the start and end of gradational trends.

The tessellation method has been extensively tested on synthetic data, geochemical data and natural gamma data. It produces visual results which are intuitive for a geologist to interpret. It has potential for applications in automated logging of exploration drill holes, lumping and classification of geological units for 3D modelling, and identifying location and sharpness of boundaries for grade control.

Acknowledgements: this work has been supported by CSIRO Mineral Resources and the Deep Exploration Technologies CRC.

## **Taking Exploration Geochemistry to greater depths towards 4D landscape geochemistry of Australia's cover**

**Steven M. Hill**

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Regional geochemical surveys offer the potential advantage of providing a measurement of the 'fertility' of an exploration target that eventually has to be defined by its geochemical enrichment if it is to be a high-grade mineral deposit. Yet despite this advantage, many mineral explorers are exclusively, or almost exclusively, basing their exploration programs on drilling geophysical "bumps" in regional data sets, with little regard for geochemical analysis. Perhaps there have been some shortfalls in how geochemical techniques have been developed and promoted for exploration? This presentation examines some of the limitations of previous testing and promotion of geochemical techniques for exploration through cover. It shows how there has been a detrimental fixation for researchers to discover seemingly magical geochemical techniques that promise to be a 'silver-bullet' for exploration. In many cases techniques are promoted where they have only been tested on a tightly constrained transect across previously discovered and drilled mineralisation. In other cases, explorers have hoped to extend the lower thresholds of analytical detection, while at the same time have not led the development of better and representative sampling techniques and constraining variables such as lithological controls and landscape settings on the meaning of geochemical results. There has been less emphasis on repeatability of results as well as ensuring that expressions of buried mineralisation could in fact be made from surveys designed to cover frontier regions where 'background' values prevail and underlying mineralisation occurrences are unknown. Instead greater emphasis is called for an understanding "landscape geochemistry" in four-dimensions, particularly providing geochemical data on cover materials in Australia. This provides the opportunity to use the geochemistry of the cover to enhance mineral exploration rather than sampling viewing the cover as an impediment.

## HyLogging Unconventional Petroleum Core from the Cooper Basin, South Australia

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The Cooper basin is currently Australia's premier onshore hydrocarbon producing province and hosts a range of unconventional gas play types, including the very extensive basin-centred and tight gas accumulations in the Gidgealpa Group, both shallow and deep dry coal seam gas associated with the Patchawarra and Toolachee formations, as well as the shale gas plays in the Murteree and Roseneath shales. Characterisation of mineralogical properties of shales is critical to hydraulic fracture design and development of unconventional hydrocarbon resources. Properties are sensitive to variations in mineralogy, especially clays and historically, acquisition of a suite of rock mechanics analyses has been on a point source basis rather than on a continuous sampling approach which is uncommon. In this paper, a near continuous 382 m cored section comprising the Early Permian Roseneath and Murteree shales, the Epsilon Formation and the top portion of the Patchawarra Formation from Holdfast 1 well (DH261958) in the southern Cooper Basin was measured using robotic core scanning spectroscopy with automated mineral identification. HyLogger™ incorporates visible, near infrared, shortwave infrared and thermal infrared hyperspectral measurements recorded every 0.8 cm along the core at the rate of approximately 1 m per minute. These data are co-registered with a high resolution image and a laser profile of the core. XRD and thin section petrology from Holdfast 1 well completion report provided relative proportions of minerals including quartz, kaolinite, dickite, muscovite, illite, chlorite and siderite that enabled the modelled versus actual mineralogies to be constrained in the Thermal Infrared (TIR) with a correlation coefficient of 0.85 for quartz, 0.79 for muscovite and 0.68 for kaolin. Illite and siderite did not enjoy the same degree of correlation. However, in the Short Wave Infrared (SWIR) there was no meaningful correlation, particularly in the identification of siderite. This result is consistent with results from other carbonaceous HyLogged cores from the Cooper Basin. HyLogger logging, when integrated with other petrophysical and analytical core data, provides a useful tool to better understand unconventional reservoirs and may assist in identification of permeability sweet spots.

## Dates and dynamics – Snowball Earth comes of age

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Due to ice albedo feedback, Earth could exist in any of three discrete climate states under identical radiative forcing—no ice, small ice or all ice. The all-ice state, popularly known as Snowball Earth, is self-terminating because CO<sub>2</sub> from normal volcanic outgassing slowly accumulates in the atmosphere (and ocean) until the greenhouse effect overwhelms the high albedo, causing rapid total deglaciation. These ideas were applied to the Cryogenian period to account for glaciation even of carbonate platforms, which occupied the warmest parts of the surface ocean and where no mountains existed. Cap carbonate sequences, unique to Cryogenian glaciations, resulted from carbonate dissolution in response to ocean acidification as CO<sub>2</sub> rose, followed by carbonate reprecipitation due to ocean warming and deacidification in the glacial aftermaths. As pelagic carbonate was absent, the dissolved carbonate was provided by glaciers. Climate theory predicted that Snowball glaciations (cryochrons) would be long-lived and their terminations synchronous on different continents. These predictions are borne out by recent studies. U-Pb and Re-Os ages for tephra zircon and sedimentary organic matter, respectively, indicate that the Sturtian cryochron lasted for ~58 Myr and terminated at ~659 Ma in Australia, South China, Mongolia and Laurentia. The Marinoan cryochron terminated at ~635 Ma in Australia, South China, Laurentia and southern Africa. Some have proposed that the Sturtian represents multiple discrete glaciations, but only one Sturtian cap carbonate exists in any area and wherever dated it is ~659 Ma. The prediction that extreme atmospheric CO<sub>2</sub> levels existed during and after a cryochron is supported by carbon, boron, calcium and triple-oxygen isotope data from multiple cratons. Furthermore, models increasingly reconcile geological observations with Snowball ice sheets, which were dynamic, sensitive to orbital forcing, prone to dry valley development and subject to enhanced seasonality at all latitudes. A paleontological prediction, that cryochrons and their aftermaths would result in irreversible evolutionary change, is less well supported. Eukaryotic (sterane) biomarkers indigenous to pre-Sturtian oils and bitumens are markedly different from Ediacaran ones. Inferentially, green algae replaced red algae as the dominant eukaryotic primary producers. On the other hand, cellular fossils imply that certain eukaryotic crown groups—red algal, green algal, testate amoebozoan and possibly other protistan groups—evolved before the Sturtian and did not go extinct. Sterane biomarkers suggest that stem group metazoans also existed before the Sturtian, and demosponges before the Marinoan. Where could they have survived? Models suggest that ice-free dust sources existed throughout the cryochrons, and that most of the global dust flux accumulated as cryoconite (dark dust suffused with organic matter) on the surface of the sea glacier in the equatorial ablation zone. Flux estimates imply 4-40 m Myr<sup>-1</sup> of cryoconite accumulation. Such a flux would rapidly saturate the surface, producing vast pans of supraglacial meltwater from solar absorption. Cryoconite removal by meltwater flushing through moulin creates a stabilizing feedback that maintains a warm ice surface without triggering deglaciation. Cryoconite pans may have covered <60 million km<sup>2</sup>, making Snowball Earth more biotically benign than previously assumed. The Snowball Earth concept continues to evolve.

## New imagery for Port Phillip Bay and Yarra Delta drilling corroborates late Holocene channelling and evidence for bay-drying between ~2800 yr BP and ~1000 cal. yr BP.

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New swath mapping surveys have recently been carried out by Port of Melbourne Corporation over the northern and western sides of Port Phillip bay. They reveal wide river-channels cut ~5m deep into the bay floor. C<sup>14</sup> shell dates from sediment cores indicate channel infill ages range from <491 to >9274 cal. yr. BP. A date-hiatus exists between ~869 and 2880 cal. yr. BP and represents a recent channeling event. This recent channeling suggests the central basin down to -22m was sub-aerially exposed during the late Holocene at a time of stabilized present sea-levels outside the bay. During the last 10-year “millennium” drought period (~1999 to 2009), 20% less fresh water than normal (~2.2 km<sup>3</sup>/yr.) was input into the bay, causing local increased salinity. Were it not for the bay connections to Bass Strait through narrow Nepean bay bar tidal channels, evaporation rates for the bay (normally ~2.3 km<sup>3</sup>/yr.) could have seen bay levels fall. To produce bay floor river channel features, it has been proposed that sand blocked the Nepean bar channels for possibly 1000 years, disconnecting bay levels from open ocean levels (Holdgate *et al.* 2011). Port Phillip bay became an evaporating lake, and the Yarra and Werribee rivers incised new channels across this progressively exposed muddy lake floor. The late Holocene channels incise into >4.0m of underlying early to middle Holocene marine to non-marine mud and muddy sand. In turn the late Pleistocene channeling incises more than 24m into sub-bottom acoustically refractive stiff clays of the Plio-Pleistocene Fishermans Bend Silt.

Using over 500 civil engineering geotechnical bores across the Yarra Delta, maps have been made of the Holocene and pre-Holocene surfaces. This compilation identifies that a comparable stratigraphy to the bay exists in the Yarra Delta ie. marine and lagoonal shelly sediments of the Coode Island Silt and barrier sands of the Port Melbourne Sand infill last-glacial channels cut into Plio-Pleistocene Fishermans Bend Silt. New C<sup>14</sup> shell dates from the Coode Island Silt and Port Melbourne Sand have shown an age range between 8341 and 2760 cal. yr. BP. These sediments infilled and inundated former swamplands that covered low-stand river valleys of the Yarra and Maribyrnong Rivers across Port Melbourne and South Melbourne. After 2760 cal. yrs. BP active sedimentation in the delta ceased as base-levels fell, river sediments bypassed the delta because of falling bay levels. The Yarra and Maribyrnong River courses also shifted progressively westwards behind growing beach barriers of the Port Melbourne Sand.

The Port Phillip and Yarra Delta environment was fully marine between ~7500 and ~4000 cal. yr. BP with bay levels peaking at +2.0 m based on the upriver extent of Coode Island Silt. Bay levels fell between ~2880 and ~1000 cal. yr. BP due to Nepean bay bar blockages, before fully marine conditions were restored. The Holocene “fluctuating bay levels” has widespread implications on Port Phillip’s water balance, salinity, Yarra Delta sedimentation, pre-European climatic events, aboriginal occupation, tribal boundaries and legends of bay flooding.

*Holdgate, G. R., Wagstaff, B. and Gallagher, S. J. (2011) 'Did Port Phillip Bay nearly dry up between ~2800 and 1000 cal. yr BP? Bay floor channelling evidence, seismic and core dating', Australian Journal of Earth Sciences, 58: 2, 157 — 175.*

## Burial and exhumation of late Palaeozoic land surfaces in southeastern Australia

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The antiquity of the Australian landscape has long been the subject of debate, with some studies inferring extraordinary longevity ( $>10^8$  Myr) for some subaerial landforms dating back to the early Palaeozoic. A number of early Permian glacial erosion surfaces in the Fleurieu Peninsula, southeastern Australia, provide an opportunity to test the notion of long-term subaerial emergence, and thus tectonic and geomorphic stability, of parts of the Australian continent. Here we present results of apatite fission-track analysis (AFTA) applied to a suite of samples collected from localities where early Permian glacial erosion features are developed. Our results indicate that the Neoproterozoic-lower Palaeozoic metasedimentary rocks and granitic intrusions upon which the glacial erosion surfaces generally occur were exhumed to the surface by the latest Carboniferous-earliest Permian, probably as a far-field response to the intraplate Alice Springs Orogeny. The resulting landscapes were sculpted by glacial erosive processes. AFTA results suggest that the erosion surfaces and overlying Permian sediments were then heated to between ~60 and 80°C, which we interpret as recording burial by a Permian-Mesozoic sedimentary cover, ~1-2 kilometres in thickness. This interpretation is consistent with both existing thermochronological datasets from this region, and with palynological and geochronological datasets from sediments in offshore Mesozoic-Cenozoic-age basins along the southern Australian margin that indicate substantial recycling of Permian-Cretaceous sediments. AFTA suggests that the exhumation which led to the contemporary exposure of the glacial erosion features probably began during the late Cretaceous-early Paleogene, during the initial stages of compressional shortening that has shaped the Mt Lofty and Flinders Ranges in South Australia. Our findings are consistent with several recent studies, which suggest that burial and exhumation has played a key role in the preservation of Gondwanan geomorphic features in the contemporary Australian landscape.

## **Insights into the nature and extent of sedimentary basins underlying the Eucla Basin from reprocessing and interpretation of the 13GA-EG1 Eucla-Gawler Seismic Survey**

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One of the main objectives behind the acquisition of the 13GA-EG1 Eucla-Gawler Seismic Survey was to image the crustal architecture of the geology underlying the Eucla Basin, and to establish the subsurface extent of this and older basins, such as the Bight, Denman and Officer basins. The distribution of the Cenozoic Eucla Basin is reasonably well constrained offshore by petroleum industry seismic reflection datasets, but a paucity of both seismic data and drilling penetrations onshore mean that the thickness of the basin, and the presence of older sedimentary units sandwiched between the Eucla Basin and cratonic basement, is poorly understood. Older sedimentary sequences whose presence beneath the Eucla Basin have been confirmed by widely-spaced drilling, but whose thickness, extent and character are uncertain include Lower Cretaceous clastic units that form the northern extent of the prospective Bight Basin, Upper Palaeozoic (?Permian), glacially-influenced sediments ascribed to the Denman Basin, and the Neoproterozoic-Lower Palaeozoic Officer Basin. Initial interpretations of the eastern part of 13GA-EG1 indicate that the combined Eucla and Officer basins may reach a maximum thickness of ~1.8 s TWT over the Coompana Province, though there is large uncertainty associated with this interpretation due to the possible presence of seismic multiples. This contribution reports on the insights into the thickness of the Eucla Basin and the basins that underlie it based on reprocessing of the western section of 13GA-EG1, with the shallowest ~2 s of the profile specifically targeted in order to enhance seismic reflectivity, and thus enable more confident interpretations.

## 13GA-EG1 Eucla-Gawler Seismic Survey – Acquisition and Processing

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The 834 km Eucla-Gawler 2D land vibroseis reflection seismic survey was acquired from Haig WA, November 2013, and continued east along a track parallel to the Trans Australian Railway ending at Tarcoola, SA, February 2014.

The deep crustal seismic survey was proposed to image the crustal architecture underlying the Eucla Basin and its relationship to the Gawler Craton to the east. The data may also indicate large structural zones that may have provided fluid pathways for mineralisation.

The seismic data were collected using 3 or 4 vibroseis 30 tonne trucks, shaking for 12 seconds 3 times for each vibe point, i.e. 4 trucks x 3 sweeps x 30 tonnes = 360 tonnes vibrating on the surface, to generate enough energy to image crustal structures down to the Moho through a 12 km spread of geophones.

The seismic reflection processing was complicated and continually tested and adjusted due to constant variations in the geology along the line. Variations in surface elevation, weathering layer depth and weathering layer velocity can degrade the final seismic image and these effects were removed using near surface refractor models, which also show the basin and weathering layers depth to bedrock and velocity variation along the seismic line.

For the western part of the seismic line, the average refractor velocity for the base of the Eucla Basin is 5870 m/s, typical of basement. Near the WA and SA border the bedrock refractor layer drops deeper and another basin layer begins with an average refraction velocity of 4700 m/s, indicating a very fast sedimentary sequence beneath the Eucla Basin. In the Gawler section of the seismic line, the base of the surface weathering layer has an average refractor velocity of 5800 m/s, similar to the west.

Normal moveout (NMO) correction was applied with stacking velocities which best image the reflections. The stacking velocities clearly show the extent and variation in velocity and depth of the near surface weathering and variations in the bedrock velocities down to about 20 km depth.

Dip moveout (DMO) correction has the effect of correcting the NMO to account for different dips occurring along the line, enhancing dipping structures. Many dipping structures and faults are imaged throughout the whole line, at all depths up to the base of weathering. Migration was applied to move the dipping structures to their correct location on the final images. Faults can be easily identified on the pre-migration stacks as large diffractions.

In some regions, the data appeared to have low amplitude and incoherent reflectivity and this has some correlation with thick weathering or sedimentary layering at the surface. In other areas multiples of reflections were seen due to energy reverberating between the hard limestone in the near surface and the hard basement.

This seismic data provides new insights into unknown geology in this area. Weathering, basins, crustal architecture and the Moho are imaged.

## New geochronological, geochemical and Pb isotopic data for Tasmanian granitoids: possible controls on Sn mineralisation

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Large volumes of Mid-Palaeozoic granitic intrusions were emplaced across Tasmania, and some of them are associated with world class Sn–W deposits. Previous studies have focused mainly on the relationships between granite petrogenesis and source rocks, and rarely on fertile versus infertile granitic magmas, or on the geochemical controls on Sn–W mineralised granites. This study investigates the George River Granodiorite, Mt. Pearson Granite, Grant Point, Bicheno Granite and Coles Bay Granite along the eastern coast, and the Housetop, Meredith, Pine Hill, Heemskirk and Pieman Heads granites exposed in western Tasmania. Whole-rock analyses show that these Tasmanian granites are typically grouped into I-type and S-type granitic rocks and that no A-type granites occur in Tasmania. The George River Granodiorite with hornblende-biotite-plagioclase association has a zircon LA-ICP-MS U-Pb age illustrating that it is one of the oldest I-type magmas in Tasmania, and that it intruded prior to the Tabberabberan Orogeny. The Grant Point Granite has a mineral assemblage (muscovite-biotite-K-feldspar), peraluminous affinity, chemical patterns of trace elements and zircon U-Pb dating that indicates it is an S-type pluton emplaced coeval with the George River Granodiorite. The metaluminous I-type Mt Pearson Granite also intruded prior to the Tabberabberan Orogeny. The peraluminous I-type Coles Bay Granite has a U-Pb age of  $388 \pm 7$  Ma. It is one suite of the granitic plutons widespread in eastern Tasmania that formed after the collision of eastern and western Tasmanian terrains around 390 Ma. The western Tasmanian granites mostly intruded from 374 to 360 Ma, and are moderately to strongly fractionated, including the Housetop Granite, Meredith Granite, Pine Hill Granite, Pieman Heads Granite and Heemskirk Granite. These granites are associated with several world-class Sn–W deposits, and were emplaced during the post-collisional stage of the Tabberabberan Orogeny. Pb isotopic compositions of K-feldspars from the studied granites define a narrower range than the whole-rock Pb isotopes of respective granites, particularly for the highly fractionated intrusions. These isotopic results, combined with previous studies, suggest that those moderately to strongly differentiated granites in western Tasmania had been highly contaminated by crustal rocks that may include the Proterozoic amphibolites in lower crust and Neoproterozoic to Cambrian sedimentary rocks. Similar to Sn-mineralised granites worldwide, the Sn-bearing granites in eastern and western Tasmania formed on a post-collisional and extensional margin, a favourable environment to deposit stanniferous source rocks through intensive chemical weathering. Prolonged fractional crystallisation, low oxygen fugacity and enrichments of volatiles (B, F, Cl, Li etc.) were fundamental factors to promote Sn metal extracted and enriched in magmatic – hydrothermal fluids exsolved from the crystallised felsic magmas. Additional factors, such as a broader variety of reactive host rocks in western Tasmania and a greater degree of unroofing of the eastern Tasmanian granites have contributed to the world class Sn–W deposits being associated mostly with the western granites with small exposures, rather than with the large granitic batholiths in eastern Tasmania.

## Volatile exsolution in felsic magmas: evidence from boron, oxygen and strontium isotopic analyses of tourmalines from western Tasmanian granites

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The Heemskirk Granite and Pieman Heads Granite crop out along the western Tasmanian coastline. The two Devonian-Carboniferous granites are characterised by abundant tourmaline-rich textures which are commonly exposed in their apical regions. These distinctive tourmaline- and quartz-rich textures can be divided into tourmaline patches, tourmaline orbicules, tourmaline cavities and tourmaline veins, as well as unidirectional solidifications textures (USTs), according to their morphologies, sizes, mineral assemblages and contact relationships with host granites. These textural features occur in discrete layers in the roof zones of granitic sills within the Heemskirk and Pieman Heads granites. Tourmaline patches commonly occur below a tourmaline orbicule-rich granitic sill. Tourmaline-filled cavities have typically developed above the tourmaline-quartz orbicules in the upper layer of the white phase of the Heemskirk Granite. Tourmaline veins penetrate all exposed levels of the granites, and have locally cut the tourmaline orbicules and cavities. The tourmalines are mostly schorl (Fe-rich) with minor fiotite, and commonly present distinctive compositional zonation patterns. In-situ SIMS analyses show that boron isotopic compositions ( $^{11}\text{B}$ ) of tourmaline have a broad range, from -21.7 ‰ to +4.1 ‰. Oxygen isotopes ( $^{18}\text{O}_{\text{v-SMOW}}$ ) of tourmaline vary between +6.5 ‰ and +14.9 ‰, similar to the  $^{18}\text{O}_{\text{v-SMOW}}$  range of quartz (+5.0 ‰ to +16.1 ‰) intergrown with tourmaline. The  $^{11}\text{B}$  and  $^{18}\text{O}_{\text{v-SMOW}}$  compositions are mostly consistent with magmatic-hydrothermal origins, with fluids derived from the granitic plutons. There is minor evidence that fluids from external sources (e.g., meteoric water, boron-bearing fluids from peripheral metasedimentary rocks) may have contributed to the formation of tourmaline-filled veins. Six tourmaline separates measured by multi-collector ICP-MS reveal that initial  $^{87}\text{Sr}/^{86}\text{Sr}$  compositions change from 0.719525 to 0.750317, indicating that their parental magmas were strongly contaminated by continental crust. Both B- and O-isotopic compositions of tourmaline increase sequentially from early-formed patches, orbicules, to cavities and late-stage veins. Because  $^{11}\text{B}$  preferentially fractionates into an aqueous fluid (or vapour) phase relative to a coexisting silicate melt, the elevated isotopic trends among various tourmaline-rich textures are interpreted to have been produced by magmatic-hydrothermal volatile exsolution during the final crystallisation stage of the granite intrusions. Volatile-rich hydrous fluids separated from the crystallising aluminosilicate magmas due to liquid immiscibility. Boron-bearing volatile bubbles migrated between grain boundaries within the crystallising melt. When the magmas solidified, the dispersed bubbles formed disseminated tourmaline patches that have B- and O-isotopes similar to the parent melt. Tourmaline orbicules with elevated B- and O-isotopic compositions are explained to be the products of boron-bearing vapour bubbles that buoyantly ascended upward and were localised in a sill layer above the tourmaline patches. Compared to tourmaline orbicules, the tourmaline cavities are more evolved isotopically, and they are probably associated with aqueous fluids what  $^{11}\text{B}$  is selectively fractionated into tourmaline-filled miarolitic textures. The progressive increase in Sr isotopic compositions of tourmalines from patch, orbicule, via cavity to vein in the Heemskirk Granite, provide evidence for evolved Sr sources incorporated into these tourmaline-rich textures.

## LA-ICP-MS U-Pb zircon ages of the Carboniferous volcanic and sedimentary rocks of the Songliao block, NE China: implications for the tectonic evolution of the eastern segment of the Central Asia Orogenic Belt

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The Songliao block is in the centre of NE China, located at the eastern segment of the Central Asia Orogenic Belt (CAOB). This block has been generally considered to suture with the Xing'an block during the Paleozoic along the Hegenshan-Heihe belt, which marked the closure of the Paleo-Asian Ocean and the amalgamation of NE China. However, the closure timing and the tectonic setting has not been fully elucidated due to the lack of the precise age dating for the volcanic and sedimentary rocks in the Songliao block. In this study, the LA-ICP-MS U-Pb zircon age analyses were conducted for a suite of volcanic and sedimentary rocks collected from the Carboniferous stratigraphic formations in the northern border of the Songliao block, in order to shed new light on the tectonic evolution of this area. Both the basaltic sample from the Baishan formation and the rhyolitic sample from the Hetaoshan formation show porphyritic textures with aphanitic groundmass and subhedral to angular plagioclase being porphyroblast. The magmatic zircons with clear oscillatory zonings from the basaltic and rhyolitic samples yield mean  $206\text{Pb}/238\text{U}$  ages of  $301\pm6$  Ma and  $318\pm9$  Ma respectively, which can be considered as the volcanic eruption ages. The sedimentary rocks from the Kunaerhe formation are mainly composed of quartz, lithic fragments, and rounded plagioclase, poorly sorted and cemented by the clayey groundmass, indicating the relatively short transportation distance. Detrital zircons of the sedimentary rocks are various both in morphology (prismatic, columnar, rounded) and in structure (oscillatory zoning, concentric zoning, nebulous rim, metamorphic rim, structureless), indicating their varied provenances. All the isotopic analyses for detrital zircons generate a relatively tight age-cluster, ranging from 316 Ma to 513 Ma. The youngest zircon age is  $316\pm6$  Ma (the apparent  $206\text{Pb}/238\text{U}$  age), which is consistent to the volcanic eruption age. Considering all data together, it can be proposed that (1) a volcanic event took place during the Late Carboniferous along the northern border of the Songliao block, which is most likely incurred by the subduction of the Paleo-Asian-Ocean; (2) the sedimentary rocks were formed in the volcanic arc environment and accepted the depositional materials directly from the arcs. Therefore, it can be concluded that the eastern segment of CAOB underwent oceanic crust subduction and formed arc-related basins during the Late Carboniferous period.

## **Detection of mineral system signatures through cover - A bigger picture**

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Australian researchers have long played a globally leading role in developing new approaches and technologies to support the minerals industry in exploration, most often through collaboration involving multiple organisations and with close industry engagement. UNCOVER can position Australian exploration geoscience research for an even stronger future of technology development that tackles the exploration through deep cover challenge.

As we move into exploring the deeper cover regions of Australia, we need to determine detectable signatures of buried mineral systems and ore systems from a number of varied sample media and with different technologies. Arguably, the challenge posed by the depth of cover to find the mines of the future is going to be in the 100s of m, given current mining practices from the surface combined with the economic realities. Firstly though, we need to know the extent of that thickness of cover, its stratigraphy, lithogeochemistry and physical properties. Comprehensive data that will in turn aid in more effective processing and interpretation of the regional data-sets collected e.g. magnetics, and increase confidence in our geological models of the sub-surface.

When it comes to testing, the DETCRC development of CT drilling plus associated real-time sensing tools provide for an exciting future in new approaches to regional drilling to enable detection of mineral systems at large scales. New research in measuring uncertainty using Bayesian approaches to geophysical interpretations of geological models is improving our knowledge of risk whilst providing us the ability to plan and efficiently reduce that uncertainty as we go. Quantifying the issue of magnetic remanence and its potential effect on our ability to locate and target anomalies is also now possible and a national remanence data-base will also assist us to develop the analytics to data mine regional data for depth to magnetic basement outputs. Finally, our ability to detect an anomaly rests not in the direct detection itself but in being able to place the data point into a regional geological context. For example, research on the geochemistry of the Fortescue Group volcanics assessing burial metasomatism effects has been undertaken so that we can position the industry to place perceived geochemical anomalousism from similar lithologies into a broader geological and indeed regional context. Similarly, in the Capricorn distal footprints project, this approach is being used for specific mineral chemical analyses and in the analysis of groundwater from farm bores. Although regional geophysics is commonplace we still face the challenge of having much less access to geochemistry from buried geology on a regional scale that could support such anomaly identification and to reveal the patterns across scales. One vision might be to unlock the vast industry held data of geochemical analysis to provide for such data, while targeted collection of new rock property data could then allow this geochemistry to be assessed into the regional geophysical data – a path to integration of geochemistry and geophysics with the tools to simulate, image and ultimately detect mineralised mineral systems (and their gradients) through cover.

## Taphonomy of leaf wax *n*-alkanes in soils: Field transect and experimental degradation experiment

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Leaf wax *n*-alkanes (C25-C35) are widely used biomarkers for terrestrial plants, but little consideration is given to the formation and modification (taphonomy) of sedimentary *n*-alkane accumulations in soils and sediments. Deposits of *n*-alkanes from plants become integrated into soil as a result of different factors including wind ablation acting on the leaves and leaf fall. Once deposited, leaf wax *n*-alkanes accumulate in the soils and can preserve in sediments for many millions of years. It has been hypothesized that the distribution (average chain length, or ACL) of *n*-alkanes in soils and sediments can provide insight into the types of plants present, as well as the conditions the plants were subjected to, at the time of deposition. Field and experimental studies were conducted to determine whether the *n*-alkane ACL signal recorded in soils is representative of the current plant species present, and to also determine how biodegradation processes occurring within the soils affect that signal.

To explore whether soil *n*-alkane ACL reflects the current plant community, modern plant and soil samples were obtained from a bioclimatic transect made up of a number of TERN biodiversity monitoring plots (AusPlots and TREND) across Australia. Samples of the top three dominant plant species (determined by % cover, n = 59) present at each plot and the surface soil (n = 20) at each plot had *n*-alkanes extracted and analysed for ACL.

Results from the bioclimatic transect field study show that using the top three dominant plant species at each plot, weighted by their *n*-alkane concentration, is an inadequate measure for predicting the measured ACL observed in the soils. This may be due to timing of sampling which may affect the dominant species present, due to ephemerality of different plant species. It may also be that percent cover is an inadequate representation of biomass of each species at each site. Also, percent cover of the top three dominant plant species at each site may not account for other *n*-alkane contributors outside of the hectare plots. As well as this, leaf waxes accumulate over an extended period and thus ecological shifts could affect the time-averaged signal recorded in the soils.

Further to this, we explored whether post-depositional modification of *n*-alkanes in soils accounts for the soils being unrepresentative of the dominant plants present. An experimental study analysing the effects of biodegradation of *n*-alkanes in soils over time was conducted utilising incubated soil samples mixed with a variety of different organic amendments, such as green waste, garden clippings, manure and other composts, obtained from CSIRO. Incubation of samples was halted by drying of the soil samples, preventing continued microbial activity. Samples at 0 months and 18 months were analysed for *n*-alkane ACL and concentration.

Results from the experimental study indicate that concentration of *n*-alkanes decreased markedly over the 18 month incubation period. Nonetheless, ACL remained quite steady over the 18 month period. Further to this, the carbon preference index (CPI), which indicates whether there is an odd-over-even predominance of *n*-alkane chain lengths present, showed no trend over 18 months. This is contradictory to the assertion that CPI decreases as a result of degradation and can be used as an indicator of *n*-alkane degradation. These results suggest that inputs to soils have a greater influence on *n*-alkane ACL than any post-depositional modification.

## 120 Myr of episodic mid-crustal metamorphism and fluid-rock interaction during the Alice Springs Orogeny: the Strangways Range, central Australia

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Garnet Sm-Nd and monazite U-Pb geochronology from the Strangways Range, central Australia, indicate that metamorphism and fluid-rock interaction in kilometre-scale mid-crustal shear zones occurred over a period of ca 120 Myr during the Palaeozoic intracratonic Alice Springs Orogeny (ASO). The shear zone samples span a region of approximately 5000 km<sup>2</sup> across the entire length and breadth of the Strangways Range. They transect ca 1700 Ma granulite facies metasediments and felsic gneisses, and are characterised by hydrous schist belts containing garnet-staurolite-biotite-muscovite-quartz ± kyanite ± sillimanite assemblages. The ages obtained in this study indicate that fluid-assisted metamorphism occurred within the shear zones at ca 445 Ma, ca 380 Ma, ca 360 Ma and ca 330 Ma, suggesting a protracted and episodic history of fluid-rock interaction during the ASO.

Garnet major element X-ray maps suggest multiple thermal events across this 120 Myr interval. Zonation patterns typical of a retrograde thermal history are associated with ca 445 Ma metamorphism in the eastern Strangways Range. In the western and southern regions, zonation patterns indicate prograde thermal histories at ca 380 Ma and ca 330 Ma, respectively. Mineral textures from the shear zones also suggest varying thermal histories: ca 380 Ma shear zones show late kyanite porphyroblasts while ca 330 Ma shear zones show late staurolite porphyroblasts. Initial *P-T* pseudosection modelling of a garnet-staurolite-biotite-muscovite schist from a ca 330 Ma prograde shear zone indicate peak metamorphism reached 6–7 kbar and 610–660 °C. Shear zone-hosted kinematic indicators across the Strangways Range are often ambiguous. However, in the eastern region, ultramylonitic shear zones with reverse-sense (NE-up) kinematics are truncated by ultramylonites with normal-sense (NE-down) kinematics. Monazite U-Pb geochronology from the normal-sense ultramylonites predominantly record ca 380 Ma metamorphism but also preserve single ca 445 Ma ages from some grains. In combination with the observed kinematics, this suggests that ca 445 Ma contractional faults were extensionally reactivated at ca 380 Ma.

The results obtained in this study suggest that structurally-controlled metamorphism and fluid-rock interaction were associated with multiple prograde thermal episodes and spanned almost the entire duration of the 450–300 Ma Alice Springs Orogeny. The spatial scale and regional dominance of hydrous schist belts transecting anhydrous basement, along with their protracted activity over ca 120 Myr, suggests a substantial and enduring source of fluids during the ASO. Conceivably, the spatial and temporal evolution of the ASO shear zones is linked to the availability of fluids in the mid-crust. Initial results from oxygen and hydrogen isotope analyses show a shift to heavier <sup>18</sup>O and D values in the fluid-affected shear zones when compared with their adjacent granulite facies wall rocks. This suggests that deeply circulated basinal brines may be the source of fluids during metamorphism. The consistency of heavy <sup>18</sup>O and D values from numerous shear zones recording varying metamorphic ages suggests an enduring source of basinal fluids during the ASO. The data presented in this study provides a foundation for further research into the source of fluids and the role of fluid-rock interaction in intraplate reactivation.

## Re-assessing the Hunter-Bowen Orogeny: insights from Gympie Terrane deformation

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Widespread Permian to Triassic deformation affected eastern Australia during the so-called Hunter-Bowen Orogeny. The underlying cause of this period of tectonism remains unclear, but previous suggestions include accretion of a supposedly exotic island arc (Gympie Terrane) and flat-slab subduction in response to the arrival of a buoyancy anomaly at the trench. At a wider scale, Permian-Triassic orogenesis is not restricted to eastern Australia, in fact it is recognised along the entire southern margin of Gondwana. However, efforts to understand this major orogeny are hampered by the lack of robust constraints on the style, timing, intensity, and distribution of deformation. One place where the effects of Permian to Triassic deformation in eastern Australia may be studied directly is the Gympie Terrane in southeast Queensland, which contains a nearly complete record of volcanism and sedimentation that spans the transition from earlier rifting into widespread contractional deformation during the Hunter-Bowen Orogeny. However, the structural geology of the Gympie Terrane are yet to be fully described and the relationship to regional tectonic events is unclear.

Here we present the results of structural mapping of the Gympie Terrane, complemented by a synthesis of Permian to Triassic deformation in eastern Australia and other Gondwanan fragments that are now dispersed in the SW Pacific. Heterogeneous deformation appears to be a major characteristic of the Hunter-Bowen Orogeny at the continental scale, resulting in major variations in deformation intensity both along and across the fold belt. Our results show that the final pulse of Hunter-Bowen deformation at ~235-230 Ma caused intense deformation in the Gympie Terrane and strongly affected surrounding regions. However, other pulses of regional Hunter-Bowen deformation at ~270-260 Ma and ~253 Ma appear to be completely absent within the Gympie Terrane. Previous suggestions that accretion of the Gympie Terrane caused the Hunter-Bowen Orogeny are difficult to reconcile with the observed structural history of the Gympie Terrane and distribution of deformation in eastern Australia. Coeval deformation in the Ellsworth and Pensacola Mountains (Antarctica), Cape Fold Belt (South Africa), Falkland Islands, and La Sierra del la Ventana (Argentina) suggests that the likely geodynamic mechanism was much broader in scale and was possibly related to changes in global plate configuration and increased convergence rates.

## **The Strategic Plan of the Australian Geoscience Council – development, implementation and early results**

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In late 2014 the Australian Geoscience Council embarked on development of a new Strategic Plan. This has already been widely distributed through our 8 Member organisations (AAG, AusIMM, AGIA, AIG, ASEG, GSA, IAH and PESA). As the peak body of Australian Geoscience we represent over 8,000 geoscientists.

Given that our Mission is defined in our Constitution we started with our Vision. This maps our path forward and gives us guidance at each step in making decisions. The Vision we agreed on is appropriately challenging: We will raise the profile of Geoscience to be pre-eminent in Australia and to be recognised as one of the great fields of general science with Physics, Chemistry and Biology.

To maintain our focus on this Vision we have developed three Strategic Pillars: Geoscience Education, Geoscience Advocacy and Geoscience Sustainability. We consider these almost self-explanatory, the third pillar focusing on actions that enable us to ensure the first two continue to be developed long into the future. For each of the Strategic Pillars we have defined Strategies and within each of the Strategies we have defined Targets. Full details of our Strategic Plan are on the AGC website at <http://www.agc.org.au>.

This Strategic Plan is particularly important because the AGC is in the fortunate position of currently being well-resourced through the results of the very successful International Geological Congress in Brisbane (the 34th IGC). With this however comes the obligation to proactively and responsibly use these resources to support Australian geoscience. We have taken the approach of allocating an annual budget for five years based on the pillars, strategies and tactics in our Strategic Plan. During the course of this period we aim to develop additional sources of income to enable further promotion of Australian Geoscience into the future.

Some of the immediate successes that the AGC has achieved with the Strategic Plan are:

- 1) integration of the efforts of our Member organisations,
- 2) coherent development of Geoscience Education in Tertiary, Secondary and (eventually) Primary institutions complemented by public and ongoing professional development education
- 3) engagement with the Australian Academy of Science in developing the next decadal plan for Australian Geoscience (through the AAS-NCES subcommittee)
- 4) formulation of approaches that will provide us with the ability to effectively and proactively lobby Federal and State Governments on important issues including:
  - ) UNCOVER
  - ) Support for ongoing funding of government geoscience agencies, both Federal and State
  - ) Advocacy for satisfactory geoscience representation in Australian Research Council (ARC) funding allocations
  - ) Support for policy initiatives to help manage the impact of the resource industry business-cycle on our Member organisations and the geoscientists that they represent.

## Hydroclimate responses to increases in greenhouse gas concentrations and land use and land cover changes

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To investigate the impacts of increased GHG concentrations and land use and land cover change (LULCC) on hydroclimate, two sets of numerical experiments were performed using the fully coupled Community Earth System Model. In the first set of experiments, GHG levels were set to preindustrial (1850) levels, but the land was set with potential and current vegetation cover. In the second set of experiments, land settings were kept the same, but GHG levels were set to present-day (2000) levels. The results show that increased GHG concentrations led to significant increases in precipitation and evapotranspiration at mid- and high-latitudes during both warm (May–September) and cold (November–March) seasons. However, there were significant decreases in precipitation, evapotranspiration, runoff, and soil moisture in the North American semi-arid region during the warm season. LULCC caused a weakening of the hydrological cycle in Eastern Asia, Southern Asia, and Europe. In the semi-arid regions of Africa and Eastern Asia, increased GHG concentrations increased precipitation and evapotranspiration in both seasons; meanwhile, the opposite effect was observed for precipitation, evapotranspiration, runoff (including surface runoff and sub-surface runoff), and soil moisture in the semi-arid region of North America. During both seasons, LULCC plays a more important role than increased GHG concentrations in changing evapotranspiration in Southern Asia and Europe and in altering runoff in the semi-arid region of North America. In contrast, increased GHG concentrations play a dominant role in determining changes in evapotranspiration in the semi-arid region of Eastern Asia during the cold season, as well as changes in precipitation, evapotranspiration, and runoff at high latitudes during both seasons.

## Petrology, geochemistry and geochronology of mafic lithologies at the Olympic Dam iron oxide Cu-U-Au-Ag deposit: implications for tectonic settings and ore-forming process

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Olympic Dam, South Australia, is a supergiant iron oxide Cu-U-Au-Ag deposit. In the early exploration model leading to the discovery of the Olympic Dam deposit, the sedimentary sequences on top of altered mafic rocks were considered desirable targets. We have confirmed the occurrence of two generation of mafic lithologies at Olympic Dam using *in situ* apatite U-Pb dating. The first group is correlated with the ca. 1590 Ma Gawler Range Volcanics (GRV) and the Gawler silicic large igneous province (SLIP), consisting of intensely altered olivine-phyric basalt, and other mafic dykes of various textures (aphanitic, porphyritic, and doleritic). The second group comprises basaltic to mainly doleritic dykes (named the Olympic Dam dolerite), belonging to the ca. 820 Ma Gairdner Dyke Swarm and the Gairdner large igneous province (LIP).

Compositions of Cr-spinel and olivine-phyric basalt samples of mafic GRV (including Olympic Dam samples) indicate derivation of mafic GRV from a heterogeneous mantle source that may have been modified by subduction. The correlation of the Olympic Dam dolerite with the Gairdner LIP implies that Olympic Dam was affected by rift magmatism at ca. 820 Ma. Therefore, from the perspective of mafic magmatism, the evolution of the Olympic Dam deposit can be linked to the cycle of two supercontinents: the assembly of Laurentian at ca. 1590 Ma and the break-up of Rodinia at ca. 820 Ma.

Both generations of mafic rocks are altered and are characterised by a secondary mineral assemblage of magnetite-apatite ± chlorite ± quartz, which is comparable to the inferred early reduced Fe oxide alteration present in the periphery and at depth of the deposit. Intensely sericite-altered samples of the ca. 1590 Ma olivine-phyric basalt yielded a post-primary Rb-Sr isochron age of ca. 1180 Ma, probably recording the last widespread sericite alteration event in these rocks. Drill core assays (e.g. up to 26 wt. % CO<sub>2</sub> and 50 wt.% of Fe<sub>2</sub>O<sub>3</sub>) of the ca. 1590 Ma olivine-phyric basalt reflect the variable abundance of various secondary minerals. A wide range of compositional variation (six-fold) of Cr with extreme concentrations up to ~6000 ppm, and positive correlation between Cr and other incompatible elements (e.g. Ti and Zr) in the olivine-phyric basalt suggest significant whole-rock mass and/or volume loss due to hydrothermal alteration. Geochemical comparisons between the more altered ca. 820 Ma Olympic Dam dolerite and the less-altered equivalents reveal that a number of elements have been added or removed as a consequence of alteration. Generally elevated Zn and Pb but depleted Cu concentrations of a number of Olympic Dam dolerite suggest that the dolerite can potentially be an additional source of copper to the Olympic Dam deposit.

Magmatic-hydrothermal activities (ca. 1590 Ma, 1180 Ma, 820 Ma) recorded in both generations of mafic rocks can be correlated with ages (spanning from ca. 1590 Ma to 570 Ma) obtained on the Olympic Dam Breccia Complex, the immediate host to the ore. This implies an all-encompassing, multi-stage, prolonged hydrothermal system at the Olympic Dam deposit.

## The National Virtual Core Library – Unique multifaceted national infrastructure

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Australia, like the rest of the world, faces several well recognised challenges: decreasing resource and energy discovery likely coming from increasing depths, a blanketing cover of deeply weathered rock, plus increasing pressures to sustainably manage the overall environment (e.g. water, food, land stability and resources) to maintain our quality of life.

Information gained from drilling is thus increasingly valuable to understand the nation's subsurface geology. Australia has huge historical drill core assets, which penetrate the cover and sample what is underneath. During its establishment AuScope successfully argued that these irreplaceable cores should be value-added and made more accessible to facilitate research addressing the above challenges.

The AuScope National Virtual Core Library (NVCL) was thus created - a unique and growing public infrastructure network characterising the geology and mineralogy of the top 2 km of the Australian continent. This is being achieved using distributed robotic infrared spectroscopy and imaging applied routinely to thousands of drill holes held in State, Territory and Company hands and made accessible freely via the internet to facilitate all branches of earth science research in industry and academe.

The NVCL is unique: it involves nine collaborating agencies including all State and Territory Geological Surveys, AuScope and CSIRO; it crosses jurisdictional boundaries facilitating research over whole geological provinces; it embodies state-of-the-art spectroscopic and software technologies covering the widest wavelength and mineralogical range currently available, and it provides a fresh, cm-scale view of the rocks and mineral assemblages not previously possible.

Recent addition of industry cores and further NCRIS funding, matched 3:1 by the Geological Surveys, ensure representation of many of the nation's classic mineral deposits and provinces. Knowledge from these cores should feed directly into Australia's critical Uncover Initiative (AAS, 2012) and facilitate future discoveries through better characterising the cover and the distal footprints of fertile and non-fertile mineral provinces and their often cryptic hydrothermal alteration footprints.

To date over 830,000 metres of drill core comprising >2,300 drill holes have been scanned and value –added in 6 years. In addition the project has also spawned over 212 publications, 186 government uses, 195 commercial uses, 143 industry collaborations, and technological improvements

A significant outcome has been the diversity of geological environments sampled. Applications cover not just hard rock precious, base metal, high-grade iron and rare earth deposits, but also sedimentary basins for improved stratigraphic correlation and important for uranium, oil, oil shale, unconventional gas, coal and even opals. Other research has included hydrologic studies and to gain improved understanding of the deeply weathered profiles that cover much of the continent. Even geotechnical studies for underground tunnel infrastructure have been considered. This diversity has also meant that by working together the NVCL teams have learnt from each other and been able to recognise the need for constant improvements to the systems and mineral reference libraries that drive much of the automated analysis.

NVCL quality, diversity and future needs all demonstrate very clearly how such collaborative research infrastructure cannot be undertaken by any one agency on its own. The enormously valuable database that is being built is a true national archive the nation should be proud to have invested in as its contribution to our sustainable future.

## Some empirical hyperspectral core characterisation tools for NVCL TIR HyLogging data

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The thermal infrared data stream produced by the NVCL HyLogger-3 instruments is yielding multiple opportunities to characterise the mineralogy and lithology of the numerous drill holes being scanned by all the Geological Surveys around Australia.

As a result of examining many of these drill holes we have developed several valuable and partly empirical indices for characterising and domaining drill holes. These include a Felsic-Mafic Index or FMI, the TIR Background Offset and the TIR background Slope.

Salisbury et al. (1991) introduced the Christensen frequency (CF), resulting from observing a systematic shift of the major reflectance feature of silicates from shorter to longer wavelengths. This introduces a feature, in the wavelength domain, of minimum reflectance and absorption, where the refractive index of silicates approaches 1. This feature can be used to determine whether a rock or its constituent minerals is more silicic (shorter wavelengths) or more mafic or ultramafic (longer wavelengths), as shown, for example, for the shift from quartz at 7600 nm to actinolite near 8500 nm. While this may sometimes be valuable for analysing HyLogging data we have found an alternative index, called the Felsic Mafic Index, or FMI, a more valuable tool for characterising certain lithological environments especially those representing a wide range of felsic / mafic/ ultra-mafic or calc-silicate environments. We observe greater mineralogical dispersion and less impact by volume scattering effects that sometime beset TIR core logging data than the CF. The paper demonstrates the implementation of the FMI to characterise and domain several mineralogically-complex drill holes.

We have also observed two other characteristic behaviours of TIR data in response to (i) sulphides and (ii) hematite and magnetite that can be taken advantage of. Bright sulphide-bearing rocks demonstrate a common offset of their base thermal infrared reflectance that can be mapped and highlight the presence of many sulphides, especially pyrite and chalcopyrite. In the absence of assays the TIR Background Offset Index can rapidly draw attention to the presence of, even disseminated, sulphides amongst hundreds of thousands of core logged spectra, and generally accelerate the core logging / characterisation process.

Hematite and magnetite spectral reflectances also exhibit TIR characteristics of a generally positive slope to longer wavelengths for magnetite and a negative slope for hematite. While hematite can be characterised in the VNIR magnetite cannot and indeed rapidly turns a SWIR spectral response into “spectral” with only a small contribution. Especially in IOCG and other environments where both hematite and magnetite may be present or define domains of oxidising and reducing conditions indices that map the slope of the TIR reflectance can be a valuable further discriminator. Examples from Olympic Dam and Wirrda Well, on the Gawler Craton and Cannington in Queensland provide good illustrations of these methods.

## **Robert Bedford and the Adelaide Scientific Establishment**

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Robert Bedford (1874-1951), born Robert Arthur Buddicombe in Shropshire, was an Oxford graduate based in the small farming community of Kyancutta, Central Eyre Peninsula, South Australia. Although Bedford commenced studying at Oxford as a medical student he eventually graduated with an honours degree in physiology. He subsequently worked as a scientist in Freiberg, Naples, Birmingham, Shrewsbury, the Natural History Museum, Kensington and at the Plymouth Museum. After a business failure, Bedford changed his surname and migrated to Australia in 1915 with his second wife and two children; subsequently three more children were born in Australia. He applied to enter the medical school at Adelaide University in 1920 but was rejected despite the fact that he was clearly well qualified. The fact that he was undergoing divorce proceedings from his first wife at the time probably did not assist his application. Bedford acted as an unofficial doctor in the Kyancutta area for many years; this included bringing almost 100 babies into the world. Bedford had wide ranging scientific and other interests and established his own museum at Kyancutta. He was much more successful than Adelaide University staff in collecting material from the Henbury Meteorite craters south of Alice Springs and became an expert on meteorites. He is best known in the geological community for his five taxonomic papers on the superbly preserved lower Cambrian archaeocyaths from the Ajax Mine near Beltana in the Flinders Ranges. These papers were published in the Memoirs of the Kyancutta Museum, a journal that Bedford established and financed. These papers are still regularly referenced in papers dealing with archaeocyaths. Bedford fell out with the scientific establishment in Adelaide and in particular with Sir Douglas Mawson, who was not only Professor of Geology and Mineralogy at Adelaide University, but also a former President of the Royal Society of South Australia, President of ANZAAS for five years in the 1930s and the long standing Honorary Curator of Minerals at the South Australian Museum. Bedford was denied membership of the Royal Society of South Australia. Towards the end of his life, Bedford sold most of his archaeocyaths to the Princeton University including many type specimens. However, the specimens from one of the papers on archaeocyaths, published in the Memoirs of the Kyancutta Museum, are housed in the South Australian Museum.

## Precise zircon U-Pb dating of volcanic horizons in the Palaeoproterozoic Wilyama Supergroup of the Curnamona Province: advances in stratigraphy of the Olary Domain.

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The ~1720–1640 Ma Wilyama Supergroup was deposited in an epi-continental rift basin accompanied by felsic and mafic magmatism, and hosts the largest known Pb–Zn–Ag accumulation at Broken Hill. A stratigraphic scheme for the South Australian portion of the Curnamona Province, the Olary Domain, was erected in 2008 (Conor and Preiss 2008). SHRIMP U-Pb dating demonstrated that, broadly speaking, there are more breaks in sedimentation in the Olary Domain, with the sedimentary succession being more continuous in the Broken Hill Domain. The Olary Domain contains the oldest known rocks of the Curnamona Province. These are assigned to the Curnamona Group, comprising the older Wiperaminga Subgroup and the younger Ethiudna Subgroup. The Curnamona Group does not outcrop in the Broken Hill Domain, but may be present at depth. SHRIMP dates on felsic volcanic units within the Wiperaminga and Ethiudna Subgroups are in the range 1721–1712 Ma, but age differences between the Wiperaminga and Ethiudna Subgroups and the formations within were beyond the resolution of the SHRIMP U-Pb dating technique.

New chemical abrasion-thermal ionization mass spectrometry (CA-TIMS) U-Pb data on select volcanic horizons has greatly improved the internal stratigraphic resolution of the Curnamona Group. The oldest units of the Ethiudna Subgroup, the Toraminga Formation and Tommie Wattie Formation, contain volcanic rocks that crystallised at  $1716.1 \pm 0.5$  Ma and  $1716.0 \pm 0.4$  Ma, respectively. Volcanics in the overlying Peryhumuck Formation crystallised  $\sim 5$  million years later, at  $1711.1 \pm 0.4$  Ma. A volcanic unit within the George Mine Formation, assigned to the older Wiperaminga Subgroup, produced an age slightly younger than Tommie Wattie Formation, of  $1713.7 \pm 0.5$  Ma. This disparate result highlights the difficulty in establishing a time framework and consistent stratigraphy in highly deformed and metamorphosed domains. It is possible that unrecognised thrust faulting has placed the lower grade rocks of the Tommie Wattie Formation over the higher grade granofels and paragneiss of George Mine Formation. Another possibility is that the felsic rock selected for dating in the George Mine Formation is not volcanic, but a subvolcanic granite sill: SHRIMP dates indicate that A-type granites of the Basso Suite intruded the Wiperaminga Subgroup at  $\sim 1713$ – $1711$  Ma. A third explanation is that Tommie Wattie Formation–George Mine–Formation boundary is diachronous. The results do not contradict the observed stratigraphic order within a single section. The George Mine Formation and Peryhumuck Formation samples both come from the same section at Cathedral Rock Creek, whereas the Tommie Wattie Formation volcanic is 34 km away, in a different inlier.

## A thermochronological transect through the Western Tian Shan (Uzbekistan and Tajikistan)

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Central Asia is dominated by vast mountain ranges, with peaks up to 7000 m, however is thousands of kilometers away from the nearest plate margin. The timing and mechanisms of deformation within Central Asia are still unclear and there is particularly little known about the deformation history of the southwestern verges of Central Asia. This study is focused on the thermal history of major suture – fault zones in the western Tian Shan (Uzbekistan and Tajikistan), in order to unravel the timing of deformation and exhumation in southwestern Central Asia. The Tian Shan is the southernmost and highest expression of the Central Asian Orogenic Belt, which stretches 2500 km from Uzbekistan in the West to Xinjiang, China in the East. The mountainous Tian Shan relief was originally formed by the late Carboniferous – early Permian collision of the Paleo-Kazakhstan and Tarim Karakum continents. The generation of the Tian Shan was followed by punctuated reactivations during the Meso-Cenozoic due to the incremental accretion of continental fragments onto southern Eurasia during closure of the Tethys Ocean. Its current topography is still growing as a result of ongoing India-Eurasia convergence, making the Tian Shan the world's most active intracontinental mountain range.

A series of ~40 samples were collected in a north-south transect across the main structural architecture, from the northern Tajik Pamirs to the Uzbek and Tajik Tian Shan. These samples have been analysed using multi-method (apatite U-Pb, apatite fission track, apatite and zircon (U-Th-Sm)/He) thermochronology, in order to elucidate the amalgamation and reactivation history of the western Tian Shan. An apatite U-Pb date of 251 +/- 3 Ma (based on 64 single grain analyses), obtained along the main Pamir - Tian Shan suture, correlates well with the proposed timing of final amalgamation of Central Asia. Low temperature thermochronological results indicate preserved fast cooling events during the late Triassic – early Jurassic (~230-185 Ma) and mid Cretaceous (~125-100 Ma) in the western Tian Shan verges and Oligocene (~35-25 Ma) and late Miocene (~10 Ma) cooling along the Tian Shan – Pamir suture zone. The timing of these cooling events correlates with distal continental collisions, associated with the progressive closure of the Tethys Ocean, which drove the exhumation of the Tian Shan. The youngest events date the timing of more recent pulses of mountain building, associated with the growth of Tibet and ongoing India-Eurasia indentation. Ongoing research following on from this work aims to shed more light on the timing and extent of strain propagation and fault reactivation within southwestern Central Asia as a whole, as a response to plate-margin and intracontinental tectonic processes.

## Trace element mobility in shock deformed zircon revealed by atom probe microscopy – A shocking tale!

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The mineral zircon ( $ZrSiO_4$ ) is used widely in the geosciences to date geological events. Recent work has documented that the plastic deformation of zircon can modify the distribution of trace elements within the zircon lattice, thereby raising the possibility of being able to date deformation of Earth's crust. However, the processes responsible for element migration during zircon deformation are unclear. Here we combine atom probe tomography (APT), electron backscatter diffraction (EBSD) and transmission Kikuchi diffraction (TKD) to address this problem.

The Stac Fada Member of the Stoer Group, NW Scotland represents ejecta from a meteorite impact event about 1.2 billion years ago. EBSD data from this rock unit reveals the presence of the extremely rare high-pressure polymorph of  $ZrSiO_4$ , reidite, within the host zircon. This provides unambiguous evidence of shock pressures in excess of ~30 GPa. In addition, the host zircon and reidite lamellae both contain low-angle boundaries, which are interpreted to represent recovery and the migration of shock-induced dislocations into lower energy configurations in the latter stages of the impact event. TKD analysis of one of these low-angle boundaries, captured within a FIB-milled atom probe needle, reveals a lattice disorientation of  $2^\circ$  across a zone of ~20 nm width. Atom probe analysis reveals elevated concentrations of Y, Al, Be and Mg within the low-angle boundary, which we interpret to reflect trace element migration associated with the mobility of both oxygen vacancies and dislocations during recovery. The prospect of a dynamic dislocation-migration process being responsible for geologically instantaneous trace element modification within shocked zircon has potential implications for the dating of impact events by high-spatial resolution U-Pb geochronology.

## The biological and chemical evolution of the Baltic Sea Basin reflected in changing sulphide geochemistry. Initial results from IODP Exp. 347.

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The trace element chemistry of anoxic sediments and sedimentary rocks has previously been shown to correlate with the chemistry of the ocean (Algeo., 2004). Recent studies have used the trace element content of ancient sedimentary pyrite to track first order changes in ocean chemistry through geological time and display good parallels with traditional whole-rock methods (Large et al. 2014, 2015). However, no evidence for the possible diagenetic effects on the preservation of the authigenic seawater signal has been presented for this or other methods. Without the preservation of coeval seawater to offer a direct comparison, the possibility of diagenetic overprints requires that sedimentary pyrite analysis and other methods should only be considered semi-quantitative. The recent IODP Exp. 347 “Baltic Sea Paleoenvironment” offered an opportunity to bridge this current knowledge gap by evaluating the formation and chemistry of recent pyrite in a well-constrained context. The Baltic Sea Basin has experienced a varied history in the short time since its formation and has recorded a diverse series of environmental changes. Preserved in the high-resolution stratigraphy recovered during Exp. 347 are several sedimentary units which represent fluxes between a geographically and geochemically restricted water mass, freshwater, and brackish seawater, as well as the development of anoxic water column conditions. Here we present sedimentological results coupled with high-resolution geochemical profiles through the stratigraphy in order to build an integrated understanding of the variations of chemical partitioning within the sediments and to constrain how such observations may relate to changes in the seawater chemistry.

Analysis of the uppermost section of the sapropel shows that it captures the sediment-water interface and the uppermost seawater saturated horizon where pyrite forms. We observe that within the upper ~2m of the sediment there are systematic variations in both sulphide minerals and their geochemistry. These mineralogical and chemical differences appear to be correlated with redox horizons, the interface between the break down of organic matter, and changes in the pore water content and biologically-induced SO<sub>4</sub>-CH<sub>4</sub>-H<sub>2</sub>S fronts. Here, the dominant sulphide species vary between pyrite and pyrite-greigite. Below this horizon, pyrite dominates the sulphide mineral assemblage and its chemistry is relatively constant. We suggest that this zone has captured the dynamics, pathways and metal partitioning during the formation of syn-sedimentary pyrite and on a short time scale, less than that of residence times of many elements (i.e 100s to 1000s of years).

We have applied the pyrite chemistry technique to sections deeper in the stratigraphy and other sub-basins within the Baltic Sea in order to investigate horizons that may archive redox or basin chemical changes. Our data shows enrichments in specific trace metals in pyrite in horizons that mark critical changes in the development of the Baltic Sea and those that have independently been identified as euxinic and anoxic (Hardisty et al., in prep.). Here we discuss the dynamics and pathways of initial pyrite growth and present a series of examples where we evaluate the use of pyrite chemistry as an archive of redox changes in the Baltic Sea.

## Dating orogenic gold mineralization at the Paulsens deposit, Western Australia

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Dating orogenic gold mineralization has proven problematic, mostly due to a lack of suitable minerals for geochronology, the short time frame for gold mineralization, and the ease of resetting of common geochronometers during subsequent metamorphism and deformation. However, *in situ* Sensitive High-Resolution Ion Microprobe (SHRIMP) U–Th–Pb geochronology of xenotime and monazite has recently been used to date other styles of mineralization (e.g. the Abra Pb–Zn deposit). These phosphate minerals are robust chronometers that are resistant to isotopic resetting over a range of pressure and temperature conditions. They yield precise ages, and commonly form during a range of hydrothermal and mineralizing events, making them ideal for dating orogenic gold deposits.

The Paulsen's deposit is a mesothermal orogenic gold deposit situated in low-grade Archean metasedimentary and metavolcanic rocks of the 2.77–2.63 Ga Fortescue Group in the southern Pilbara region of Western Australia. Auriferous quartz–sulfide veins are hosted within a folded and faulted gabbro sill that intruded a succession of phyllites and sandstones of the < 2.74 Ga Hardey Formation. *In situ* dating of magmatic baddeleyite crystals at c. 2.70 Ga indicates that the gabbro is part of the Jeerinah Formation. Hydrothermal monazite from strongly altered parts of the gabbro yield a date of c. 2.40 Ga. Within the auriferous quartz–sulfide veins, locally gold-bearing pyrite grains are intergrown with zoned xenotime crystals. The xenotime cores and rims yield dates of c. 2.40 and 1.68 Ga, respectively. Xenotime from a carbonate vein that crosscuts the gabbro yields a similar date to the xenotime rims. At Paulsens East, sulfide-bearing quartz veins yield a single generation of monazite at c. 2.40 Ga. Additionally, in the surrounding phyllitic country rocks (?)andalusite porphyroblasts have locally been replaced by hydrothermal monazite dated at both c. 2.40 and 1.73 Ga. Collectively, these results indicate that the main phase of hydrothermal activity and gold mineralization at Paulsen's took place at c. 2.40 Ga, and that the region was subject to later, low-grade hydrothermal events at c. 1.73 and 1.68 Ga.

These hydrothermal events do not correspond to any known deformation events along the southern Pilbara margin. However, monazite growth in phyllites across the Pilbara region [1], as well as resetting of high-U zircons in tuffaceous mudstones of the Hamersley Group [2], have been recorded between c. 2.43 and 2.40 Ga. The c. 1.73 Ga hydrothermal event is possibly coeval with gold mineralization at the nearby Mt Olympus gold mine which is dated at c. 1.74 Ga [3]. The emplacement of carbonate veins and secondary growth of hydrothermal xenotime at c. 1.68 Ga, is synchronous with high-temperature metamorphism and deformation of the 1.68–1.62 Ga Mangaroon Orogeny in the Gascoyne Province. Our results indicate a significantly different, and more complicated low-temperature tectonothermal evolution for the southern Pilbara region than previously thought. *In situ* dating of accessory phosphate minerals can not only provide robust ages for mineralization, but also help unravel the regional low-temperature, tectonothermal history of a region.

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## The role of radiogenic heat in prolonged intraplate reworking

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The growth and stabilization of the lithosphere is ultimately controlled by its evolving thermal structure. Melt generation and extraction from deeper levels to produce granites at shallower levels in the crust is an important process of crustal differentiation. In general, melt-producing reactions are strongly temperature-dependent; therefore, the thermal gradient in the crust will impact the depth at which melting occurs and thereby affect the differentiation process. Equally so, chemical differentiation will fractionate the heat-producing elements (HPEs), moving them up to the shallow crust, which will change the thermal structure with time. Since rheology is also temperature-dependent at the plate scale, the lithosphere is progressively strengthened as it becomes more differentiated, promoting the long-term stability of the continents. By contrast, at the regional scale, surficial processes such as erosion and sedimentation may redistribute the HPEs. Those areas enriched in HPEs will tend to have a higher thermal gradient in the crust, which will be weaker and more susceptible to reworking than adjacent areas, so that deformation is likely to be localized in these HPE-enriched regions.

Links between intraplate crustal deformation and the thermal regime of the lithosphere have been investigated using numerical models, but these conceptual models must be tested using well-constrained natural systems. The Proterozoic Capricorn Orogen of Western Australia is ideally suited for such a study. After arc accretion, it records a protracted history of intracrustal differentiation and over one billion years of subsequent tectonic reworking. The early addition of juvenile arc material initially reduced the heat production of the crust, whereas subsequent recycling of the deep crust ultimately produced radiogenic granites at shallower levels. Using whole rock and magmatic zircon compositions, we show that the shallow crust of the Capricorn Orogen has been progressively enriched in heat-producing elements with time. The high heat production is mainly controlled by thorium, concentrated in LREE-enriched phosphates that grew during the late stages of crystallization of crustally derived granites. Using a numerical model, we investigate the thermal effects of this evolved crustal stratification and compare them with quantitative data on the pressure–temperature–time evolution of a non-magmatic Mesoproterozoic reworking event. The results provide new information concerning the process by which the thermal conditions necessary for the reworking of orogenic crust are generated and sustained for prolonged timescales (>110 Ma). Furthermore, the data demonstrate that thickening of radiogenic crust produces warmer geotherms and weakens the lithosphere. This weakened lithosphere is then more susceptible to changes in far-field stresses leading to crustal thinning and subsequent cooling. The results from this study show that these crustal perturbations have a fundamental control on intraplate reworking of long-lived orogens.

## **Using local geotrails to connect small volcanic geosites and provide new opportunities for geotourism - examples from the Kanawinka Geopark in the Newer Volcanic Province of South Eastern Australia**

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The Newer Volcanic Province of South Easter Australia has many geosites – there are 400 or so scoria cones, lava shields, maar craters and tuff rings, and extensive lava flows. These can be complex features. But there are also many small areas, sometimes not close to an eruption point. These include pillow lavas, road cuttings, viewpoints, columnar basalts, lava caves and stalactites, historic basalt stone walls, and the interaction of lava flows and coastlines. These more local and generally small features lend themselves to being connected by geotrails. These connected geosites can then provide for school and university visits, as well as for geotourists. In this way a group of small volcanic geosites can be connected by local geotrails to provided valuable geotourism field trips.

We can consider volcanic geosites and their extensive range of features.

### **Lava flows features**

Lava blisters sensu stricto e.g. Williamstown.

Tumuli at Byaduk flow – formerly called lava blisters by Skeats and James (1937) – but not hollow - how did these originate?

Exposed base of lava flows; a rare feature best seen at Mount Rouse.

Pillow lavas – rare features in Victoria.

The Eccles flow - Budj Bim area – drainage disruption forming Lake Condah, with its aboriginal stone houses and eel farming, and a World Heritage nomination as the world's oldest aquaculture.

### **Columnar basalt**

The Organ Pipes.

Werner and controversy with Hutton.

Hanging Rock - an area with a wide public interest.

### **Lava caves**

The Byaduk complex with stalactites of varying chemical composition.

Flow features in the caves show how they were formed.

### **Interaction of lava flows and coastlines**

Lava flows reaching the coast.

Eruption features at the coast.

Why do some lava flows seem to stop at the coast, while others are found under the sea today?

### **Lakes**

Bullenmerri and Gnotuk – maar craters with a climate change story to tell.

Fossil sites - kangaroo bone within the Lake Purrumbete tuff.

Lake Colongulac and Pejark Marsh – megafauna sites.

### **Historic features:**

Major Mitchell exploration and volcanic recognition (1836)

Lava caves with local community activities such as weddings.

Bluestone homesteads and their adjacent quarries.

Bluestone government and town buildings e.g. former Penshurst Shire of Mount Rouse (1864), now the

Penshurst Volcano Discovery Centre.

Bluestone ( basalt) monuments and cemeteries e.g. Camperdown cemetery and its significant aboriginal monument.

Stone walls (stone fences) – ages, styles, recent rebuilding – reserves.

**Lost or damaged features:**

Rubbish Cave, Mount Pordon.

Quarries – vegetated, buried, flooded, lack of access, e.g. Mount Noorat – burial of tuff-scoria contact at rim – exposed in western quarry, now buried – uncover?

Examples of many 19<sup>th</sup> century quarries around the edge of 19<sup>th</sup> century Melbourne, no longer exposed for study such as sampling for dating.

Overgrown road cuttings e.g. at Terang, with buried soil between ash deposits.

Finally, we can consider how having established a number of small geotrails in an area such as the Kanawinka Geopark, we might be able to link individual geotrails, providing further comparisons and contrasts, a richer content in the field, and possible longer field trips.

## The Olympic Dam Cu-U-Au-Ag ore deposit: towards a new genetic model

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All supergiant ore deposits pose major questions relating to the processes responsible for metal concentration and their duration. The supergiant Olympic Dam Cu-U-Au-Ag ore deposit is even more enigmatic because it is polymetallic, and the economic elements and iron are concentrated within a breccia complex hosted by undeformed, weakly altered granite. Although the age of the granite is well established at ca. 1590 Ma, the timing of metal addition and accumulation is uncertain, largely because the context and textures of the ore are variable and indicative of several genetic processes. In addition to high-precision U-Pb ages of uraninite spreading over 1 Ga (presented in this volume), here we show that different rocks and mineral assemblages record post-1590 Ma tectonic, magmatic, sedimentary and hydrothermal events.

Zircon in clasts of quartz-rich sandstone in the hematite-rich breccia (RD2751, 855–914 m) belong to three age populations ( $1612.9 \pm 9.1$ ,  $1732.7 \pm 5.5$ ,  $2485 \pm 30$  Ma) that correspond to those of detrital zircon in the ca. 1425 Ma Pandurra Formation (Cariewerloo Basin overlapping the Gawler LIP). The presence of Pandurra Formation in the breccia complex suggests brecciation and incorporation of sediments at <1425 Ma.

The Sm-Nd dates of step-leached ore samples are similar to published whole rock data and define a ~1300 Ma apparent age, which is broadly supported by Rb-Sr isochrons for the same fractions. Sericite in ca. 1590 Ma, basaltic dykes and picrite lavas at Olympic Dam has an age of  $1128 \pm 19$  Ma (Rb-Sr). A similar age is suggested by Pb isotope systematics of authigenic pyrite in a mafic sandstone belonging to bedded sedimentary facies, and galena in the mineralized sample (RU27-7551, 303.5 m).

The Gairdner Dykes intruded the breccia complex at ca. 820 Ma, and are associated with coeval brecciation and circulation of syn- and post-magmatic fluids (Huang et al., Apukhtina et al., this volume). The related hydrothermal alteration is characterized by re-distribution of Fe, Cu, Pb, P, REE etc. and precipitation of magnetite, apatite, titanite, pyrite, chalcopyrite and galena.

The youngest ages (Ordovician, ca. 440–480 Ma) are recorded by (1) authigenic apatite (U-Pb dating) in the bedded sedimentary facies, including ironstones, (2) hydrothermal apatite and monazite (U-Pb dating) in the sulfide-bearing mineralization associated with basaltic dykes, and (3) fluorite (Sm-Nd dating; Maas et al., 2011) from extensive fluorite-barite-siderite veins cross-cutting the breccia complex. Importantly, roughly Delamerian ages are reported for ‘massive’ uraninite (presented in this volume).

The described post-1590 Ma brecciation, alteration and mineralization events coincided with tectonic and magmatic events that affected the Gawler Craton margin in response to amalgamation and/or breakup of three supercontinents – Columbia (breakup 1.6–1.3 Ga), Rodinia (amalgamation 1.3–1.1, breakup 0.85–0.6 Ga) and Gondwana (amalgamation 0.6–0.3 Ga). We attribute the extraordinary metal accumulation at Olympic Dam to a favorable position at the craton’s margin, where multiple events of metal addition and redistribution can be linked to supercontinent cycles. A possibility of post-1590 Ma uranium addition will be advocated based on  $^{207}\text{Pb}/^{206}\text{Pb}$  of bulk rocks and sulfides.

## Geological and Exploration Models of Beach Placer Deposits, Integrated from Case-Studies of Southern Australia

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The processes leading to the formation of beach placer deposits generally begin inland and terminate at the coast, beginning with weathering and erosion of source rocks, followed by transport of the sediments by streams and rivers to the coast, and finally deposition of the sediments in a variety of coastal environments. There, the sediments are worked by the action of waves, tides, longshore currents, and wind, which are effective mechanisms for sorting the mineral grains based on differences in their particle size and density. These combined processes form laminated or lens-shaped packages of sediments several metres thick, and even up to tens of metres thick, which are rich in heavy minerals. Detailed study of sedimentary basins, as well as peripheral (paleo-) valleys that drained provenances, is therefore important in the exploration for heavy mineral resources. Knowledge of the basin and associated (paleo-) valley architecture and of any sources of the heavy minerals accumulated in the (paleo-) shorelines and (paleo-) valleys can be guides to the location of potential deposits, particularly in greenfield exploration areas. Evidence from sedimentology is combined with that of other geological and geophysical characteristics to arrive at a general reconstruction of basinal and paleovalley architectures and depositional environments.

Complex palaeogeography of the (paleo-) shorelines influences and can determine the sites of heavy mineral sands accumulation. Heavy mineral sands tend to concentrate in certain shoreline sediments during storms. Repeated storm erosion and reworking over centuries (e.g., the southeastern coast of Australia) or millennia (e.g., the Eucla and Murray basins of Australia) can progressively enrich heavy mineral sands deposits. Preservation of these deposits occur through subsidence of coastal sediments and during sea-level changes that can cause shorelines to migrate inland (marine transgression) or seaward (marine regression). These processes sometimes result in reworking of older heavy mineral accumulations into younger deposits.

Recent major refinements in remote sensing and geophysical techniques, data processing, sedimentology and computer-aided interpretations are providing effective, economic and efficient models and methods for exploring for heavy mineral sands in prospective provinces and terrains. For example, physical property contrasts that exist between the shoreline sediments and underlying sequences can be differentiated by geophysical methods and thereby used to locate the paleoshorelines/paleovalleys.

Australia has modern and ancient deposits of beach placers, both of which display the same or similar geologic features. The formation of these heavy mineral deposits provides one of the best examples of applying modern systems (e.g., the western and eastern coasts of Australia) as analogues to interpret and understand the geology and form of an ancient deposit (e.g., the Eucla and Murray basins of southern Australia). This study provides descriptive and exploration models of Australia's heavy mineral sands deposits accumulated in coastal environments, which can be applied to equivalent settings worldwide

## Mesoproterozoic Cariewerloo Basin, South Australia: spectral approach to mapping mineral diagenesis as a guide to fluid flow and unconformity uranium potential

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The Cariewerloo Basin is a mostly undeformed, Mesoproterozoic-age, clastic-filled intercontinental basin unconformably overlying 42,500 km<sup>2</sup> of crystalline basement rocks along the eastern Gawler Craton in central South Australia. The basin fill is dominantly red-bed sandstone sourced largely from erosion of Gawler Range Volcanics and granitic basement. Maximum preserved thickness of sediment is around 1500 m. The geological setting is similar to other Proterozoic basins with identified resources of high-grade uranium in unconformity-style deposits. Extensive cover of Neoproterozoic and younger sedimentary deposits and a lack of success with earlier drilling for uranium, underscore the need for greater understanding of processes within the basin in order to identify realistic exploration targets.

A 3D structural and lithostratigraphic framework for the basin was constructed that included re-logging and spectral scanning of selected cored holes using visible to shortwave infrared spectrometer on the HyLogger™-2 platform. The data highlighted a pattern of diagenetic dickite and illite mineral alteration that was interpreted to reflect conditions of depth of burial, modified by later fluid flow along preferred pathways. Mineralogical relationships were investigated using reflected light and scanning electron microscopy. Illite was extracted from selected samples and dated by K-Ar method. Additional drill cores from across the basin were scanned with HyLogger to provide 95 sites that were then used to model the regional pattern of mineral diagenesis.

The results indicate a broad area of low permeability and restricted circulation in basal sediments in the deeper central portion of the basin, below a persistent thin siltstone/mudstone unit. Active flow of saline acidic fluids was focussed at the basin margins and in sandstone units above the widespread siltstone member. Fluid cells with horizontal and vertical components are indicated by illite alteration developed around remnant patches of authigenic dickite. Illite crystallisation between 1260-1180 Ma reflects basinwide fluid movement, possibly in response to basin inversion or tilting associated with Musgravian/Grenvillian-age (ca. 1300-1100 Ma) tectonics. Younger fluid events during the Lower Ordovician (~470 Ma) and Upper Devonian (~380 Ma) are recorded by 'hairy illite' alteration in sandstone directly beneath the contact with overlying Neoproterozoic sediments. Basinwide fluid flow at ~1200 Ma was in contact with crystalline basement mostly along eastern and western margins of the basin. In these areas, basement rocks with compositions that provide a more reduced environment in contact with circulating basinal brines are indicated as more favourable sites for proximal uranium deposition.

## Mesoproterozoic metamorphism in the Rudall Province: revising the timeline of the Yapungku Orogeny and implications for cratonic Australia assembly

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The Rudall Province occurs at the north-eastern margin of the West Australian Craton (WAC) and has long been recognised as occupying a critical location for understanding the Australian continent assembly. The Rudall Province is one of the few localities in Australia where Proterozoic-aged medium to high pressure metamorphic assemblages are preserved (minimum apparent thermal gradients of ~60–80 °C). Evidence for regional, moderate-thermal gradient conditions (corresponding to eclogite-high pressure granulite thermal gradients of Brown, 2007), combined with evidence for thrust stacking and voluminous magmatism (Kalkan Supersuite) has led to the proposal that the Rudall Province records crustal thickening associated with the collision of the WAC and North Australian Craton (NAC) at c. 1830–1765 Ma, the so-called Yapungku Orogeny. LA-ICP-MS U-Pb zircon and monazite geochronology from metasedimentary rocks from the Connaughton and Talbot Terranes in the western Rudall Province, North Australia provides evidence for two metamorphic events at c. 1665 Ma and between c. 1380–1275 Ma. Pressure–temperature ( $P$ – $T$ ) pseudosection modelling of a staurolite–biotite-bearing assemblage from the Talbot Terrane suggests peak  $P$ – $T$  conditions of ~5.5–8.5 kbar, ~600–650 °C were attained at c. 1285 Ma.  $P$ – $T$  modelling on a garnet–clinopyroxene-bearing mafic amphibolite from the Rudall Province shows that peak metamorphic conditions of ~8–11 kbar, and minimum ~620–650 °C were attained at c. 1380 Ma and followed a clockwise retrograde evolution. The geochronology and  $P$ – $T$  modelling suggest that the age of regional metamorphism (M<sub>2</sub>, Yapungku Orogeny) is Mesoproterozoic rather than c. 1800–1765 Ma. If regional metamorphism in the Rudall Province does reflect the collision of the North and West Australian Cratons, it occurred during the Mesoproterozoic and not the Paleoproterozoic as has long been assumed. Metamorphic age data and physical conditions of metamorphism from the Rudall Province may reflect a stage-wise tectonic evolution, which involved the accretion of ribbons, and outboard migration of subduction and the back-arc over time, producing both medium- $P$  and granulite facies, high thermal gradient conditions. In this proposed scenario, the system was closed during the final amalgamation of the North Australian Craton to the accreted ribbons (West Australian Craton) during the Mesoproterozoic.

## Ultrahigh temperature metamorphism: Testing models for collision vs. extension for the c. 1640 Ma timeline, central Australia

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In central Australia, the Warumpi Province has been interpreted to be exotic and accreted to the southern margin (known as the Aileron Province) of the Northern Australian Craton (NAC) during the Liebig Orogeny at c. 1640 Ma. Therefore, the Liebig orogeny has been posited as an important timeline in the context of Australian continent assembly. We have conducted fieldwork, U–Pb monazite LA–ICP–MS geochronology and calculated metamorphic phase diagrams for ultrahigh-temperature (UHT) rocks as well as the enveloping rocks in order to investigate the possible tectonic setting of metamorphism. The UHT rocks occur at Hill 830 in the Warumpi Province and are distinctly gneissic rather than migmatitic. The rocks are mostly characterised by garnet–orthopyroxene–sillimanite-bearing assemblages with abundant post-peak cordierite. There is minor sapphirine in some samples. In field outcrops as well as in some thin sections, rectangular-shaped aggregates of sillimanite occur, which we interpret as former andalusite. In addition, relict staurolite occurs in some samples. The UHT rocks are spatially associated with mafic magmatic rocks and together these define a composite boudin that is wrapped by mylonitic and migmatitic rocks, some of which contain garnet–sillimanite–biotite–cordierite assemblages. U–Pb monazite geochronology from the UHT rocks gives concordant (upper) intercept ages of 1634–1641 Ma (consistent with existing zircon U–Pb data) and from the enveloping mylonitic migmatites gives a large, concordant age range of 1084–1208 Ma. This is the first robust documentation of Grenvillian-aged mylonitic fabrics this far west in the Warumpi Province. The metamorphic record of the UHT gneisses indicates high thermal gradient metamorphism that prograded through the andalusite–staurolite stability field and then reached peak  $P$ – $T$  conditions of ~8.7–10.7 kbar and ~830–870 °C, before decompressing to produce abundant post-peak cordierite. Thermal gradients for the metamorphic peak are ~80–100 °C/kbar. Peak  $P$ – $T$  conditions for the migmatites are ~6.5 kbar, 800 °C.

Mafic and mafic–ultramafic magmatic rocks with c. 1640 Ma ages are known from elsewhere in the southern Arunta Region, including the southern Aileron Province and Warumpi Province. The mafic magmatic rock at Hill 830 has not been dated but the probability is high that it also has a Liebig age given the age of the UHT metamorphism. In conjunction with the regional presence of c. 1640 Ma mafic–ultramafic rocks, the high thermal gradients of the tectono-metamorphic environment are reconcilable with an overall extensional setting. Therefore, we propose that the c. 1640 Ma event may instead record extension and thinning of the southern margin of the NAC, rather than collisional accretion. Our interpretation does not require the presence of a suture zone between the Warumpi and Aileron Provinces, for which evidence is lacking. If our interpretation is correct, the Liebig timeline would more reflect continental growth than continent assembly.

## Regional significance of late metamorphic reaction microstructures at Anakapalle in the ultrahigh temperature Eastern Ghats Province, India

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The Eastern Ghats Province, India, part of the Rodinian to Gondwanan Rayner–Eastern Ghats Terrane, is a classic ultrahigh temperature (UHT) metamorphic terrane, recording some of the highest known temperatures for regional crustal metamorphism. Tectonic models based on recent U–Pb zircon and monazite geochronology and metamorphic analysis propose a magmatically dominated scenario where rocks prograded to peak conditions of ~1030 °C over the period c. 1130–970 Ma. They then cooled slowly from peak conditions—but were not significantly exhumed, i.e. a counter-clockwise type pressure–temperature ( $P$ – $T$ ) evolution—over the period c. 970 to at least c. 930 Ma. Dominant rock types of the Eastern Ghats include voluminous orthopyroxene-bearing granitoids ('charnockites') and mafic granulites amongst abundant metasedimentary granulites, lending support to the advocated magmatically-dominated  $P$ – $T$  regime. A later 'M2' event has long been recognised but its regional significance in the context of large-scale tectonic models remains unclear. Throughout the province, M2 is predominantly defined by cordierite coronas on earlier assemblages. However, at the Anakapalle locality in the eastern part of the province, 'M2' is defined (in part) by extremely well-developed sapphirine–orthopyroxene symplectites post-dating earlier garnet–orthopyroxene assemblages. The earliest work attributed regional significance to the M2 evolution, whereas later work attributed the development of the UHT assemblages to localised contact metamorphism and advective transport.

We have revisited the rocks at Anakapalle to address the regional significance, or not, of the metamorphic history there. Zircon U–Pb geochronology for mafic granulite that hosts the assemblages described above shows a smear from c. 800 Ma to c. 1600 Ma, with an interpreted magmatic age of c. 1600 Ma. Monazite U–Pb geochronology from two UHT pelitic granulites at Anakapalle reveals a spread of ages over the range c. 980 to 870 Ma, with an additional, smaller age population at c. 540 Ma in one sample. The magmatic age of the mafic granulite implies the UHT assemblages at Anakapalle cannot be due to contact metamorphism. New phase equilibria forward models are used to interpret a decompression-dominated history from peak conditions of ~1000–1050 °C at ~9–10 kbar, followed by later cooling. On the basis of our results, we argue that the  $P$ – $T$  evolution at Anakapalle is of regional significance to the Eastern Ghats. Although not proven, it may be that the late cordierite elsewhere in the province also reflects a decompression-dominated  $P$ – $T$  evolution for M2. The age of M2 is probably 'Grenvillian', at least at Anakapalle, in which case large-scale tectonic models need to account for this part of the metamorphic record. However, we acknowledge that the M2 record in at least some parts of the province could reflect Pan-African tectonism.

## Petroleum migration in the Bight Basin: a fluid inclusion approach to constraining source, composition and timing

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The Bight Basin in southern Australia is a vast under-explored offshore area with promise of, but as yet limited proof for, oil and gas accumulations. The sparse number of exploration wells in the basin restricts the available material required to test the petroleum system(s) directly and to adequately predict the hydrocarbon potential of the Bight Basin. Fluid inclusions offer a unique method to test for petroleum migration, composition and timing, that would otherwise remain hidden in the rocks, and only requires small volumes of material that are unaffected by drilling processes or storage conditions.

A reconnaissance-scale fluid inclusion study of 6 petroleum wells, using CSIRO's Grain with Oil Inclusion (GOI™) technique, was undertaken to detect liquid hydrocarbons in Mesozoic (Jurassic to Cretaceous) sandstones. Oil-bearing, and in some cases gas-rich, inclusions were detected in all wells, but significantly in Gnarlyknots-1A. Although hydrocarbon-bearing inclusions occur at relatively low abundance (GOI <0.1% to 1.1%), their presence provides proof of oil generation and migration through the rocks of this sparsely explored frontier basin.

To geochemically fingerprint the fluid inclusion (FI) oil, the Molecular Composition of oil Inclusions (MCI) technique was applied to an intra-Santonian interval from Gnarlyknots-1A (Tiger Supersequence) and a Cenomanian interval from Greenly-1 (White Pointer Supersequence). The results indicate mixed organic matter input, including both algal and terrestrial plants, and suggests that components of the Gnarlyknots-1A FI oil may have been generated from marine source rock(s) deposited in suboxic-oxic environments with mixed organic matter inputs including algal and terrestrial plants. The FI oil from Greenly-1, however, was generated from clay-rich source rocks deposited in an oxic, fluvial/deltaic environment, with mainly terrestrial plant input and a minor contribution of bacteria. The success in extracting FI oil from low GOI samples potentially allows for MCI characterisation of migration pathway, in addition to palaeo-oil columns.

To understand the types of hydrocarbon trapped, and their timing, modelling of fluid composition and trapping conditions (pressure-temperature; P/T) was undertaken. The intra-Santonian migration interval in Gnarlyknots-1A trapped a variety of fluid compositions over an extended period of time. Modelled hydrocarbon compositions derived from Petroleum Inclusion Thermodynamic (PIT) include black oil, light oil, volatile oil and gas-condensate. The earliest oil entrapment took place at a minimum of 62°C as light oil and this equates to a time at the end of the Cretaceous (circa 76 Ma). The palaeo-P/T evolution recorded by the fluid inclusion record in Gnarlyknots-1A closely matches independent modelled burial histories. The modelled hydrocarbon compositions from Greenly-1 are more consistent in composition, ranging from heavy black oil to light oil. Most inclusions were trapped in a narrow temperature range of 120-130°C, and corresponding pressures of 240-290 bars. These are higher than the predicted formation temperatures from modelled burial curves, which suggests that the petroleum fluids in Greenly-1 were in thermal disequilibrium relative to the rock.

This study was undertaken as part of the Great Australian Bight Research Program, a collaboration between BP, CSIRO, the South Australian Research and Development Institute (SARDI), the University of Adelaide, and Flinders University.

## **The nature of the lithosphere in the vicinity of the Eucla-Gawler reflection seismic line**

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The recent and ongoing program of reflection profiling in western and central Australia has provided considerable insight into the nature of crustal architecture. Complementary information on the nature of the whole lithosphere comes from a broad range of seismological studies using both man-made and natural sources. The Eucla-Gawler line crosses a region for which there was little prior information. The reflection line provides important information about the crust-mantle boundary, but for the seismic wave speeds in the crust we are dependent on extrapolation of isolated refraction experiments from before 1980, and a few receiver functions at broad-band stations linked with ambient noise tomography. For the mantle component of the lithosphere the primary information comes from surface wave tomography, supplemented by analysis of Pn mantle refractions. Additional constraints come from the analysis of the large-scale features of magnetic variations for both magnetic character and depth to base of magnetisation. The synthesis of the different classes of information provide indications of distinct lithospheric units along the profile that continue into the mantle.

## **AuSREM and beyond: insights into the Australian lithosphere**

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The Australian Seismological Reference Model (AuSREM), supported by AuScope, was launched in 2012. This 3-D digital model provides a summary of the seismological structure beneath the Australian region down to 300 km on a 0.5 degree horizontal grid, with 5km depth spacing in the crust and 25 km depth spacing in the lithospheric mantle. The model has formed an important starting point for other studies of the continent, particularly the exploitation of the results from dense passive seismic arrays in eastern Australia, including AuScope investment.

AuSREM has provided a suitable background for detailed tomographic inversion and for refinement of Moho topography using new receiver-based procedures. At a continental scale AuSREM has also been exploited at a continental scale for Pn tomography that provides fresh insight into structures just below the Moho. New methods have also been brought to bear on the transition between the lithosphere and asthenosphere. The varied finer-scale results provide a richer picture of the Australian lithosphere. There are clear indications of major gradients in lithospheric properties, and of distinctive sub-structure in the major lithospheric blocks. The edges of thickened lithosphere are surprisingly sharp, and appear to control complex edge-related convective processes.

## A hydrochemical characterisation of aquifers and springs near Lake Blanche, Lake Eyre Basin, South Australia

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This presentation provides a summary of a hydrogeological characterisation study of a number of spring complexes located within the Lake Blanche region, Far North South Australia. This study was completed as part of a vulnerability assessment associated with potential coal seam gas (CSG) development within the Cooper Basin and was funded by the Australian Federal Government.

Groundwater from 14 springs and 17 wells was collected and analysed for major ions, trace elements, the stable isotopes  $\delta^2\text{H}$ ,  $\delta^{18}\text{O}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  as well as radiocarbon and  $^{36}\text{Cl}$ ; and provided the basis for source aquifer characterisations. Based on trends observed within and interpretation of hydrochemical data from water wells, five hydrochemical classifications were established. Each classification correlating to the aquifer from which groundwater's were sourced; 1) Basement rock aquifer, 2) Patchawarra Formation (Cooper Basin) aquifer, 3) J-K (Algebuckina Sandstone and Cadna-owie Formation and lateral equivalents) aquifer of the Great Artesian Basin (GAB), 4) Coorikiana Sandstone (?) aquifer (Shallow GAB) and 5) Cenozoic aquifers.

Although the majority of spring water analysis inferred a J-K aquifer source, the results from a number of other spring waters inferred other aquifers may contribute to spring flow at those locations. Most notably, Lake Blanche spring complex, located approximately 4km from the margin of the Cooper Basin and the Mulligan and Lake Callabonna spring complexes, located approximately 50 km to the south east, are likely to obtain a large proportion of groundwater from shallow aquifer systems such as the Cenozoic and Coorikiana Sandstone.

An important finding of this study was the identification of the Coorikiana Sandstone as a potentially important aquifer with respect to the supply of groundwater to springs within the area of investigation. The Coorikiana Sandstone is a thin sandstone unit that occurs between the Bulldog Shale and Oodnadatta Formation, which are the two most important confining units above the major aquifer unit (the J-K aquifer) within the South Australian portion of the GAB. Although the Coorikiana Sandstone has been previously recognized in parts of the basin to the north of the area of investigation, a review of historical logs has found sandstone and other sandy sediments at a similar depth much further to the south. Additionally, a review of historical logging data indicates that a number of wells within the area of investigation have either been completed within this sandstone unit or that water from this sandstone unit is currently leaking into the well annulus. Although further work is required to confirm this finding, this interpretation has important implications with respect to our understanding of the geology, basin architecture and the hydrogeology of this region.

A number of management and regulatory implications stem from the findings of this work, most notably with respect to recognising that groundwater dependent ecosystems are potentially supplied by multiple aquifer systems and that groundwater from the Coorikiana Sandstone is a relatively small but important resource within the area of investigation.

## BIF-style iron deposits of the Middleback Ranges, South Australia: Trace element signatures of Fe-oxides and implications for ore formation

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Banded iron formation (BIF)-style mineralization of the Middleback Ranges (MR) forms a ~60 km-long N-S-striking belt in the southeastern part of the Gawler Craton. The iron deposits are predominantly hosted within the Lower Middleback Iron Formation (LMIF), which consists of a 'mixed' basal sequence, a lower iron carbonate unit, a middle iron-talc unit and an upper iron-silica unit, all grading up sequence and laterally [1]. Deposit sequences themselves can be complex, as exemplified in the Iron Magnet deposit. Magnetite occurs as layer replacement, matrix to breccias and clasts within breccias, and within veins [1]. At higher levels, hematite is dominant and varies in textures but pseudomorphic replacement of magnetite (martitisation) is common throughout all deposits. In massive ores, hematite occurs as lamellar or anhedral, fine-grained, vuggy aggregates, often with dusty inclusions of gangue minerals. Tectonothermal events spanning the Archean to Mesoproterozoic responsible for formation and deformation of the Gawler Craton have impacted the LMIF (e.g. [2]).

Trace element signatures of Fe-oxides from these deposits may record such events. Here, we discuss the first LA-ICP-MS trace element analyses of magnetite and hematite from samples representative of deposits along the belt with the aim to understand whether distinct trace element signatures in such minerals can be used to support genetic models.

LA-ICP-MS data for magnetite and hematite show measurable concentrations of a broad range of minor and/or trace elements. Of these, some are common in BIF-style ores (e.g. Al, Si, Mn and P) but others are sparsely reported in analogous ores. Examples include rare earth elements and yttrium (REY), Zn, Cu, As, Sb, Ti, Zr, and interestingly, U (tens to hundred(s) ppm and radiogenic Pb in samples from the central part of MR. Chondrite-normalised REY fractionation trends can vary within individual samples and between deposits, with changes in the sign of Ce-, Eu- and/or Y-anomalies, overall slope (from flat to LREE-enriched), and increase in REY over 1-2 orders of magnitude. Such changes are observed in magnetite showing deformation, related to martitisation or transformation of hematite into Fe-hydroxides. Magnetite tends to be lower in REY than hematite, which is enriched in LREE, and generally displays positive Eu- and Y-anomalies. Such signatures will be discussed with respect to host lithologies signatures, their role in identifying marker protoliths for stratigraphic reconstructions, as well as processes during which the BIF formation is upgraded to Fe-ores. Importantly, recognition of measurable U in Fe-oxides from MR raises the possibility of applying U-Pb geochronology to date sedimentary iron ores. Iron-oxide geochronology, based on analysis of U-bearing hematite, was successfully applied to give Pb-Pb ages for U-bearing hematite in the Olympic Dam deposit [3]. Dating of U-bearing hematite from the present study would be critical in deciphering the geological evolution of the MR and the region.

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## Imaging fracture permeability using magnetotellurics

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We present modelling and interpretation of MT data to determine the electrical resistivity characteristics of natural fractures in the Otway Basin. We also present modelling of the electrical and flow properties of synthetic fractures to link these resistivities to fracture permeability.

Permeability in the crust comprises primary permeability, from interconnected pore space present at the time of deposition of sedimentary rocks, and secondary permeability, which can result from fractures and faults. Primary permeability is often not preserved once a rock becomes compacted or is subjected to high temperatures, and therefore at depths greater than a few kilometres, fracture permeability becomes important.

It has been shown that the introduction of an electrically conductive fluid into a natural fault network can produce changes in the bulk electrical conductivity that are measurable from the surface using the magnetotelluric (MT) method (Peacock et al 2013). We extend this concept to the imaging of natural fractures, prior to injection of fluids.

One dimensional anisotropic inversions of a broadband MT dataset from the Koroit region of the Otway Basin, Victoria, Australia have been carried out (Kirkby et al. 2015). An electrically anisotropic layer has been determined within the Lower Cretaceous Crayfish Group. The anisotropy strike is consistent between stations at approximately 160 ° east of north. The anisotropy is interpreted as fluid-filled fractures enhancing the bulk electrical and hydraulic conductivity in the NNW direction. This interpretation is consistent with permeability data from well formation tests. It is also consistent with the NNW orientation of mapped faults in the area, which are oriented favourably for reactivation in the current stress field.

To link these anisotropic resistivity characteristics to fracture flow properties, the similarities between electrical current and fluid flow have been used to explore the relationship between resistivity and permeability in fractures. Fluid and current flow have been modelled through rough synthetic fractures, generated based on characteristics measured on natural rock fractures, using a resistor network approach. Each fracture is progressively opened to investigate the changes in resistivity and permeability as the aperture is increased.

Both electrical conductivity and permeability increase non-linearly with mean fault aperture. At small apertures, electrical conductivity and permeability increase moderately with aperture until the fault reaches its percolation threshold. Above this point, the permeability increases by four orders of magnitude over a mean aperture change of less than 0.1 mm, while the conductivity increases by up to a factor of 10. Permeability increases at a greater rate than conductivity, so the percolation threshold can also be defined in terms of the electrical conductivity, expressed as the matrix to fracture resistivity ratio, M. The value of M at the percolation threshold,  $M_{PT}$ , varies with the ratio of rock to fluid resistivity, the fault spacing, and the fault offset. However,  $M_{PT}$  is almost always less than 10. Greater  $M_{PT}$  values are associated with fractures above their percolation threshold and thus open for fluid flow.

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## The birth of a Proterozoic ocean; isotopic backtracking the WAC and the SAC

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The Precambrian crystalline basement beneath the Eucla Basin likely hides critical constraints on the Proterozoic stitching together of the West Australian Craton (WAC) and the South Australian Craton (SAC). The Eulca Basement is divided into two major units, the Madura Province and the Forrest Zone; these blocks lie between the Albany-Fraser Orogen on the west and the Galwey Craton on the east.

We present the results of a comprehensive Hf isotopic study of dated zircon from stratigraphic drill hole samples from this key region. The apparent evolution array in our data of the Forrest Zone and Madura Province is similar to the spread of data from the Musgrave Province of central Australia, heading to an apparent fractionation event at c. 1.9 Ga. However, this is not just a simple reworking process in that new depleted mantle addition is also clearly demonstrated at various points, especially at c. 1.9 Ga in the Haig Cave Supersuite. Rather, results imply a mixing array localised around a  $^{176}\text{Lu}/^{177}\text{Hf}$  ratio of 0.018 with scatter to higher  $^{176}\text{Lu}/^{177}\text{Hf}$ . In addition, evolved material is also necessary to explain scatter to lower  $^{176}\text{Hf}/^{177}\text{Hf}$  values, and could reflect incorporation of a small Archean crustal component.

This apparent evolution array unifying the Madura Province and Forrest Zone is distinctive from most other regions of Australia, but has been recorded between intervening Archean Cratonic blocks, notably between the South and West Australian Cratons. Supporting evidence for a new crustal growth event at c. 1.9 Ga in the Musgrave Province was previously derived from oxygen isotope data, implying at least some pristine mantle-derived melts at that time and new data has now identified inherited 1.9 Ga zircon with radiogenic Hf isotopic compositions. Additionally, Nd and Hf isotopic data from the Rudall Province suggests a 1.9 Ga source in some melts. The magmatic history of the Albany-Fraser Orogen, Musgrave Province and Eucla Basement records to varying degrees new asthenospheric melt, primordial lower crustal material that was initially produced during a 1.9 Ga fractionation event, and a minor evolved Archean component, which may reflect isolated crustal slivers detached from the hyper-extinct marginal cratons.

Much of the melting in the Eucla Basement is of material that originated as oceanic crust at 1.9 Ga or thereafter, that was to variable degrees isotopically modified during convergence of the WAC and the SAC. A fundamental observation on the Forrest and Madura datasets is the lack of significant old evolved crust with magmatism repeatedly driven by new depleted mantle addition and reworking of the proceeding periods of MORB like input, commencing at c. 1.9 Ga. The Eulca Basement isotopic evolution pattern is consistent with this region reflecting development of a Proterozoic ocean to ocean-continent transition zone.

## Evolution of the Central Asian Orogenic Belt in the Paleozoic – A subduction epicentre during the formation of Pangea

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One of the largest accretionary orogens on earth, the Central Asian Orogenic Belt (CAOB), is situated in the middle of Eurasia, or more precisely between the East European (Baltica) and the Siberian cratons, and the Tarim and Turan blocks. It was active throughout the Paleozoic and contains mainly Precambrian fragments and arc related terranes. There is still an ongoing debate on how the individual terranes were arranged prior to the final amalgamation in the late Paleozoic. Generally, models between an archipelago type and a single arc type setup are discussed. Geological evidence suggests that at least some terranes, which make up the proposed Kazakhstanian microcontinent, are derived from early Paleozoic Gondwana. We undertook an intensive paleomagnetic study on areas in the Kyrgyz Tianshan and Kazakh Karatau Mountains on rocks ranging from Cambrian to Permian in age. We conducted standard paleomagnetic measurements to test if the characteristic remanent magnetization is of primary origin or not. This is inevitable because of the numerous occurrence of remagnetization and inclination shallowing events especially in Paleozoic rocks, which can fundamentally bias paleogeographic reconstructions. We were able to detect several areas within the Karatau Range, which suffered three phases of remagnetization related to orogenic events. Because distinct phases of orogenic movements are described there, it was possible to reconstruct the deformational history of this area. On the other hand, we detected large scale inclination shallowing in red beds from the Kyrgyz Tianshan. Results from a similar section yielded a reconstruction of this area at very low latitudes. We were able, however, to robustly correct for that bias and conduct the pre-shallowed primary inclination.

Taken together all our results with some recent high quality studies from Kyrgyzstan and Kazakhstan we delineate the paleogeographic history of the Kazakh terranes:

Originating at about 40°S from the Gondwana margin at about 500-540 Ma some fragments separated and migrated northwards. During the Upper Ordovician a collision-accretion event lead to a first phase of remagnetization and probably represents the formation of Kazakhstan. The microcontinent moved then further north until it reached a position of about 30°N in the Devonian at about 370 Ma. Between the Devonian and the final amalgamation in the Permian, Kazakhstan occupied a latitudinal stable position. During the final amalgamation a subsequent counterclockwise rotational movement about a vertical axis of the whole area took place with maximum amounts of 100°. During this rotation phase the crust got fragmented, which is shown by a wide range of rotational amounts of single blocks.

We further suggest that, since Siberia and Baltica were still moving between 400 and 250 Ma that Kazakhstan might represent a subduction epicentre. Subsequently more terranes and finally Baltica, Siberia, Tarim and Turan lead to the formation of Laurasia surrounding the CAOB, which lead ultimately to the formation of Pangea.

## Large scale reorganization within supercontinents – The Pangea Controversy

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One of the largest and enduring enigmas related to paleogeography based on paleomagnetism is the precise configuration of the last supercontinent Pangea. Paleomagnetic data from Gondwana and Laurasia before Late Permian times yield a significant north-south overlap of ~1000 km in a standard Wegenerian reconstruction. This led to the proposal (Irving, Nature, 270, 304-309, 1977) of an alternative configuration – Pangea B – where Gondwana is shifted by about 3000 km to the east relative to Laurasia. A transformation of this Pangea B to the Wegenerian Pangea A must have happened before the opening of the Atlantic in the Jurassic and has been proposed to have taken place before the Late Permian (Muttoni et al., EPSL, 215, 379-394, 2003), when the paleomagnetic data are in agreement again. This model would, however, require the existence of a major right-lateral shear system that occurred between Laurasia and Gondwana and was active for about 20 Myr. Driving mechanisms of this shear zone have been related to rifting of the Neotethyan Ocean to the east and the subduction of the Panthalassan Ocean to the west.

However, for some authors the misfit prior to the Late Permian was an artefact of several sources of error within the paleomagnetic dataset. These are for example related to inclination shallowing of the magnetic signal in sediments and a paleomagnetic field influenced by non-dipolar components.

In order to seek more evidence for the postulated large intra-Pangea mega-shear-zone, we sampled about 50 rock formations ranging in age from 260-285 Ma in Sardinia (Aubele et al., G3, 15, 1684-1697, 2014), southeast France (Aubele et al., Tectonics, 31, 2012) and northeast Spain (Aubele et al., in prep.). Incorporating some other results from the same areas and from rocks of the same age, we obtained evidence for a vast array of vertical axis rotations, which deviate the observed virtual geomagnetic poles (VGPs) away from the expected positions predicted by the apparent polar wander path (APWP) of Eurasia (e.g., Kirscher et al., JGR, 116, 2011). All resultant VGPs plot on small circles about the according sampling areas and intersect with the APWP at the expected age. Deviations indicate clockwise and counterclockwise vertical axis rotations up to 60°, respectively, in a non-systematic manner. We relate this to small fault bounded blocks within the large shear zone. Additional studies of Triassic and Jurassic rocks from similar areas in France and Sardinia, where these rotational movements are absent, constrain the rotation age to be pre-Mesozoic.

Our results thus favor the occurrence of major tectonic movements during the existence of Pangea, which are consistent with an active mega-shear zone. So even though the supercontinent is surrounded by subduction zones, which keep the continental pieces in place, major tectonic movements evidently happened during that time prior to the final break-up.

## **Photogrammetry-assisted mapping of solution collapse breccia pipes, Colorado Plateau, U.S.A.**

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The Colorado Plateau in Arizona, U.S.A., hosts hundreds of solution collapse breccia pipes (Wenrich, 1985). These pipe-like bodies of fragmented rock and matrix initially formed due to the dissolution of the Redwall Limestone (Mississippian) during the development of an extensive karstic terrain and the formation of caverns. At various times the ceiling of these caves would fail and the overlying formations collapse into the void. Further dissolution was then followed by an upward stoping process, finally resulting in a pipe-like structure filled with angular to rounded fragments of broken rock and matrix – the breccia (up to 1300 metres high). The collapse was also accompanied by brittle and ductile deformation in the surrounding, horizontal strata, and probably caused subsidence on the surface. Further a sharp contact zone (sheeted zone) with concentric, near vertical ring fractures, and steeply inward dipping strata separates the fragmental material from the enclosing rocks. The general aspects of the formation of these features are understood (e.g. Wenrich, 1985), but the details of the subsidence mechanisms have not previously been investigated. Recent erosion (~5 Ma ago) and exhumation of the pipes resulted in multiple surface exposures. Most of the target breccia pipes are exposed in the canyon walls and inaccessible. Therefore Terrestrial Digital Photogrammetry, a remote sensing technique, was employed for data acquisition. This technique, combined with high precision topographic measurements recorded by means of a Differential GPS, allowed the generation of accurate and undistorted 3D models from 2D imagery using software packages such as Agisoft Photoscan or CAE Sirovision™. The correctly scaled and georeferenced models allow the identification and mapping of key geological features of the rock mass comprising the pipes, including such physical features as block size and shape, and discontinuities. Within the fragmental material of the pipe core, there is an outer zone comprised of concentric flow layering (now lithified) which wraps vertically around the outer margins of the core forming a prominent collar-like shape in eroded canyon wall exposures. The inner portion of the pipes preserves evidence of flow processes that once occurred in the pipes (prior to lithification) including multiple overprinting zones of internal subsidence (flow within the broken material), near horizontal layering, open and closed breccia frameworks on a massive scale (blocks can be several metres across) and maintenance of bulk composition in the clast distribution of the breccia. In addition to characterising the natural pipes and their formation, the information could be used to develop dynamic flow simulation models for induced cave mining.

Reference: Wenrich, K.J. 1985. Mineralization of breccia pipes in northern Arizona: Economic Geology, v. 80, no. 6, p. 1722-1735.

## **Geodynamic numerical modelling for examining tectonic scenarios of the Halls Creek Orogen**

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Deciphering the development of ancient geologic terranes is difficult and multiple scenarios are often proposed for their formation through time. Numerical modelling can play an important role in developing and testing geodynamic hypotheses and help us explain the evolution of early earth.

The Halls Creek Orogen (HCO) is used as a case study for numerical modelling to reveal the tectonic evolution of a Precambrian orogen. The HCO consists of three parallel, north-northeast trending zones (western, central and eastern) which are each interpreted as distinct tectonostratigraphic terranes. These zones contain geological units formed during the early Paleoproterozoic that may have originated in different settings and times, and were likely juxtaposed during the 1870-1850 Ma Hooper and 1835-1805 Ma Halls Creek orogenies. There is some controversy as to how the Halls Creek Orogen developed. The 1865 Ma Tickalara Metamorphics seem to be a key unit within the Halls Creek Orogen for solving this. The formation of the protolith sedimentary and igneous rocks of central zone have been described as either forming in an oceanic island arc setting above an easterly dipping subduction zone outboard of Kimberley Craton, or in an ensialic marginal basin, closer to the margin of Kimberley Craton.

If the Tickalara Metamorphics represent an oceanic island arc, an east dipping subduction may have formed towards an over-riding North Australian Craton. Retreat of the subduction zone and then reversal of subduction polarity may have followed until the 1835-1805 Ma Halls Creek Orogeny, which resulted in the collision of the eastern and central zones. In contrast, the ensialic marginal basin may have been initiated due to the westward subduction zone stepping back following collision of a continent fragment sometimes before 1900 Ma.

The two plausible tectonic scenarios of the Halls Creek Orogen are examined through a series of 2D thermo-mechanical-petrological numerical experiments based on I2ELVIS code. The lithospheric architecture of the Halls Creek Orogen constrained between thicker cratonic masses namely North Australian Craton and Kimberley Craton. These numerical models allow the examination of the geodynamic setting scenarios of the Halls Creek Orogen through time. Finally, understanding the tectonic evolution of the east Kimberley has implications for the assembly of the Australian cratonic blocks and the formation of the Columbia supercontinent.

## Zircon radiation damage thermochronology: A case history from Tasmania

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The possibility that changes in physical properties accompanying the accumulation of radiation damage in zircon could be used as a tool to measure geological ages was first proposed more than 60 years ago. Later studies however, revealed that radiation damage could be thermally annealed as well as enhance He diffusion. These complexities soon led to abandonment of zircon radiation damage ages for application in geochronology. The later successful application of zircon fission track dating however demonstrated that a specific type of radiation damage age could form a viable geochronology technique.

With the advent of modern (U-Th)/He thermochronology, several zircon studies have demonstrated the potential for their broad application in geochronology. Although thermally activated volume diffusion is thought to be central in controlling He migration, crystal defects and radiation damage, are also considered important. A first-order proxy for estimating the degree of accumulated radiation damage in zircon grains is derived by calculating an estimate of the  $\Sigma$ -dosage ( $D\Sigma$ ) from its effective uranium concentration [eU]. Plots of zircon (U-Th)/He (ZHe) age versus [eU] may be positive or negative depending on degree of radiation damage and thermal history. We present a case study from onshore and offshore Tasmania demonstrating how ZHe data and consideration of their radiation damage may yield unexpected age relationships when used in combination with other thermochronological data.

Tasmania, hosts a large volume of Early Jurassic (~180 Ma) tholeiitic dolerite intrusions, forming part of one of the world's major continental flood basalt provinces, (Tasmania-Ferrar-Karoo Igneous Province), which is regarded as a precursor to the break-up and dispersal of Gondwana. ZHe data from dolerites yield either the age of dolerite emplacement for grains with relatively low radiation damage ( $D\Sigma = \sim 0.2\text{--}0.3 \times 10^{18} \text{ S/g}$ ), or mid Cretaceous ages for grains with increased  $\Sigma$  dosage ( $D\Sigma = \sim 0.4\text{--}1.0 \times 10^{18} \text{ S/g}$ ). Mid Cretaceous ZHe ages are also found in high radiation damage zircons ( $D\Sigma = \sim 1.0\text{--}15.0 \times 10^{18} \text{ S/g}$ ) from crystalline Paleozoic basement in the offshore eastern South Tasman Rise (STR). These ages are concordant with apatite fission track (AFT) ages for dolerites in southeastern Tasmania, and for eastern STR basement consistent with their slightly younger apatite (U-Th-Sm)/He ages, and represent a cooling episode probably related to denudation associated with continental extension prior to opening of the Tasman Sea. Vitrinite reflectance data from Lower Permian sediments underlying the dolerites (but not in close contact) indicate they experienced maximum post-depositional temperatures of ~140°–160°C. This was achieved in the mid Cretaceous during maximum burial under the now largely eroded Mesozoic Victoria Basin. In western Tasmania, AFT ages are somewhat younger (Late Cretaceous to Early Tertiary) than the corresponding mid Cretaceous ZHe ages, and are interpreted as dating local cooling related to transform margin formation in that area.

Zircons from Tasmanian dolerites and offshore basement with high  $\Sigma$ -dosage form a quasi age plateau and appear to record a distinctive, widespread mid Cretaceous cooling episode. Our findings underscore the complexity of the zircon radiation damage-He diffusion relationship.

## Remobilisation of REE, Y and U during feldspar replacement reactions in IOCG systems: examples from the Olympic Cu-Au Province, South Australia

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The presence of feldspar replacement reactions has long been recognised as a diagnostic property of iron-oxide copper-gold (IOCG) systems [1]; however the exact role they play in the genesis of such deposits remains poorly constrained. Detailed studies of deuterian coarsening and albitisation have highlighted the ability of such reactions to alter the physical and chemical properties of the host rocks during fluid-rock interaction at the micro- to nanoscale. This invokes the idea that feldspar replacement reactions might be more important than once thought, and may even be a prerequisite for deposition of IOCG mineralisation.

The Olympic Cu-Au Province, eastern Gawler Craton, South Australia, provides a unique opportunity to constrain the role feldspars play in IOCG genesis. Recent studies combining microanalysis with observations from the macro- to nanoscopic scales have outlined changes in the textures and geochemistry of feldspars in fresh to altered host rocks from different settings within the province [2]. Such studies have also highlighted the applicability of feldspars as geochemical tracers of the magmatic-to-hydrothermal evolution of a system, and for understanding the effects which abundant *in-situ* feldspar replacement reactions have on the host rocks.

The presence of REE-fluorocarbonate mineral inclusions within albite and other hydrothermal feldspars, together with chondrite-normalised REE+Y (REY) fractionation trends for feldspars supports local remobilisation of such trace elements within the host rock, but importantly, out of feldspar crystal lattice itself. Significantly, this is observed in the unmineralised host rocks at depth or at the periphery of the IOCG orebody, likely representing the earliest stage of Fe-REY-U metasomatism in the nascent IOCG system. Comparison of REY fractionation trends between ~1.6 Ga Hiltaba suite granites and ~1.8 Ga Donington suite equivalents (Eyre Peninsula) highlights the enrichment of REY in the former. Given the physical dimensions of the Hiltaba suite granites (e.g. at least 7 x 9 x >2.5 km around the Olympic Dam orebody), and the abundance of feldspars in these rocks (~60% by mode), it is suggested that destruction of feldspars and leaching of REY contributed significantly to the ‘enrichment’ of REY in IOCG systems in the Olympic Cu-Au Province, notably at Olympic Dam.

Refractory magmatic mineral phases within the host rocks also display evidence of REE-U remobilisation at this early stage (e.g. recrystallisation of apatite coupled with a loss in REY + U). A common theme throughout is the leaching of REY and U from all mineral phases and re-deposition of these elements as discrete minerals, contributing to higher grades locally, and a marked ‘enrichment’ in mineralised rocks relative to background.

Further work is required to constrain certain textural and geochemical observations from IOCG systems at province, deposit/prospect, hand-specimen, and micro- and nanoscales. The overarching goal is to trace fluid-rock interaction using feldspars as a proxy for complex metasomatism involving Fe-REY-U during sequential alteration stages in an IOCG system.

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## **Ecological assessment of a Late Miocene coral assemblage near Rowley Shoals, Roebuck Basin, Western Australia**

**Korpanty, Chelsea<sup>1</sup>; Potts, Donald<sup>2</sup>; Pandolfi, John<sup>1</sup>; and IODP Expedition 356 Scientists**

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The timing and distribution of Cenozoic reef development on the North West Shelf (NWS) of Australia were facilitated by the variability and interplay of regional and local tectonics, submarine topography, global sea level, and warm coastal currents over time. Limited data from well cuttings suggest there were tropical reefs in the Browse, Bonaparte, and Northern Carnarvon Basins by the middle Miocene. More recent 2D and 3D seismic images support these findings by defining stratigraphic buildups that have been interpreted as reef structures. These images provide insights into reef locations and geometries and improve understanding of platform evolution and reef development in response to regional environmental parameters, but they do not provide ecological information.

Little is known about the ecology of Miocene reefs on the NWS, apart from sparse borehole and outcrop data. International Ocean Discovery Program (IODP) Expedition 356: Indonesian Throughflow (ITF) recovered multiple deep cores from the NWS between 29°S and 18°S to obtain a 5 My sedimentological record of regional climatic, tectonic, and biological patterns related to the timing of onset and variability of the Indonesian Throughflow. At the northernmost site (U1464), near the Rowley Shoals in the Roebuck Basin, fossil zooxanthellate corals were recovered from ~309.0 – 511.0 mbsf (metres below sea floor), and biostratigraphic evidence suggests that they are of Late Miocene age. This collection provides a rare ecological sample of a Late Miocene reefal assemblage on the NWS. Post-cruise research is focussing on identifying these corals and relating their ecology to the sedimentology of Hole U1464C and to regional and global climate variation during the Miocene. The overarching goals are to better understand Late Miocene reef communities on the NWS and their responses to local environmental changes, and to relate this new assemblage to contemporaneous assemblages in the central Indo-Pacific that experienced similar environmental fluctuations.

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## OSL dating revealing new insights into the landscape evolution of the eastern Musgrave area

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The eastern Musgrave area is located between the monsoon-influenced northern and the westerly-influenced southern Australia and hence can provide crucial insights into how climate changes have shaped this transition area of Australia's arid zone in the late Quaternary. The area forms part of the western-most margin of the Pedirka Desert and is bordered to the west and south by the Great Victoria Desert and to the north and east by the Simpson Desert. This region also lies at the junction of five geological provinces.

Optically-stimulated luminescence (OSL) dating was used for the first time in this area to develop a chronology of aeolian and alluvial deposition in order to understand and reconstruct the landscape evolution. Samples derived from three different landforms including a succession of source-bordering dunes located directly east of the Alberga River on DeRose Hill Station about 70 km south of Kulgera; a longitudinal dune complex SSE of the source bordering dunes; and from a sand plain exposure in an excavation pit SSW of the longitudinal dunes. Previously these deposits have all been assigned a Holocene or undifferentiated Quaternary age. Results from the OSL dating show that the majority of the source bordering dunes were deposited between 76 to 37 ka, with a prominent dune deposition phase around 44 ka. The longitudinal dunes range in age between 56 to 24 ka with underlying alluvial plain deposits dated at 64.6 ka. The sand plain deposits have been dated at 53 and 24 ka. This places all of these landforms and their associated deposits into the Late Pleistocene.

The OSL data show that there is little record of aeolian deposition during the Late Glacial Maximum and Holocene in the study area indicating that the dunes and sand plains have dominantly formed during the period between 76 to 24 ka. The OSL ages also show that they are offset from known dune formation phases in other arid regions, e.g. in the Strzelecki and Tirari Deserts or western Simpson Desert.

The longitudinal dunes are located directly to the east of the source bordering dunes, which parallel the eastern side of the Alberga River over tens of kilometers. OSL ages indicate that the source bordering and longitudinal dunes have formed nearly contemporaneous. Therefore the longitudinal dunes can be interpreted as the downwind extension of the source bordering dunes during their formation. In comparison to source bordering and longitudinal dunes described from other parts of the Australian arid zone the dunes in the eastern Musgrave lack distinct palaeosol horizons. Therefore, their depositional history represents a continua rather than sharply defined episodes, pointing to a consistent sediment supply and uniform wind regime throughout their depositional history. These aeolian landforms represent mostly fossil landforms despite the presently arid climatic regime, with limited dune crestal mobility the only sign of modern activity.

The thin sand plain deposits underlying and surrounding the dunes show more pronounced paleosol development than the dunes. They represent predominantly bypass zones with low sedimentation rates and limited alluvial activity reworking locally derived material.

## REY-signatures in apatite monitor the evolution of IOCG systems: examples from Olympic Dam and Acropolis, South Australia

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The Olympic Cu-Au Province, South Australia hosts numerous Mesoproterozoic iron-oxide-copper-gold (IOCG) deposits, of which the largest is Olympic Dam (OD). Mineralization is hosted within the Olympic Dam Breccia Complex (ODBC) which is, in turn, located within the Roxby Downs Granite (RDG), a member of the ~1.595 Ga Hiltaba magmatic suite. Breccia-hosted mineralisation contains dominant hematite, Cu-(Fe)-sulphides, carbonates, sericite, chlorite and a range of discrete U- and REY-bearing minerals (Ehrig et al. 2012). Apatite is an important and, locally very abundant component of both the pre-existing host rocks and mineralisation. The Acropolis (AC) prospect, approximately 25 SW of OD, is hosted in altered felsic Gawler Range Volcanics (GRV) and ~1.85 Ga Donington suite granite. Mineralisation at AC occurs in veins and breccias containing iron-oxides, apatite, K-feldspar, sericite, chlorite, carbonates, Cu-(Fe)-sulphides and discrete U- and REY-bearing minerals.

Due to its widespread occurrence and capacity to incorporate a wide array of elements sensitive to changes in mineralising conditions, apatite chemistry has been used as a means of gaining insights into processes of metallogenetic interest (e.g. Harlov 2015). We present new LA-ICP-MS data for apatite hosted in weakly- to pervasively-altered RDG within drillholes S and SE of the ODBC and for apatite from GRV-hosted veins and breccias from two drillholes intersecting the AC prospect: ACD1 (magnetite-dominant); and ACD2 (martite-dominant). The two drillholes are ~5 km apart.

RDG-hosted magmatic apatite has high REY concentrations (mean ~50,000 ppm), and commonly consists of inclusion-rich cores overgrown by zones of extreme REY enrichment (mean ~105,000 ppm). Both zones display a LREE-enriched chondrite-normalised fractionation trend with strong negative Eu-anomaly, with a weak Ce-anomaly in the rims. Both zones undergo depletion of REY along fractures filled by hematite, sericite and monazite. Chondrite-normalised fractionation trends show preferential removal of both LREE and HREE, but not MREE, and a weakening of the negative Eu-anomaly.

Earliest hydrothermal apatite is seen in pervasively hematite-sericite altered RDG as small grains intimately intergrown with sericite, hematite and florencite. Such apatite displays a strongly MREE-enriched chondrite-normalised fractionation trend with a weak negative Eu-anomaly. Early hydrothermal apatite from the AC prospect shows a LREE-enriched chondrite-normalised fractionation trend in grains intimately associated with early magnetite mineralisation comparable to that seen in magmatic RDG apatite. However, such grains contain altered domains of MREE-enrichment and depletion in REY along fractures and grain rims. Apatite intimately intergrown with and containing inclusions of sericite, hematite and monazite displays a flat to MREE-enriched chondrite-normalised fractionation trend.

Although numerous parameters may be responsible for the change from LREE- to MREE-enriched apatite signature, it would appear that LREE-enrichment is more commonly a feature of magmatic and early hydrothermal apatite whereas MREE-enriched trends are characteristic of later, more advanced stages of mineralisation. Changes in fluid chemistry, in particular those affecting REY transport, could be responsible. Alternatively, the strong MREE-enrichment may relate to co-crystallisation of later apatite with LREE-consuming minerals such as monazite, florencite and bastnäsite and with HREE-consuming xenotime.

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## Sponges as environmental indicators in the Red Crust ferrimicrobialite horizon, Flinders Ranges, South Australia.

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The Red Crust is a metre-scale horizon at the top of the Wilkawillina Limestone or equivalent within the Lower Cambrian succession of the Arrowie and Stansbury Basins, South Australia. It consists of a wide variety of ferrimicrostromatolites, *Frutexites* and other ferrimicrobialites. Although previously interpreted as a subaerial unconformity, the Red Crust is reinterpreted as the result of a 'ferruginous excursion' of anoxic Fe<sup>2+</sup>-enriched deep marine waters into a shallow-water environment. Although such an excursion would normally be considered detrimental to metazoan life, in many places the laminated facies of the Red Crust was colonized by numerous small calcareous sponges. These are dominantly *Gravestockia pharetronensis* Reitner, first described from archaeocyath bioherms in the Mt Scott area, and are widespread within the upper part of the Wilkawillina Limestone. Usually they are found encrusting archaeocyaths, and as such occur just below the Red Crust in the archaeocyath 'reef-tract' of the Brachina Gorge area.

*Gravestockia* do not occur within the manganese-rich, deeper-water facies of the Red Crust but are abundant in the laminated ferrimicrobialites overlying the reef-tract. They have not been observed within domains of digitate ferristromatolites, but occur mainly as erect and symmetrical thimble- to 'tree-stump'-shaped individuals 0.2-1.0 mm in diameter and height; low domal, conical, hour-glass-shaped or 'leaning' forms are less common. Numerous individuals can occur upon single lamina. In every case, the succeeding ferrimicrobialite lamina drapes, without any onlap, over each individual, showing that the *Gravestockia* grew in the interval between laminae formation. In a few places development of the *Gravestockia* was arrested by a ferrimicrobialite lamina, and the *Gravestockia* is only represented by the base-plate and a few spicules. *Gravestockia* also grew as irregular crudely equidimensional individuals within *Frutexites* thickets, lacking the well-defined base-plates and penetrating 'roots'.

The close association of *Gravestockia* with ferrimicrobialites, especially within *Frutexites* thickets, suggest that the sponges had some ability to survive 'ferruginous' environments, which may have been less demanding in the intervals between the formation of each lamina. This survival ability may have been due to the presence of complex (symbiotic?) microbial assemblages within the sponge tissue, which allowed some biological 'flexibility' in tolerating adverse environmental conditions. Studies of present-day sponges have shown that some have a remarkable ability to survive periods of low oxygen availability. The influx of ferruginous waters was episodic, even oscillatory, allowing the growth of numerous *Gravestockia* upon ferrimicrobialite laminae during the less-ferruginous intervals. However, *Gravestockia* were able to survive within *Frutexites* thickets, suggesting that these formed during less 'ferruginous' intervals.

## Geochemical and Isotopic Constraints on the Origin of Central Australian High Heat Producing Granitic Suites

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Located in the southern part of North Australia Craton (NAC), the Anmatjira-Reynolds Ranges host some exceptionally well outcropping granitic suites and associated mafic units formed during the Palaeoproterozoic. These granitic suites are anomalously enriched in high heat producing elements and yield radiogenic heat production values as high as 4 times above the modern global upper crust average ( $1.69\mu\text{Wm}^{-3}$ ).

Previous studies on these granitic suites mainly focus on their ages and metamorphic paths throughout the geological history. However, the origin(s) of the heat-producing elements enrichment in these granitic rocks has attracted very little attention. This study aims to describe the geochemical characteristics and constrain the likely source(s) of these ca 1800 Ma granitic suites from the Anmatjira-Reynolds Ranges.

Samples from four different granitic suites are classified as mildly to strongly peraluminous. Both granitic and mafic suites are strongly depleted on Nb and Ti. Most granitic samples display negative Eu anomalies ( $\text{Eu/Eu}^*=0.12-0.95$ ) and Sr depletions – suggesting that plagioclase was stable in the source region. Similarities between the spidergrams and REE plots of the different granitic suites suggest that they were derived from a similar source. Initial Nd values from around zero to negative values of both mafic and granitic samples indicate that significant crustal material was incorporated into their protoliths.

The zircon age spectra for inherited zircons from the granitic suites and published detrital zircon data from the surrounding widespread Lander Rock Formation are similar. This suggests that the possible source of the U-Th enriched granites in Anmatjira-Reynolds Ranges is from rock strata similar to the Lander Rock Formation.

## **Advances in mineral spectroscopy for rapid resource characterisation – examples from South American base metal deposits**

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The collection of spatially continuous mineralogical data is important to address many of the challenges in mining operations. Certain gangue mineral assemblages may be associated with specific ore types and may be used to classify the various domains of the ore body. Selected mineral phases, such as wollastonite, chlorite or kaolinite, may impact on grinding circuits or flotation cells and have to be identified as early as possible. Other minerals, such as talc or swelling clays, may weaken the stability of open pit operations, requiring a fast and accurate localisation.

Reflectance spectroscopy can be used to rapidly characterise mineral assemblages across different ore deposit styles, ranging from epithermal, porphyry and skarn systems to channel iron deposits. The increasing availability of the thermal infrared wavelength region (ca. 6000 to 14500 nm) with technologies such as the HyLogger3 enables the detection of, for example, quartz, feldspar and garnet. This allows the routine mapping of all major gangue minerals when combined with visible-near and shortwave infrared reflectance spectra and helps to identify mineral phases that are key for advanced resource characterisation. This paper aims to describe how hyperspectral drill core scanning technologies can provide detailed mineralogical information throughout the mining life cycle, from exploration through to mine planning and operation, using case studies from South American base metal deposits. This includes the extraction of quantitative mineralogy from visible-near, shortwave and thermal infrared reflectance data, calibrated using QXRD and QEMSCAN and the related limitations of each of the three technologies. Furthermore the scope for modelling other geometallurgically important parameters, such as hardness, from spectral signatures will be addressed.

## Relationship of geochemistry and mineralogy to parent lithology and the degree of weathering in regolith

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The relationship between whole rock geochemistry and mineralogy interpreted from infrared reflectance spectroscopy and XRD has been assessed in order to evaluate degree of weathering in parts of the Edmund Basin, located in the Western Australian Capricorn Orogen. Furthermore we tested the application for remote sensing data for mapping lithology and the degree of weathering by comparing the regolith geochemistry and mineralogy with potassium radiometrics and ASTER AlOH group composition values from the sample coordinates. Hyperspectral visible near (VNIR) and shortwave infrared (SWIR) reflectance spectra were collected with a FieldSpec<sup>3</sup> Hi-Res from 522 archived regolith samples (mostly from stream sediments) of the Geological Survey of Western Australia and Commonwealth Science and Industrial Research Organisation geochemical sampling campaigns. The acquired reflectance spectra were processed in The Spectral Geologist (TSG™) software by using a Multiple Feature Extraction Method (MFEM).

Thirty XRD analyses on samples having multi element geochemistry analysis confirmed the sheetsilicate mineralogy inferred from the SWIR data. XRD results show that the most abundant in selected regolith is quartz, which is not detectable in the SWIR. Kaolinite is most abundant in colluvial samples and present in smaller quantities in nearly all samples. White micas (muscovite and illite) are also present in most samples, being more abundant than quartz in samples originating from siltstone-mudstone lithologies. Chlorites are most commonly present in the samples originating from mudstones and siltstones.

The Chemical Index for Alteration (CIA) and  $\text{Al}_2\text{O}_3-(\text{CaO}+\text{Na}_2\text{O})-\text{K}_2\text{O}$  ternary diagram (A-CN-K) were used to compare geochemical with mineralogical results to investigate the degree of weathering in the different rock types. Samples with a high CIA are associated with high kaolin group abundance. When compared to lithologies underlying the regolith, sandstones show higher CIA than siltstones. The weathering trend indicated by increasingly elevated  $\text{Al}_2\text{O}_3$  in respect to  $(\text{CaO}+\text{Na}_2\text{O})$  and  $\text{K}_2\text{O}$  is associated with an overall increase of Al-clay abundance. Advanced weathering is accompanied by particular increase in kaolin group abundance. Hyperspectral-derived Al-clay composition indicates longer wavelength white micas along the weathering trend from feldspars to muscovite and illite, whereas shorter wavelength Al-clays, such as kaolinite, are associated with advanced weathering. The multispectral ASTER-derived AlOH group composition shows relatively good match with the weathering trends, with again Al-rich clays present in the strongly weathered parts and Al-poor clays in the slightly weathered domain. The potassium content from geochemical analyses was found to correlate moderately well with potassium radiometrics. Our study showcases the mapping of the degree of weathering by a combination of ASTER AlOH group composition and potassium radiometrics, potentially even distinguishing bedrock lithologies (e.g. siltstone versus sandstone).

## **Groundwater System Understanding, Resource Exploration and Assessment in the 21<sup>st</sup> Century: Inter-disciplinary Systems Science Using Advanced Sensor Technologies, and High Performance Computing in the Era of 'Big Data'.**

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Internationally, the use of advanced computational research infrastructure to manage, integrate and analyze 'big data', is revolutionizing science workflows, and creating exciting new opportunities and insights through integration of traditional science methods with 'discovery science' that enables data mining and analysis of large volume (spatial and temporal) datasets.

In Australia, groundwater system understanding, resource exploration and assessment, has been hampered by a paucity of data at all scales. This contrasts with the depth of understanding of minerals and petroleum systems, and reflects the disparity in investment in geoscience data acquisition and analysis between these sectors. However, over the past decade, advances in new satellite and airborne sensor technologies provide an opportunity for rapid multi-scale mapping, measurement and monitoring of the physical state of the crust, including resolution of key elements of surface and sub-surface hydrological systems. These advances have been mirrored by the development in advanced computational research infrastructure which is now giving the groundwater research community access to high-resolution (spatial and temporal) biophysical datasets (e.g. climate, ecology, geoscience and geospatial) relevant to broader hydrological systems understanding. This infrastructure facilitates integration of multiple datasets and rapid and improved signal processing, inversion, and sophisticated analysis. These datasets provide a catalyst for collaboration, with inter-disciplinary approaches enabling new discovery science in a 'big data' environment, and enabling the qualitative and quantitative analysis and modelling of landscape and hydrological system processes.

Geoscience Australia, in partnership with other Agencies, is currently developing e-research infrastructure for applied groundwater research. GA's (WATERSHED) research infrastructure enables rapid mapping and analysis of remote sensing, geophysical and hydrogeological datasets. This research infrastructure accesses the Australian Geoscience DATACUBE for the spatio-temporal analysis of Landsat (and MODIS) data, and GA's GFXVGL virtual laboratory for the management, analysis and inversion of geophysical data. In parallel, GA has streamlined methodologies and workflows for the mapping and characterisation of groundwater resources in frontier hydrogeological areas (eGRIDz); the mapping of seawater intrusion (eSWIM); the mapping and assessment of groundwater salinity hazard (eSALT); and the mapping of landscapes, hydraulic interconnectivity, fluxes and groundwater-dependent ecosystems (eLIFE).

This talk will demonstrate the application of this new research infrastructure and methodologies in national and regional-scale projects in the Murray-Darling Basin and in northern Australia. This new capability provides the platform for development a new generation of customised surface and groundwater maps and models that incorporate temporal data on climate and surface water availability. These new products and insights provide improved parameterization of regional and borefield-scale numerical groundwater flow models, and are being used to underpin water resource planning and assessments. The integration of temporal remote sensing data into holistic landscape analysis approaches is also transforming groundwater resource exploration and assessment strategies, and has led to more cost-effective targeting of potential groundwater resources and managed aquifer recharge (MAR) targets over large areas of the Australian continent. These new approaches and products are also being used to de-risk investment in irrigated agriculture and associated infrastructure.

## Neotectonic Controls on Landscape and Drainage Morphology and Evolution in the Western Murray Basin: Novel Tectonic Geomorphology Mapping

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The role of geodynamics/tectonics in the evolution of Australia's landscapes, geology, drainage and palaeo-drainage has often been overlooked or under-estimated. New insights into active tectonics have been gained through new active and passive satellite imagery (e.g. SPOT, Landsat, Hyperspectral, and Shuttle Radar Terrain Mapping (SRTM)), and airborne sensor technologies (e.g. Light Detection and Ranging (LiDAR), gamma radiometrics), which provide national- to regional-scale, high-resolution, land-surface mapping. These technologies by themselves have enabled accurate landscape and drainage-element mapping and topographic recognition of regional deformation. A unique neotectonic record of landscape, drainage and groundwater evolution has been revealed, preserved in part due to relative aridity, subdued power of fluvial processes, low depositional-landscape gradients, and in part due to dynamics of the fast moving Australian plate.

In the sub-surface, mapping of palaeo-landscape elements has been made possible through the use of airborne electromagnetics (AEM) that derives 3D hydrostratigraphic and tectonic element maps from the conductivity structure. In the Western Murray Basin, AEM datasets have mapped intra-plate fault systems including discrete 'blind' faults and broader deformation domains that shape the 3D geological architecture and underpin landscape, geological and hydrological processes. New insights into paleo-landscapes have also been gleaned through recognition that in Australia's semi-arid to arid landscapes, some radar-based imaging (including the SRTM) penetrates to depths of ~2m where the soils and sub-soils were dry at the time of acquisition. This has enabled mapping of near-surface palaeo-lakes and palaeo-river courses.

The utility of these new sensor technologies is maximised when used within the framework of advanced e-research computational infrastructure, which facilitates integration of multiple datasets, and sophisticated spatial, temporal and quantitative analysis, 3D mapping, and 4D reconstruction of landscape evolution. In the Western Murray Basin, new tectonic geomorphology maps have been developed by integrating multiple remote-sensing and geophysical data sources, validated by surface mapping, drilling and landscape and groundwater geochronology. These new maps incorporate mapping of sub-surface deformation elements, and the kinematics of landscape evolution.

This new mapping approach has enabled improved recognition and interpretation of Lower Darling landscape features such as older pre-dunefield river courses; regional scale (~10 km) uplifted blocks; disruptions such as river diversions, crossing lake shorelines, uplifted former lake floors or boinkas, and abandoned dune plinths; and relict landscape vegetation and/or mineral assemblage associations. Additionally, at a regional scale the recognition of underlying crustal deformation elements has allowed explanation of landscape features that have defied explanation since geomorphic mapping in the 1970s and regolith mapping over the past decade. These features include: the origin of the *en-echelon* overflow Willandra Lakes; the origin and valley-margin location of the flood-out Menindee Lakes; the overflow pattern and defeat of the Teryawenya Lakes; the highly variable location and morphology of the flood-out Anabanch Lakes; the repeated course switching of the lower Darling river and the multiple intersection of scroll-plain tracts just south of Menindee.

New generation tectonic geomorphology maps have great practical potential, and have been used successfully to predict groundwater resources and to constrain sampling strategies for minerals and energy exploration.

## Fault Zone Hydrogeology in Near-Surface Depositional Landscapes: an Inter-Disciplinary Approach

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Over the past decade, a relatively rich record of neotectonics has been revealed in continental Australia, with active intra-plate deformation zones identified through seismicity monitoring and satellite and airborne terrain mapping (e.g. SRTM, LiDAR). The latter have permitted the surface morphotectonic expressions of active fault systems to be identified, while detailed trenching, ground geophysics and regolith geochronology have revealed fault geometry and kinematics. However, there have been few investigations into the permeability heterogeneity and anisotropy introduced by these faults, and even less attention paid to the implications for groundwater processes and flow.

In the Western Murray Basin, a novel, inter-disciplinary approach has been developed to map and characterise neotectonic intra-plate fault systems in unconsolidated, near-surface sediments, and determine their hydrogeological character and impacts on groundwater flow. The approach entails mapping of the 3D hydrogeological framework using a combination of airborne, ground and borehole geophysics, remote sensing and drilling, with fault zone hydrogeology revealed through the use of hydrochemistry and hydrodynamics, and studies of vegetation response to water availability.

In the study area, LiDAR data identified a number of potential fault scarps, but surface fault expressions are typically obscured by dune-mantling, and/or eroded and buried during post-faulting sediment deposition. However, the sub-surface expressions of these and other 'blind' intra-plate fault systems were revealed using airborne electromagnetics (AEM) surveys, with fault geometries and offsets (up to 25m vertically) confirmed through drilling and ground geophysics (e.g. seismic reflection). The AEM data have permitted the mapping of hydrostratigraphy in 3D, including the offset and juxtaposition of unconfined and semi-confined aquifers, and 'holes' in regional aquitards, while key hydraulic parameters (e.g. aquifer texture, salinity & transmissivity) have been determined by integrating AEM data with borehole geophysics (e.g. nuclear magnetic resonance (NMR)), petrophysics and pore fluid hydrochemistry.

The mapped faults are an important element in the hydrogeological conceptual model. Hydrochemical data show that the Calivil Formation semi-confined aquifer (at depths >30m) is recharged primarily in high flow events along the Darling River. The hydrograph response to flood events along the Darling River in 2010 demonstrated that recharge of the Calivil Fm aquifer occurred prior to overbank flooding, within a few days of high flows being recorded in the river. Studies of overlying aquitards, including permeability measurements and modelling of aquitard advection and diffusion rates, indicate that bypass flow is essential to explain the groundwater responses. With very few 'holes' in the aquitard mapped, recharge through fault juxtaposition of the upper unconfined aquifer (connected to the river) with the underlying Calivil Fm aquifer is considered a key recharge mechanism.

However, previous studies of fault zone structure and permeability within inter-layered unconsolidated sand-clay sequences point to likely complexity in fault zone hydrogeology, and reductions in porosity, permeability and lateral flow within fault zones through inter-layer mixing, cataclastic deformation, clay smearing and diagenesis. Taking these factors into consideration, the inter-disciplinary approach developed in this study has integrated deterministic and stochastic approaches to unravel complex conduit-barrier system behaviour and parameterise a numerical groundwater flow model. The hydrogeological conceptual model has also been adapted to successfully target potential groundwater resources elsewhere in the Lower Darling Valley.

## Neotectonic Controls on Australia's Surface and Groundwater Systems

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Over the past two decades, the traditional 'regolith' view of an ancient, stable continent has been augmented by a deeper appreciation of the dynamic nature of the Australian plate. There is growing recognition of connection between plate-scale force balance, distribution of seismicity, and evolution of landscapes, geology and drainage systems. These new insights have been made possible through quantitative studies of crustal deformation incorporating high-resolution geodetic measurements and calculation of dynamic topographic effects; the use of geochronology to constrain the timing and rates of deformation; local-scale studies of individual faults to constrain fault geometry and kinematics; and detailed geomechanical investigations. In the subsurface, geophysical techniques are increasingly revealing 'blind' fault systems and discrete deformation domains that underpin landscape, geological and hydrological processes. Together these studies have revealed a unique neotectonic record of landscape, drainage and groundwater evolution, preserved in part due to relative aridity of the climate, subdued power of fluvial processes, low gradients in depositional landscapes, and in part due to dynamics of our fast moving plate. Together they have important implications for energy, mineral and groundwater resources and their discovery, curation, and environmental management. At long wavelengths ( $>10^3$  km), dynamic topographic effects induced by the plate's northward motion have contributed to tilting of the continent, while dynamic uplift has produced a relatively small topographic range and low hydraulic gradients. This has resulted in slow-moving regional groundwater flow systems. At intermediate ( $10^2$ - $10^3$  km) wavelengths, regional dynamic topography effects have played a significant role in the development of major drainage basins, such as the Lake Eyre Basin, and uplands, such as the south eastern highlands. This is reflected in valley and river morphology and the character and distribution of aquifers and aquitards at the catchment scale. Intermediate-scale tectonics and regional tilting has important consequences for the development of regional- to intermediate-scale groundwater flow systems (e.g. Great Artesian and Murray Basins), impacting their tempo and capacity to flush accumulated salt.

At short wavelengths ( $<10^2$  km), active deformation is manifest by the development of discrete intra-plate fault systems that modifies local landscapes and often controls and modifies drainage and palaeo-drainage. At basin and local scales, mapped fault systems are often localised by reactivation of crustal-scale faults and/or are localised at zones of crustal heterogeneity. In many Eastern Australian coal basins such zones appear to be characterised by in-situ stress heterogeneities that have important consequences for development and management of unconventional resources.

Due to the low gradients of many Australian floodplains, even faults with small offsets may have large 'keystone' effects on surface water and groundwater systems. This effect can involve step changes (abrupt transitions in space and time) for both the hydrological architecture (including the surface drainage network, river incision and alluvial sediment deposition) and hydrological processes (e.g. surface water-groundwater interaction, inter-aquifer leakage and spring discharge). These changes influence the distribution, evolution and sustainability of surface drainage systems, groundwater resources and dependencies such as phreatophytic vegetation, while also influencing pore pressure/effective stress variability, compartmentalisation and groundwater flow within sedimentary basins.

## Siberian basaltic flood volcanism: synchronous mass extinction and genesis of giant Ni-Cu-PGE sulphide deposits.

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The Ni-Cu-PGE deposits of the Noril'sk - Talnakh camp in Artic Siberia formed in association with the largest known outpouring of mafic magmas Earth history, synchronous with the Permo-Triassic (P-Tr) mass extinction event (Campbell et al., 1992). In this project we study the relationship between a specific ore-type (globular ore) abundant at Noril'sk, and degassing of large amounts of sulphur dioxide into the upper atmosphere associated with the P-Tr mass extinction event.

A striking characteristic of the Noril'sk deposits is the widespread occurrence of a specific ore-type termed 'globular ore'. In order to shed light on its formation, we performed detailed textural and mineralogical studies together with in-situ XRF geochemistry to constrain the composition of the sulphide and silicate phases within this ore-type. The results support the interpretation that the partially enclosed polymineralic assemblages spatially associated with the sulphide globules represent former segregation vesicles (Anderson Jr et al., 1984), generated by volatile saturation of the silicate magma, and subsequently filled by highly fractionated silicate-oxide-sulfide assemblages.

Deposits of the Noril'sk Ni-Cu-PGE camp represent the only known occurrences of ore formation in high-level intrusions under subaerial lavas. This peculiar setting would engender rapid pressure fluctuations accompanying explosive eruptions, favourable to degassing of the sulphides and host silicate magma. This degassing event would release large volumes of SO<sub>2</sub> and nickel into the atmosphere (the latter through attachment of chalcophile-rich sulfide liquid droplets to SO<sub>2</sub> gas bubbles; Mungall et al., 2015). A sudden atmospheric nickel flux has been suggested as a catalyst for a major bloom in methane-producing bacteria (Rothman et al., 2014) contributing further to a catastrophic atmospheric toxicity event. Hence vapour saturation and segregation during ore forming processes at Noril'sk may be the critical process linking the formation of the world's most valuable magmatic sulphide orebodies and the most catastrophic mass extinction in Earth history.

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## Transect from Walcha to Yarras in search of the Manning Orocline, NSW

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The southern New England Orogen from west to east, consists of a buried volcanic arc, concave to the east forearc basin (Tamworth Belt) and a subduction–accretion complex (Tablelands Complex) associated with a W-dipping subduction zone. Many authors believe that these was deformed into a megafold in the north (Texas-Coffs Harbour Orocline) and two smaller scale, megafolds (Manning-Hastings/Nambucca Orocline) in the south between 275–260 Ma. It is generally accepted that the Texas-Coffs Harbour Orocline is a classical orocline because it shows rotation of bedding and early foliations about a vertical axis. By contrast, the Manning and Hastings/Nambucca Oroclines have been the subject of much speculation with some advocating their existence and others sceptical of their presence. The basis for the presence of the Manning Orocline is a folded S<sub>1</sub> cleavage, the hinge zone of which occurs between Walcha and Yarras. The transect carried out in this study to confirm the existence of the Manning Orocline crosses the hinge zone of this structure. This transect encompasses multiply deformed, HTLP rocks associated with the Tia Complex as well as LTHP subduction-accretion rocks of the Tablelands Complex.

Structural mapping, b cell parameter white mica and petrographic studies of the rocks west and north of Walcha indicates the rocks contain an S<sub>2</sub> fabric rather than S<sub>1</sub> as suggested by others. Further, these rocks record HP-LT and HT-LP assemblages indicating two different metamorphic events. Thus it is not possible to delineate the hinge zone of the Manning Orocline north of Walcha because the rocks have a far more complicated history. Further evidence negating the presence of the Manning Orocline comes from the sequences between Walcha and Yarras that show a consistent younging to the west. If an orocline had formed near Walcha there should be a reversal in the younging direction. This has not been observed.

These critical observations argue against the presence of the Manning Orocline.

## The Australian Geoscience Data Cube – Transforming our ability to map and monitor the land surface with petabytes of Earth observation data

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This paper presents some of the most recent and promising developments in the Australian Geoscience Data Cube (the AGDC). The AGDC is revolutionizing our capacity to work with large volumes of satellite Earth observation data, leading to improved understanding of systems, new approaches to mapping, monitoring and change detection, and ultimately to results that are useful from local to national scales.

The AGDC organises petabyte stores of Earth observation data in a high performance computing environment using open-source data formats and tools. The Data Cube has compelling advantages, viz.:

1. **Efficiency.** In the AGDC complex data preparation and calibration steps are completed once by the data custodian, and the ‘analysis ready data’ are stored on spinning disc. Specialists are free to exploit the data rather than repeating these steps. Time-consuming searching and extraction of scenes from an archive is also avoided.
2. **Many more observations are available for analysis.** The AGDC user chooses to use individual pixels that meet quality thresholds. All pixels are retained, and clear pixels from cloudy or incomplete images (e.g. Landsat-7), are therefore available at the discretion of the user. In practice this places an order of magnitude more data points at the disposal of the user to deliver more reliable analysis.
3. **New data streams can be easily included.** The AGDC is a set of measurements, such as surface reflectance and surface temperature, referenced in space and time. Data from new platforms are reduced to like measurements, albeit from new instruments, allowing for relatively direct integration in the Data Cube. The measurement approach is now gaining wide acceptance with space agencies and the user community. Geoscience Australia and others are working to be able to include new data streams, including Sentinel-1/2/3, and Himawari-8, into the AGDC. Importantly, the provenance of each data point must be captured. The Data Cube also scales to accommodate large volumes of new data.
4. **The time dimension is exploited.** The AGDC is a rich set of observations at each point on the land surface through time. Capturing the dynamics of the land cover is essential to robustly classify, describe, and detect change in the land surface. Also possible are time-statistics, such as the median surface reflectance observed in each season. These show great promise as independent variables in spatial models.

This material is based on the work of a multi-agency team of technicians and scientists. The AGDC initiative is a partnership between Geoscience Australia, the National Computational Infrastructure, and CSIRO. These partners are working with others, including the United States Geological Survey, the Committee on Earth Observation Satellites (CEOS), NASA, the European Space Agency, the Group on Earth Observations (GEO), Australian government agencies, State governments and researchers to develop and apply the AGDC and to realise its potential in, and beyond, Australia.

## Age, duration and isotopic signature of the Cambrian Stavely Arc, western Victoria—a zircon perspective

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The Stavely Arc is considered to be a continental-margin arc system that developed on the eastern margin of Australia in the mid-late Cambrian. Rocks of the Stavely Arc outcrop over a very limited extent in western Victoria, and are interpreted from geophysical images to extend along strike under shallow cover—prompting exploration interest for arc-related mineral systems. The joint Geoscience Australia–Geological Survey of Victoria Stavely Project is investigating the regional geology and mineral systems of the Stavely region, and included drilling 14 stratigraphic holes designed to test regional geological models and subsurface geology. Drill core and rock outcrop were sampled for zircon U-Pb, Lu-Hf, O isotope and trace element geochemical analyses. The analysed samples presented here include rocks from the Mount Stavely Volcanic Complex (MSVC), including mineralised dacitic porphyries, and the intrusive Bushy Creek Igneous Complex (BCIC).

New SHRIMP U-Pb zircon ages indicate the igneous rocks from the MSVC and BCIC are tightly constrained to between c. 510–500 Ma. New age data and other new geological constraints indicate that mineralised dacitic porphyries were syn-eruptive with the MSVC and rocks of the BCIC.

Zircon O isotope data from the porphyries yield  $\Omega^{18}\text{O}$  values less than those of the normal mantle zircon range (i.e.  $< 5.3 \pm 0.3\text{\textperthousand}$  VSMOW) through to values similar to and greater than normal mantle values. We interpret the lower than normal mantle  $\Omega^{18}\text{O}$  values to have been derived from melting of hydrothermally altered, possibly subducted oceanic crust, without significant interaction with the overlying continental crust at the time of emplacement.

The mineralised porphyries display  $\text{\Delta}^{14}\text{Hf}$  values indicative of contemporary depleted mantle, while the  $\text{\Delta}^{14}\text{Hf}$  values of the MSVC rocks are more evolved. This suggests that there were multiple, magmatic pulses with different degrees of crustal interaction/assimilation (i.e. the porphyries had little to no crustal input, while MSVC volcanic rocks had a source with some crustal input).

## Tectonic/Structural influences on the Nullarbor Plain – new evidence from the large cave systems

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Karst regions contain subsurface evidence of tectonic influences through the patterns of mapped cave systems. Most of the world's karst areas have been deformed and metamorphosed but Australia contains three very large karst sheets of unaltered, undeformed tertiary cool carbonate platforms. The Nullarbor Plain, the Murray Basin and the Gambier Karstfields are preserved along Australia's southern passive margin due to continental 'trailing edge' uplift and the near absence of significant compressive tectonic influences. Several similar karst sheets are found in the northern hemisphere in the Caribbean region (Florida, Yucatan), similarly placed on the east passive margin of North America.

These karst sheets themselves are broad, shallow and relatively brittle on a crustal scale. Fractures across and within the limestone sheets are 'etched' by groundwater as major cave systems. A structural analysis of the orientation and distribution of these karst features can reflect the regional tectonics beneath, rather in the manner of a template.

Recent studies have been undertaken in one of these sheets, the Gambier Karstfield in southeastern South Australia, through analyses of cave distributions, orientation and alignments of major cave features at Naracoorte (Lewis et al 2006) and subsequently for deep cenote (sinkhole) features at Mount Gambier (Webb et al, 2010). Initially apparent relatively random distributions of major caves have become clarified to reveal tectonic imprints ('up-printing').

The Nullarbor Plain is by far the largest such tertiary karst sheet in the world. It thus may present a strong template model of sub-continental stress regimes across central southern Australia. Tectonic/Structural information about this region is limited as (to date) it has not been of economic interest to the mining or oil and gas industries. Groundwater quality is marginal and usage is minimal so that sparse hydrogeological information is available. Some recent surface imagery has provided important evidence for structural influences on the Nullarbor karst sheet. This is compared with an initial integration of the subsurface karst and large cave data (60 years of underground exploration and mapping) and the structural trends which they reveal. It is proposed that in a similar way to the Gambier Karstfield, the large Nullarbor cave patterns reveal tectonic stress fields under the Plain but on a sub-continental scale. From this it is suggested that large unmodified karst sheets and their cave arrays can provide an additional tool for interpreting basement tectonics in Australia and elsewhere.

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## **South Australian Geology and the State Heritage Register – balancing the Natural and Built environment listings. Example: The Naracoorte Caves Complex**

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South Australia's State Heritage Register contains 2,284 listed places. Included in this list are archaeological and geological sites, significant trees and gardens. However, the majority of places are from the 'Built' environment, ranging from settlers' huts, community buildings, historical industrial sites to magnificent stone mansions. Only approximately 150 places are linked to the 'Natural' environment.

The SA Heritage Register is a legal instrument to protect heritage places from alteration, damage or removal without formal prior consultation. This is achieved by Heritage places being defined in the Development Act and listed in local Development Plans, ensuring consideration during any Development process.

Protection is provided to biological, botanical and indigenous sites under other forms of legislation. Therefore the State Heritage legislation for 'Natural' environments is landscape-based and oriented towards Geological, Archaeological, Palaeontological and Speleological heritage ('GAPS heritage').

As part of a process to provide a greater balance between 'Natural' and 'Built' listings, the SA Department of Environment, Water & Natural Resources (DEWNR) is providing geological and related advice to its State Heritage Unit for a series of State Heritage 'Natural' environment assessments. This includes an assessment of the heritage significance of *single* sites such as Shingle Beach near Whyalla and Glacier Rock near Victor Harbor. Two individual Naracoorte Caves are already entered in the State Heritage Register as *single* sites. However a broader *multiple* site nomination is currently being prepared. This focuses on the many significant geological, palaeontological and speleological components contained within the 28 caves of the Naracoorte Caves National Park in a larger "heritage place" nomination, more in line with the existing World Heritage and National Heritage listings at Naracoorte Caves. For 'Natural' features, a multiple site such as this is an innovation. A listing will augment the prestige of the Naracoorte Caves complex and provide a further level of protection for the land, the caves' exteriors and interiors.

In 2016, the South Australian Government has announced an initiative to promote 'Nature-based Tourism' through better public engagement with DEWNR Parks. This concept could also include more utilisation and visitation for some of our 'Built' and 'Natural' Heritage features. Finding a balance between public visitation and preservation of the feature or area can be a delicate issue in promoting awareness of Heritage features.

## **BA foundations rock! How geoscience underpins the bioregional assessments**

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The Australian Government's Bioregional Assessment (BA) Programme will significantly enhance national understanding of the potential impacts of coal mining and coal seam gas (CSG) development on water resources and water-dependent assets. This unprecedented scientific investigation involves a coordinated effort across agencies and science disciplines that focuses strongly on hydrological modelling and probabilistic assessments of impact. Modelled hydrological changes, such as streamflow reductions and aquifer drawdowns, feed directly into assessments of the impacts and risks of these changes to ecological, economic and socio-cultural assets. The delivery of this work is well advanced across selected coal-bearing sedimentary basins in eastern and central Australia, including regions with a long history of coal resource development, such as the Hunter in the Sydney Basin, as well as greenfield areas such as Queensland's Galilee Basin.

Within the multi-disciplinary BA teams, the role of geoscientists is crucial and contributes to the successful delivery of many bioregional datasets and information products. In the early stages of assessment, geoscientists are focused on providing the foundations for subsequent hydrological modelling and data analysis. Synthesis and interpretation of existing knowledge of the regional geological history, structure and stratigraphy provides a framework for wider understanding of each bioregion, with particular focus on the main coal-bearing strata. A subsequent critical step involves compiling regional coal and coal seam gas resource assessments. These clearly document a comprehensive inventory of current and potential development projects, which are then used to determine the most likely coal resource development pathway for use in the modelled assessments.

Regional geological modelling in the Galilee, Clarence-Moreton, and Gloucester basins has significantly enhanced our knowledge of basin-scale stratigraphy and structural architecture. In the Galilee subregion, for example, modelling efforts have successfully integrated the Permian–Triassic sequences of the Galilee Basin into an existing geological model of the overlying Eromanga Basin, providing new insights into the thickness, distribution and architecture of main coal-bearing strata, such as the Betts Creek beds. This type of regional geological modelling provides an important framework for conceptual models of causal pathways, the mechanism by which the bioregional assessments link activities associated with coal mining and CSG development to impacts on water-dependent assets. The regional geological models also underpin consistent basin-scale architecture used to develop a suite of high quality numerical and analytical groundwater models.

Geoscience is clearly a core and valued component of the Bioregional Assessment Programme. However, one of the real strengths of the BA's has been the close interaction and integration of geoscience with other key disciplines such as hydrology, ecology and risk and impact analysis. Although geoscience has increasingly seen closer interaction with other science disciplines over recent decades, the bold vision of the BA's represents a major shift in tackling nationally important science challenges. There are many valuable lessons arising from the BA's that will help drive the nature and focus of future multi-disciplinary investigations, with geoscience proving to be fundamental to this approach.

## Supercontinent-superplume coupling in Earth history: toward a new tectonic paradigm

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The question of what drives plate tectonics remains a major challenge to geoscientists. Key clues lie in geological and palaeomagnetic records of the evolving global palaeogeography and related tectonic processes, records of mantle plume activities in both the continental and oceanic realms through time, and clearer pictures of the physical and chemical structure and dynamic interactions of the Earth's interior. Major breakthroughs over the past 30 years put us in a position to make a major stride in answering this question. These include: (1) widely accepted cyclic occurrences of supercontinent assembly and break-up (i.e., supercontinents Pangea with a life span of 320–170 Ma, Rodinia 900–700 Ma, and Nuna/Columbia 1600?–1300? Ma); (2) seismic tomographic discoveries of two equatorial and antipodal large low shear velocity provinces (LLSVPs, or superplumes) that dominate the lower mantle and appear to have been the base for almost all mantle plumes since at the Mesozoic, and of subduction of oceanic slabs all the way to the core-mantle boundary, which together suggesting whole-mantle convection; (3) the recognition of possibly cyclic occurrence of global plume activities that may have been related to the LLSVPs and even supercontinent cycles (Earth's coupled supercycles); (4) the recognition of true polar wander (TPW—rotation of the entire mantle and crust relative to the planetary rotation axis and the core) as an important process in Earth history, reflecting Earth's major internal mass redistribution events such as those related to the supercycles; and (5) rapidly enhancing computer modeling power enabling us to simulate all aspect of Earth's dynamic inner working.

Although some believe that the two LLSVPs or superplumes are long-lived in Earth history and are thus independent of the plate system, here I present a self-consistent working hypothesis (e.g., Li and Zhong, 2009) that features the followings: (a) supercontinent and superplume events are both cyclic and coupled in time and space (the supercycles); (b) circum-supercontinent subduction leads to the formation of two antipodal superplumes, corresponding to the positions of the supercontinent and the superocean, respectively; (c) superplumes can bring themselves and the coupled supercontinents to equatorial positions through TPW events, and eventually lead to the breakup of supercontinents; and (4) the breakup of a supercontinent gradually changes the Earth from a dominantly circular subduction system to scattered multiple-subduction systems, thus weakening the antipodal superplumes until after the formation of the next supercontinent. This working model, along with other hypotheses, can be further tested with improved knowledge of (1) supercontinent cycles and TPW events, (2) the temporal and spatial variation of plume activity in both the continental and oceanic realms, and their relationships to supercontinent cycles, (3) the Earth's internal structure and properties, and (4) through integrated global syntheses and geodynamic modeling. We aim to achieve this though both the ARC Laureate Fellowship project and IGCP 648 "Supercontinent Cycles and Global Geodynamics" (2015–2019; <http://geodynamics.curtin.edu.au>).

Li, Z. X., and Zhong, S., Supercontinent-superplume coupling, true polar wander and plume mobility: plate dominance in whole-mantle tectonics. *Physics of Earth and Planetary Interiors* 176, 143–156, 2009.

## Plume and superplumes: their formation, nature and geodynamic roles

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Mantle plume was recognised during the inception of the plate tectonics theory as an element of the whole-mantle convection that plays a key role in supercontinent breakup. Until recent years, mantle plume had often been considered by proponents as a thermal feature arising from the core-mantle boundary driven by heat conducted from the core. Seismictomographic work over the past decade with increasing resolution has demonstrated that at least some of the mantle plumes sourced from the lower mantle.

The concept of mantle superplume started from the discovery of a burst of plume-related magmatism in the Pacific Ocean during the mid-Cretaceous, the regional extent of plume events coinciding with the present-day Pacific geoid high (the Pacific superswell). Intensive plume activities also occurred over supercontinent Pangea during its breakup, the position of which features an equally large present-day geoid high (the African superswell). Seismictomographic work since the 80s has demonstrated that the positions of the two superswells coincide with that of two Large Low Shear Velocity Provinces (LLSVPs, or mantle superplumes) in the lower mantle. It has been further observed that almost all the known mantle plumes since the Mesozoic formed above the two superplumes.

There are outstanding questions regarding the two superplumes: (1) why they both are located near the equator, and are about 180° apart? (2) how they formed? (3) how long have they been there? (4) how stable are they? (5) are they thermal or chemical features, or both? and (6) what roles superplumes and plumes play (if any) in plate tectonics? Recent seismic tomographic and gravity analyses confirmed earlier geodynamic speculations that the two superplumes are thermal as well as chemical features, with their upper portions likely to of a basaltic composition. Some researchers believe that the antipodal superplumes in the present-day lower mantle have been a long-lived and stable feature since Earth's early history. However, we have been arguing that the formation of the antipodal superplumes (along with secondary plumes above them) in the lower mantle are coupled in time (with a lag time) and space with the supercontinent cycle. In our model, circum-supercontinent subduction of cold slabs to the lower mantle causes the formation of antipodal domes of hot and dense lower mantle, or superplumes, one of which being aligned with the positions of the respective supercontinent. If a supercontinent and antipodal superplumes were not near the palaeoequator when the superplumes were formed, the Earth's spinning would bring them to the equator through true polar wander. The complete breakup of the supercontinent, at least partially driven by plumes/the superplume, would eventually weaken and even diminish the global circular subduction system, thus the antipodal superplume system. Such a dynamic and mobile supercontinent-superplume coupling system has been proved viable by geodynamic modelling with increasing sophistication.

There is another class of rare, singular plumes (termed lone plume) formed away from LLSVPs, such as the late Cenozoic Hainan plume. A mechanism of slab-driven plume generation, similar to what had been proposed for the formation of superplumes, has been proposed and geodynamically tested.

## Burial and exhumation of the Xigaze forearc basin, south Tibet, implication for the process of India-Asia collision

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Forearc basin system preserves the significant information regarding the origin of the forearc basement and erosional and post-collision between continents which facilitates for our understanding continental dynamics. The Cretaceous Xigaze forearc basin, located the southern margin of Asian continent in South Tibet, records the processes of the Neo-Tethyan ocean subduction and subsequent India-Asia collision through its burial and exhumation history. In this paper, we present a suite of low-temperature thermochronology data from an N-S transection of the Xigaze basin near Xigaze, South Tibet. The zircon U-Th/He (ZHe) and apatite fission track (AFT) data consistently show northward younging trend, while the apatite U-Th/He (AHe) data are all Middle Miocene ages, comparable with the regional data along the Indus-Yarlung zone (boundary between Indian and Asian plates). The synthetic thermal modeling indicates the central and north portions of the Xigaze basin kept heating until by ~35 Ma, which is probably attributed to the continuous deposition by that time after transiting to a foreland basin in the Paleocene. Further, the southern portion of the Xigaze basin ceased burial since Late Cretaceous due to the obduction of the Xigaze ophiolite, and commenced to slowly uplift at around ~60 Ma, the timing of the initial Indian-Asian's collision in South Tibet and propagated to the north. Because the ongoing convergence between two plates, it causes the regional uplift and large amount of materials removed from the Xigaze basin, mainly including the Cenozoic Tso-Jiangding group of the basin, which provided a source for the two fluvial basins (Liuqu and Kailas) along its northern and southern flanks during the latest Oligocene-Early Miocene. Then, along with the ongoing crustal shortening and uplift, the Xigaze basin has experienced rapid exhumation caused by the fault activity (e.g. Great Counter Thrust) and river incision.

## Three-dimensional measurement of semi-track lengths in apatite fission-track analysis

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Apatite fission-track (AFT) lengths are a crucial component for modelling time-temperature histories. AFT length data are traditionally measured on horizontal confined tracks, i.e., tracks that are fully enclosed within the interior of the crystal and horizontal to the observation surface. These tracks are revealed by a chemical etchant passing down pathways such as other tracks or cleavage surfaces intersecting both the observation surface and the measured tracks, and serve as the fundamental type of dataset for AFT annealing models. In contrast, semi-tracks, i.e., tracks exposed on and randomly truncated by the observation surface, do not provide straightforward information about the true lengths. Yet previous studies suggest that semi-track lengths are still potentially useful in thermal history modelling. An advantage of using semi-track lengths is the possibility of obtaining a large number of length measurements even in samples with few confined tracks. Further, semi-track length measurements can be carried out on the same grains that are used for age dating, which is particularly beneficial for detrital studies because thermal histories of individual provenance groups could be reconstructed separately.

To date, it has been impractical to measure the true lengths (i.e. corrected for dip) of semi-tracks due to the poor resolution and z-axis calibration in conventional microscopes. As a result, there are no appropriate annealing models for semi-track lengths. The latest generation of microscopes has higher precision along all three microscope axes, so that semi-tracks can now be measured accurately in three-dimensions (3D).

To investigate the annealing behaviour of semi-tracks, we carried out 3D measurements of semi-track lengths (>1000 per sample) on ten Fish Canyon Tuff apatite samples that contain only induced tracks and which were prepared at University College London. These samples were initially heated to 600°C for 24 hr to totally anneal spontaneous tracks, and then irradiated with thermal neutrons to produce induced fission tracks. Nine of the samples were reheated under different thermal conditions. Seven of these were again irradiated with thermal neutrons to produce mixed track-length distributions. Conventional confined tracks lengths were measured as well. Because of the inherent statistical relationship between length distributions of confined and semi-tracks, we can deduce the distribution of one length type from the other, and examine the discrepancies between theoretical and experimental results. This will lead to robust procedures for combining data from the two kinds of length measurements.

Our data reveal that length distributions of measured semi-tracks correlate well with the theoretically expected plateau that decays towards longer semi-track lengths, with two important differences. First, there are significant deficits of very short semi-tracks (<2-3 μm) in each sample, and second, the longest semi-tracks measured are slightly shorter than expected from the confined tracks. These discrepancies are probably due to anisotropic etching and length-bias. A better understanding of their role in geometries of semi-track lengths invites further investigation.

## **Defining geochemical exploration parameters for the Cloncurry Mineral District, Queensland**

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The Queensland Exploration Council-funded Geochemistry Through Cover (GTC) project 2015-2016 aims to advance the explorers ability to geochemically explore the covered terrain of the Cloncurry Minerals District. This collaborative project is testing several partial leach techniques, an emerging extractable gas-in-regolith method and vegetation chemical analysis.

Three ‘blind target’ trial locations were chosen with contrasting thicknesses of transported cover or regolith (<10m, 30-50m and >100m). Eight analytical techniques for soil or regolith material were chosen for trial including commercially available partial extraction methods from different laboratory groups, traditional strong acid digestions and field portable XRF (pXRF). Two size fractions of the sampled regolith were collected at each site for comparison. Vegetal matter from selected species growing at the trial sites was also collected and analysed. In addition, samples of gas were extracted from the regolith to test for evidence of gas compounds being released from oxidising ore minerals at depth.

Initial results indicate that surface anomalism can be generated by mineralisation through significant regolith cover. Just as importantly, the project demonstrates the continued relevance of ‘traditional’ geochemical techniques, especially for chalcophile elements, in areas of thin to moderate transported cover. All partial leach techniques trialled provided increased resolution of anomalies in areas of thick cover and evidence of bedrock-related or ‘litho-geochemical’ variations through thick (>50m) cover sequences. The results from these field trials have also highlighted the importance of a thorough, systematic and repeatable sampling procedure with regular collection of QA samples.

The geobotanical results indicate significant variations of abundance of certain pathfinder elements between the species sampled. Results have also shown that observation of species variation and distribution above the target area can also give useful indications for structural controls and the potential for mineralisation even in areas of significant cover.

## **Geochemical evolution of the mafic volcanic sequences in the Cloncurry District, Queensland: Implications for crustal accretion and prospectivity.**

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The Cloncurry District is one of the classic Iron Oxide Copper Gold (IOCG) terrains. However, the geochemical characteristics of the numerous mafic intrusives (dominantly dolerites) which are often spatially and temporally associated with mineralisation have never been studied in detail.

Specifically, the newly described dolerite-associated Great Australia-Taipan-Mongoose-Magpie (GATPMM) deposits are situated in close proximity to Cloncurry, and are thought to represent Cu-Co-carbonate-rich, Au-poor 'end-member' style of IOCG mineralisation that has not been documented elsewhere in the district.

The GATPMM deposits are analogous with regards to their paragenetic sequence, structural setting and mineralisation styles, and are characterised by their mineralogically simple, carbonate-magnetite rich, chalcopyrite-dominated sulphide mineral assemblages. Mineralisation is strongly structurally controlled and is regularly associated with mafic volcanic rocks. This host-rock affiliation is considered to be the result of dolerite having both a rheological and chemical control on Cu-Au mineralisation.

These dolerite-associated deposits offer an attractive reward to exploration efforts, being Cu-rich, potentially high-grade and in close proximity to existing mine infrastructure. Previous studies have highlighted that these bodies are confined to magnetic highs, with affinities towards structurally and chemically complex dilatational sites.

Trace element geochemistry from the newly described deposits and active exploration projects will be used to discriminate volcanic stages and to assess the evolution of the melt source. Age dating will also be attempted to provide further geological constraints on the relative timing of mafic volcanism and its implications for crustal accretion, mineralisation and prospectivity in the district.

## Exhuming fragments of the past: Proterozoic tectonics in the east Kimberley region, Australia

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The east Kimberley region, northern Western Australia, is host to the Halls Creek Orogen and preserves evidence of tectonic activity that dates back to the Earth's most significant stages of continental growth, the Paleoproterozoic assembly of the Columbia supercontinent. An integrated geological-geophysical investigation of this region has led to a better understanding of its tectonic evolution, including the influence of significant crustal-scale structures in developing regional architecture, and their role on the emplacement of magma and the circulation of hydrothermal fluids. Significant deep crustal scale features include a north-trending fault or shear zone that extends 400 km, running obliquely across the orogen, and three north-west trending orogen-perpendicular structures. An anomalous zone of high metamorphic grade rocks occupy the centre of the orogen and is co-located with a distinctive gravity high, and between two cross-orogen structures. This feature is consistent with excess mass and represents either a large mafic-ultramafic intrusion or a high-density crustal fragment. Possible tectonic models that could explain these geophysical and metamorphic anomalies could include the accretion of a crustal fragment to the Kimberley Craton prior to the 1865-1850 Ma Hooper Orogeny or the intrusion of voluminous mafic magmas into the middle crust. The development of this anomalous region is likely the result of along-strike variations in subduction dynamics such as those observed in modern-day convergent plate settings. Variations in slab-geometry accommodated by orogen-normal structures may help explain subduction mechanisms that occurred during this important period of east Kimberley formation, and that of the North Australian Craton. Understanding the relationship between these types of geophysical and metamorphic anomalies within a geological and 3D crustal architecture framework aids our insight to the mechanisms that may have operated during the Paleoproterozoic, and influenced the development of Columbia.

## Stepwise exhumation of the Triassic Lanling high-pressure belt in Central Qiangtang, Tibet: insights from a coupled study of metamorphism and deformation

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The E–W-trending Central Qiangtang high pressure-low temperature (HP–LT) metamorphic belt (CQMB) demonstrates a Pre-Cenozoic tectonic origin for rocks exposed in the Tibetan Plateau. The well-exposed Lanling HP–LT rock complex was chosen in order to decipher the mode and process by which the complex was exhumed, in comparison with neighbouring blueschist and/or eclogite rocks. After detailed lithological and structural mapping, three NS-trending metamorphic domains with distinct mineralogical features were distinguished. They occur as mélanges involving mafic intrusions and terrigenous clastics that were pervasively foliated and have been brought into contact with each other by ductile shear zones.

Outcrop-scale structural analyses demonstrated that the three domains have consistent structural styles, and involve intense NNW-SSE trending ductile shearing. Microscopic observations show that in the core domain, the rocks experienced a temperature rise plus a pressure decline after peak conditions were reached. This is evident in post-tectonic garnet porphyroblasts and a pulse of epidote/zoisite growth in the surrounding phengite schists. Blueschists in the mantling domains display a characteristic lack of porphyroblastic garnet growth, and underwent temperature-increasing hydrated retrogression. Pervasive epidote/zoisite swarms/veins formed while phengite schists occasionally developed tiny post-tectonic garnets and exhibit the effects of low-temperature dynamic recrystallization. Compilation of radiometric dating for high-pressure minerals in Lanling and entire Central Qiantang allow a two-step exhumation model to be formulated. It is suggested that eclogitic rocks were brought to blueschist-facies levels starting at 244–230 Ma, with exhumation continuing to 227–223.4 Ma. The core domain with its mantling blueschists were then exhumed together, reaching greenschist-facies conditions by 223–220 Ma which perhaps continued to ~211 Ma.

## Calcrete sampling for gold from the Albany-Fraser Province, Western Australia

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Calcrete sampling continues to be used in gold exploration throughout semi-arid Australia and in other countries. Calcrete is a common constituent of soils developed in semi-arid parts of the world and is commonly comprised of calcite. Far from being a diluent to mineral exploration, gold is unique in that it resides in calcrete above and adjacent to deposits, even those buried beneath exotic sediments such as sand dunes. Calcrete sampling is a geochemical technique driven by a combination of biotic and abiotic processes. Vegetation plays a role in the creation of geochemical anomalies in calcrete by absorbing gold in deep roots and translocating it to the surface via evapotranspiration (foliage) and subsequent leaf decomposition.

The Albany Fraser Province (AFP) is a new and exciting multi-commodity province located at the south eastern margin of the Yilgarn Craton. Several substantial mineral deposits have been recently discovered including gold (Tropicana-Havana) and nickel-copper (Nova-Bollinger). The complexity of the landscape evolution and regolith development is hindering the full potential of discoveries. This includes the erosional and depositional features of regional overburden driven by sea-level changes during the last ~60–50 Ma, which has significantly impacted exploration protocols required in the region. Information on methods in greenfield exploration provinces is commonly tightly held and those from the AFP are no exception. However, we are able to show independent geochemical results from three prospects from the Woodline area in the AFP.

A regolith map was constructed and a series of soil profiles were sampled. Organic-rich soils, vegetation (twigs) and surface lag were collected along a transect over mineralisation at 50 m intervals. Multi-element geochemistry was performed and a number of interesting results were found including those summarised below:

- 1) Gold was closely associated with calcrete which is ubiquitous in the soil profile.
- 2) A displaced gold anomaly in calcrete was located in younger colluvium; the most likely explanation is that it was transported to this position.
- 3) The absence of an anomaly over mineralisation on the transect (in any sample media) was due either to on-going erosion of material (containing accumulated Au) or the weakness and/or depth of the mineralisation itself.
- 4) Other metals were found associated with minerals other than calcite including nickel, which has an affinity with manganese.

By understanding landscape evolution, geomorphological features of the region, and targeting specific horizons in the soil profile, mineral explorers will improve their understanding and enhance sampling methodology. Traditional surface soil sampling alone is not the optimal method to use in these terrains. The study demonstrates that some gold in calcrete anomalies are transported and care should be taken when interpreting the data. The highest soil gold concentrations are not at the surface but are located a few tens of centimetres below this where the calcrete is more abundant. Furthermore, how calcrete geochemistry relates to a landscape affected by several marine transgressive-regressive cycles in this region may greatly improve our understanding of how it links with geology at depth. This may have implications for prioritizing calcrete geochemical anomalies.

## Carboniferous orogenic gold deposits in the Hodgkinson Province, Queensland, Australia – genesis constraints from new geochronology, stable isotope geochemistry and fluid inclusion data

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Three distinct styles of orogenic gold deposits are present in the Hodgkinson Province, hosted by Silurian to Devonian turbidites and mostly occurring distal from Carboniferous to Permian magmatic rocks. Most deposits are characterised by free gold in laminated to massive quartz veins, with minor pyrite, arsenopyrite and ferroan carbonates. The second major deposit style is characterised by refractory, or ultra-fine, gold in arsenopyrite and pyrite grains, occurring in thin veins and stockworks or disseminated in host turbidites in and adjacent to fault zones. Quartz-stibnite ± gold veins represent the third distinct style of gold mineralisation in the region. All three mineralisation styles are characterised by strongly anomalous arsenic (>100 ppm). Elevated antimony is common in refractory gold mineralisation (generally from 10 ppm to 100 ppm) and particularly pronounced in stibnite–quartz veins.

Ar–Ar geochronology, fluid inclusions and stable isotope geochemistry of C and O of quartz and carbonates were studied in samples from Atric, Northcote, Tregoora, Kingsborough, Maytown and Munburra ore fields, representing all three styles of gold mineralisation in the region. Oxygen isotope compositions of quartz varied mostly within a range of  $^{18}\text{O}_{\text{VSMOW}} = 15\text{\textperthousand} - 19\text{\textperthousand}$ , with slight but generally consistent differences between gold-quartz veins ( $15\text{\textperthousand} - 17\text{\textperthousand}$ ), stibnite-quartz veins ( $17\text{\textperthousand} - 18\text{\textperthousand}$ ) and refractory gold deposits ( $17\text{\textperthousand} - 19\text{\textperthousand}$ ). Ankerite and siderite in the Tregoora and Atric refractory gold ore fields are characterised by  $^{18}\text{O}_{\text{VSMOW}} = 15.2\text{\textperthousand} - 16.8\text{\textperthousand}$  and  $^{13}\text{C}_{\text{CPDB}} = -8.1\text{\textperthousand} - -19\text{\textperthousand}$ . Examination of a series of samples representing refractory gold deposits indicated that the primary fluid inclusions were essentially destroyed by deformation and frequently cut by inclusion-free quartz veins, rendering them unsuitable for detailed studies. Examined gold-quartz and stibnite-quartz veins contained common low-salinity (<5% NaCl)  $\text{CO}_2$ -rich fluid inclusions (with minor  $\text{CH}_4$  and  $\text{N}_2$ ), homogenising mostly between 220 °C and 300 °C, sometimes together with aqueous inclusions homogenising mostly between 120 °C and 200 °C.

Ar–Ar geochronology of mica-rich whole rock separates were investigated in samples from mineralisation and proximal alteration zones, representing all three styles of orogenic gold mineralisation in the Hodgkinson Province. Results suggest that all significant orogenic gold deposits in the region formed in the Carboniferous (tentatively, in three main episodes: ~340–350 Ma – refractory gold deposits, and ~320–330 Ma and ~300–310 Ma – gold-quartz vein deposits), while the relatively minor West Normanby goldfield probably formed in the early Permian (~280 Ma). The indicated four episodes of gold mineralisation closely correspond to the documented episodes of magmatism in other parts of the province, spatially distal (commonly >50 km) from coeval mineralisation. The fluid inclusion and stable isotope data, generally similar to typical orogenic gold deposits elsewhere and consistent with the dominantly crustal metamorphic sources of mineralising fluids, do not show any evidence of a direct involvement of magmatic fluids in the formation of gold deposits. The general temporal correspondence between magmatic events and gold mineralisation are interpreted as a consequence of both phenomena being different manifestations of the same crustal heating events, driving metamorphic devolatilisation in some parts of the province and magma generation in others.

## Early Permian mineral systems of Cape York, north Queensland, Australia

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The Cape York region contains regionally widespread gold-silver deposits, less common spatially restricted tin-tungsten deposits and rare molybdenum occurrences. Significant gold deposits in the region commonly occur in areas of outcropping Proterozoic metamorphic rocks and Devonian granites, but, notably, not in the vicinity of plutons of Carboniferous to Permian Kennedy Igneous Association. Tin-tungsten deposits mostly occur within the historic Archer River tin field, and are spatially distinct from the main gold camps but adjacent to several minor gold deposits. Some historically mined alluvial deposits in the area produced gold, tin and tungsten, suggesting a possible spatial association between the gold and tin-tungsten deposits.

The tin-tungsten mineralisation is probably genetically related to the emplacement of the early Permian highly fractionated, reduced, felsic I-type Wolverton Adamellite, which outcrops over most of the tin province. However, the genesis of the gold deposits, previously described as shear-hosted, remains poorly constrained. Establishing their geochemical signatures, properties and likely genesis of mineralising fluids, geochronological constraints and camp to regional-scale metallogenic controls are a major focus of the mineral system investigation by the Geological Survey of Queensland, as discussed in this paper.

The current investigation has confirmed close spatial association between gold mineralisation and early Permian felsic dykes and plugs around and to the south of Coen, in the Alice River, Ebagoola, Yarraden and Coen gold camps. Gold mineralisation commonly occurs in steep quartz veins along and cutting steep north-west trending felsic dykes. U-Pb geochronology (SHRIMP – Geoscience Australia) indicates the uniform magmatic emplacement age of mineralised felsic dykes across the region (~280-285 Ma) - broadly synchronously with (but possibly slightly older than) the Wolverton Adamellite (~281 Ma) and other early Permian plutons north of Coen. These new results provide the first reliable geochronological constraint on the age of gold mineralisation in the region.

Auriferous quartz veins commonly indicate multiple stages of quartz veining associated with gold mineralisation. Gold is found not only in paragenetically early fine-grained quartz with disseminated pyrite and arsenopyrite, but also in late-stage coarse “dog-tooth” quartz with evidence of open-space growth. Multi-stage hydrothermal breccias are common in the Coen field, with gold present both in the clasts of sulphide-rich quartz and the sulphide-poor matrix of quartz with epithermal textures. Most common sulphides are pyrite and arsenopyrite, with locally significant galena, sphalerite, stibnite and silver sulphosalts and rare molybdenite. Gold deposits across the region have generally similar geochemical signatures, mostly characterised by strongly anomalous As, commonly with elevated Sb, Pb, Zn and locally – Bi and Mo.

Investigations in the Archer River area, in and around the historic Archer River tin field, indicate that relatively minor gold mineralisation in the area was precipitated from relatively high-temperature saline fluids (with halite observed in fluid inclusions). Fluid inclusion homogenisation temperatures range between 250 and 430°C. Geochemical evidence, in addition to fluid inclusion studies, further suggests the magmatic nature of auriferous mineralising fluids, possibly genetically associated with the Wolverine Adamellite and associated tin mineralisation.

## The Syros Eclogite-Blueschist Boulder Mélange is not related to subduction

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Here we consider the tectonic evolution of the boulder mélange exposed in northern Syros, in the heart of the Cycladic Eclogite–Blueschist Belt, in the Aegean Sea, Greece. Although the mélange is usually attributed to subduction, this is unlikely on structural and petrological grounds. An alternative hypothesis is that the mélange involved Alpine obduction of a small Cretaceous back arc basin that formed in association with the creation of an ocean-continent transition related to a mantle-biting detachment fault. Alpine obduction appears to have been followed by extreme extension, with the sum of these movements leading the formation of a tectonic shuffle zone. The existence of such a structure is consistent with the petrology of the adjacent tectonic slice, which comprises Cretaceous gabbro, pillow basalts, and serpentinite. The rocks in the mélange are variably overprinted, with the original mineralogy variably consumed by (~53-50 Ma) <sub>1B</sub> and (47-42 Ma) <sub>1C</sub> Alpine high-pressure metamorphic mineral parageneses.

The largest of the boulders are not ‘aerolithons’. This is a name given to them by the local inhabitants expressing the belief that they were dropped into place from above. Equally implausible is the petrological explanation, that these boulders are dense bodies that floated upwards through the mantle from the upper-surface of an underlying subduction zone at depth. The boulders could not have reached their present level in the crust by travelling through this less dense matrix. Serpentinite does not coat the boudins so it is not possible to call on effects related to buoyancy. The explanation for the origin of the mélange that fits the structural observations is that the boulders are nothing more than large boudins caught in an Alpine, post- <sub>1C</sub> ductile shear zone in which they were sheared, stretched and skinned.

This contribution reports new <sup>40</sup>Ar/<sup>39</sup>Ar geochronological data that further constrain the timing of porphyroblastic episodes of high-pressure metamorphic mineral growth during the operation of these major ductile shear zones. It is also demonstrated that the boulder mélange is located in one of a number of large kilometer-scale tilt blocks that litter the upper-plate of an Eocene–Oligocene Tethyan-style metamorphic core complex. Similar, also kilometer-scale, large tilt blocks outcrop above an identical post- <sub>1D</sub> extensional shear zone that ran from ~35-30 Ma on the adjacent island of Sifnos, with the same metamorphic and structural evolution evident in both cases.

## The Timing of Exhumation in the Northern New Guinea Highlands

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A continuous mountain chain stretches from east to west on the island of New Guinea, with peaks exceeding elevations of 4000m. The northern part of these ranges may be marked by a regionally extensive normal fault system, that stretches from west to east, across the entire island of New Guinea. This structure has been named the North Papua Detachment, because its existence has been inferred in the west, and extrapolated from there to the east. Here we report the results of a study conducted in the northern flank of the highlands in Papua New Guinea, in an attempt to determine the timing of uplift and exhumation associated with the operation of these faults, and the subsequent erosional retreat of the fault scarps.

In the area of interest, the range front is formed by the Ramu-Markham Fault Zone, south of which is the Marum Ophiolite, which overlies the Asai Beds sediments. These are intruded by the Bismarck Granodiorite, which has produced a zone of contact metamorphism in the surrounding sediments. Should the existence of the North Papuan Detachment be confirmed, this would have the Marum Ophiolite in its upper plate. Metamorphosed sediments and granitoids in the lower plate would have been extracted from beneath the obducted ophiolite. Extension with this geometry would have heated the overlying ophiolite from below, annealing fission tracks in apatite at the time of relative displacement. In contrast, rocks in the inferred lower-plate would have been rapidly cooled at the time of their uplift, with rapid cooling continuing until they were exposed as the result erosional retreat of fault scarps.

(U–Th)/He geochronology on zircon and apatite from the Bismarck Granodiorite returned ages of 5.9 $\pm$ 0.9 Ma and 2.9 $\pm$ 0.3 Ma (95% c.l.) respectively. Younger limits on  $^{40}\text{Ar}/^{39}\text{Ar}$  K-feldspar apparent age spectra match the zircon (U–Th)/He data. Older 8–12 Ma ages represent post-emplacement cooling of the Bismarck Granodiorite, and the effects of the contact metamorphism that it caused. Plagioclase and hornblende from the Marum Ophiolite return older ages, timing its emplacement.

## **Controls on coal accumulation in continental and coastal foreland basins: comparative study of the coal beds of the Early Cenozoic Powder River Basin and the Pennsylvanian Eastern Kentucky Coalfield, U.S.A.**

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The Cenozoic Powder River Basin and Carboniferous Central Appalachian Basin are both foreland basins with major coal reserves but they differ substantially in their coal distribution pattern and coal quality. The paleolatitude, paleoclimate, tectonic subsidence and paleoenvironments of the two basins were compared to better understand the major controlling factors of coal accumulation to understand the causes of these differences. The major coal-bearing strata (Fort Union Formation) in the Powder River Basin formed at a latitude of ~51°N during the Late Paleocene with tectonic subsidence of 38-48m/Myr. The paleoclimate was humid and temperate. The three major coal-bearing formations in the Eastern Kentucky Coalfield of the Central Appalachian Basin (Pikeville, Hyden and Four Corners Formations) formed at latitude of ~3°N during the Middle Pennsylvanian under subsidence rates of 102-116m/Myr. The paleoclimate was ever-wet tropical. Peat accumulation rates generally increase from high to low latitude because the increased solar radiation leads to the acceleration of vegetation growth. Given other conditions being equal, the Eastern Kentucky Coalfield might be expected to be more suitable site for coal accumulation than the Powder River Basin, however, the average thickness of the thickest coal beds in the Powder River Basin is about five times that of the Eastern Kentucky Coalfield. Tectonic subsidence and paleoenvironment were inferred to be the major influencing factors. Rapid tectonic subsidence can provide more accommodation space for sediments but may also give rise to the drowning and termination of peat swamps. In the case of the Eastern Kentucky, fast subsidence might have hindered the deposition of thick coals. Peat swamps in the Eastern Kentucky Coalfield developed in coastal environments and therefore accommodation rates were also controlled by relative changes in sea level. Periodic marine inundations resulting from frequent rapid rises in sea level during the Pennsylvanian may have been an important factor in creating the relatively thin coal beds. In the Powder River Basin there is an upward change from strata containing thick coals and fluvial strata to strata containing thinner coals and lacustrine strata – this upward transition appears to be strongly related to an increase in tectonic subsidence rates over time.

## The challenges in building a continent-wide VLBI array

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Geodetic Very Long Baseline Interferometry (VLBI) is the only geospatial technique to provide a complete set of Earth Orientation Parameters and is essential for the maintenance of the terrestrial reference frame.

The AuScope VLBI array, consisting of three 12-m diameter radio telescopes at Yarragadee (WA), Katherine (NT) and Hobart (TAS), has been the busiest geodetic VLBI facility in the global network, operating at a rate of up to 210 days per year, producing up to 6 TB of data per station per day, all remotely controlled and monitored.

The next challenge, in coordination with other VLBI stations in the international network, is to upgrade the AuScope array so that it can produce positioning data at the 1 mm level. This concept, the VLBI Global Observing System (VGOS) will require continuous 24/7 operations and significantly higher data volumes, presenting some significant technical and organisational challenges.

VGOS would benefit greatly from a high level of automation, from scheduling through to analysis. The centrally-operated AuScope VLBI array is serving as a testbed for these automation techniques. Here we describe the challenges we are addressing, how we are using simulations to understand where the most beneficial improvements can be obtained and present the progress we have already made.

## **Palaeomagnetic investigation of mafic dykes in the southwestern Yilgarn Craton, Western Australia**

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Mafic dykes are ideal targets for palaeomagnetic study as they are routinely dateable and are generally more likely to preserve the primary remanence. We conducted a palaeomagnetic study on mafic dykes in southwestern Yilgarn Craton. A total of 30 dykes were sampled so far, with a minimum of six oriented drill cores from each dyke. All the samples were subjected to AF or thermal demagnetizations and most of them show stable palaeomagnetic characteristics. However, several dykes gave rather scattered directions. One of the possible reasons for the scattering is lighting strike, which is expected for dyke outcrops in the relatively flat Yilgarn Craton and confirmed by the rather high Koenigsberger ratios (usually higher than 20) of those samples. After excluding such samples, two groups of remanent directions, both antipodal, have been identified. The first one (C1) has a southeastern shallow downward (or its opposite polarity) direction, which correlates with several 1800–1700 Ma published palaeomagnetic directions from Western Australia. We are currently in the process of dating these dykes. The second component (C2) has a shallow southwestern upward (or its opposite polarity) direction. C2 direction is similar to that from the YE group dykes of Giddings (1976), which has a preliminary Rb-Sr age of ca. 2500 Ma. However, our preliminary SHRIMP U-Pb dating results suggest a younger age for dykes that carry C2 component. The preliminary results of C1 and C2 are both rather scattered, and more dykes are still to be collected and analysed to improve the quality of the results.

## Thermotectonic evolution of the Archean Yilgarn craton, Western Australia: Insights into Gondwana amalgamation and breakup

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The post-cratonisation history of the Yilgarn craton is somewhat fragmentary due to the paucity or absence of a stratigraphic record. Previously reported Rb-Sr biotite cooling ages suggest that the western craton margin was subjected to late ‘Pan-African’ tectonism (~400-600 Ma) and E-W compression, resulting in tectonic sedimentary loading. We report  $^{40}\text{Ar}/^{39}\text{Ar}$  results on muscovite and single biotite grains from well-documented sample sites broadly comparable to those sampled for Rb-Sr biotite analysis. Muscovites record consistent ages between ~2400 and 2200 Ma. Coexisting single-grain biotite results, however, reveal significant age variations, showing similar ages of ~2500 Ma across much of the craton but decreasing abruptly to ~620-1000 Ma over a ~50-100 km wide belt at the western margin. Petrographic and chemical studies indicate that biotites are distinctly different in origin, i.e. magmatic to the east versus hydrothermal to the west. The more scattered biotite ages along the western margin are therefore unlikely to represent cooling ages, but rather indicate probable fluid-induced partial or complete biotite recrystallization at ~620 Ma. This age is in agreement with palaeomagnetic reconstructions suggesting oblique collision between Great India and Australian during Gondwana amalgamation. Complementary zircon He data from low radiation damage grains ( $[\text{eU}] < 900$ ), yield consistent ages  $256 \pm 13$  Ma, whereas those with  $[\text{eU}]$  values of 900-2000 are negatively correlated with younger ages (~ 40-200 Ma). Coexisting apatite fission track ages are similar in range to zircon He ages, whereas apatite He ages are younger ( $227 \pm 18$  Ma). These data confirm that much of the Yilgarn craton experienced extremely slow cooling (<0.1 ° /Myr) from the Late Archean to Permian times. However, during the Late Permian to Triassic, the craton apparently experienced accelerated cooling (>4 ° /Myr), possibly related to earliest rifting between Greater India and Western Australia during Gondwana break-up or a response to the termination of large scale Permo-Carboniferous glaciation of western Australia.

## Structural Evolution of Carbonate Forming Deformation Bands in the Port Willunga Formation, South Australia

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Deformation bands are the predominant localized strain feature found in deformed porous (>10% porosity by volume) sedimentary rocks and are known to compartmentalize hydrocarbon reservoirs. The petrophysical and geometric properties of these fluid-baffling structures are thus extremely important to the petroleum industry when considering effective and efficient injection and recovery of fluids. The majority of literature focuses on deformation bands in sandstones. The origin, evolution, and impact on flow properties of carbonate hosted deformation bands in contrast are less well understood. We present a study on the recently recognized carbonate forming deformation bands in the Miocene-age Port Willunga Formation at Sellicks Beach, South Australia. Sellicks Beach is located 50 km south of Adelaide where the neotectonic Willunga Fault juxtaposes the Cenozoic age sediments of the St. Vincent Basin from the Cambrian metasedimentary basement. Three sequences of shear-enhanced compaction bands and pure compaction bands have been mapped in the bioclastic grainstone of the Port Willunga Formation. The primary force that controlled the genesis and evolution of the deformation bands is the regional (paleo) stress regime of the Willunga Fault. Derived horizontal maximum stress ( $H_{max}$ ) orientations coupled with regional neotectonic data allow a temporal correlation of the deformation evolution. Pore space collapse is responsible for the propagation of deformation bands at Sellicks Beach facilitated by grain reorganization, alignment, comminution, and cementation resulting in up to 18% porosity reductions. These structures are easily distinguished in the field as 1-2 mm wide tabular zones of positive relief on weathered surfaces. Episodes of both oxidizing and reducing fluid flows resulted in the formation of magnetite and iron-hydroxide cemented deformation bands. The observed magnetite and iron-hydroxide are interpreted to be alteration products of oxidized glauconite. This preliminary study provides foundational research into the temporal and geometric evolution of deformation bands in sedimentary hosted uranium systems of the Cariewerloo Basin, Athabasca Basin, and Northern Flinders Ranges.

## Electrical conductivity of the oceanic upper mantle

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Oceanic lithosphere is generated at mid-ocean ridges with the extraction of melt and volatile phases from the upper mantle. With distance and age from a mid-oceanic ridge, oceanic lithosphere is expected to thicken as the plate cools. Thus, in contrast to continental lithosphere that may undergo cycles of deformation and magmatism over millions if not billions of years, the oceanic lithosphere should exhibit reasonably uniform properties across all ocean basins.

Marine magnetotelluric (MT) measurements can be used to define the electrical resistivity structure of the oceanic lithosphere and asthenosphere. The Anisotropy and Physics of the Pacific Lithosphere Experiment (APPLE) was a marine MT program on 35 Ma crust in the eastern Pacific Ocean designed to test two fundamental hypotheses about mature oceanic lithosphere:

1. If oceanic lithosphere remains anhydrous due to primary loss of volatiles at mid-ocean ridges, then the electrical resistivity profile would be expected to be dominated by thermal (small and large polaron) conduction within olivine. In this case, the resistivity profile would be directly related to the 35 Ma geotherm, and the upper mantle would have isotropic resistivity (i.e. no angular dependence on the resistivity);
2. On the other hand, if oceanic lithosphere is partly re-hydrated due to migration of hydrogen ions from deeper sources and/or contains a fraction of melt at the lithosphere-asthenosphere boundary as temperatures approach the solidus, then the resistivity would be expected to be significantly lower and additionally highly anisotropic as hydrogen diffusivity is orders of magnitudes different for the three olivine axes, and melt tends to align with olivine orientation.

The APPLE experiment was a combination of a marine controlled source electromagnetic (CSEM) experiment to define the resistivity properties of the crust and about 40 km of lithosphere, and a marine MT program (with MT data in the bandwidth of  $10^2 - 10^4$  s) to constrain the resistivity profile between 40 and 400 km depth. Five marine MT instruments were deployed in a small zone at  $2^{\circ}12'N\ 129^{\circ}00'W$ , about 1000 km offshore San Diego, California in a depth of 4500m on 35 Ma old oceanic crust. In addition to these sites, four MT instruments were deployed along a transect to the coast in water depths of at least 3800 m.

Modelling of such data is surprisingly difficult due to the strong boundary effect of the coastlines, particularly to the east and northern margins of North America. The electrical conductance of the oceans are orders of magnitudes higher than that of the top 5 km of continental crust. To provide constraint from the continental margin, we use USAarray MT data and the 3D resistivity model of Meqbel et al., 2013 to better account for the ocean margins.

Our modelling shows that the MT responses can be reproduced from an anisotropic resistivity model and coastlines, which agrees with the second hypothesis and seismic studies which have shown evidence for seismic anisotropy in the ocean basins. The resulting resistivity profile is in disagreement with olivine conduction for a 35 Ma geotherm. Furthermore, the anisotropic ratio is small and as such, does not appear to be caused by H<sup>+</sup> diffusivity. We find evidence supporting subtle anisotropy in the oceanic lithosphere or asthenosphere, and thus conclude that a fraction of melt at the lithosphere-asthenosphere boundary may be present.

## Phanerozoic evolution of Zimbabwe: Insights from low-temperature thermochronology

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Thermochronology systems provide an invaluable toolkit for deciphering the Phanerozoic history of cratons that is often undetectable using conventional field methods. These systems are sensitive to varying temperature ranges, with temperature taken as a proxy for crustal depth, and thus they are able to record the cooling trajectory of rocks as they ascend the upper crust primarily by denudation. Hence, thermochronology data can be used to constrain the timing and rates of denudation and contribute towards a more thorough understanding of the long-term landscape evolution of continental interiors. The country of Zimbabwe in southern Africa, spanning 390 759 km<sup>2</sup>, is comprised chiefly of the Archean Zimbabwe Craton and part of the bordering Archean-Proterozoic mobile belts. The Phanerozoic record of Zimbabwe is largely unresolved and thermochronology studies are considerably lacking. The sparse data currently available are spatially limited to mainly the peripheries of Zimbabwe as well as restricted to apatite fission track data. In this study, the combined use of multiple thermochronometers with different temperature sensitivities - apatite (U-Th-Sm)/He (AHe) (~35-75 °C), apatite fission track (AFT) (~60-120 °C) and zircon (U-Th)/He (ZHe) (~140-200 °C) - are employed to unravel a significant portion of the unexplored Phanerozoic history of Zimbabwe. The data reveal a diachronous, dynamic Phanerozoic thermotectonic evolution. Single grain AHe ages range from 18.8 ± 1.1 Ma to 580.3 ± 36 Ma, AFT central ages from 94.8 ± 5.9 Ma to 433.9 ± 15.3 Ma and ZHe single grain ages from 37.2 ± 2.3 Ma to 636.0 ± 39.4 Ma. Most samples from Zimbabwe display a strong negative correlation between the ZHe age and the amount of accumulated radiation damage and hence the oldest ages (from least-damaged zircons) are the most thermochronologically meaningful. The oldest AHe, AFT and ZHe ages are located in the high elevation, central cratonic interior where rocks have experienced enhanced cooling during the early-mid Paleozoic and have since resided relatively close to the surface. AFT and AHe ages decrease markedly towards the northern, eastern and southern margins of Zimbabwe showing that these regions have been affected by younger Mesozoic and Cenozoic thermal events. Data from all three margins record a period of enhanced cooling occurring in the late Jurassic – early Cretaceous that is concurrent with the timing of early disintegration of Gondwana and most likely represents an erosional intra-plate response to compressional stresses transmitted during major plate movements. The northern and southern regions experienced greater denudation evidenced from younger late-Cretaceous AFT and AHe ages. In the southern and northern regions, the pattern of AFT and AHe ages is largely controlled by structural boundaries implying that tectonic reactivation of major structures and the associated uplift and erosion has played a key role in the evolution of Zimbabwe.

## The evolution of uraninite, coffinite and brannerite at the Olympic Dam IOCG-U-Ag deposit – linking textural observations to compositional variability

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Uraninite, coffinite and brannerite are the dominant U-minerals in the Olympic Dam (OD) iron-oxide-copper-gold-(IOCG)-U-Ag deposit, South Australia. Two generations of uraninite have been identified and termed 'early' and 'late' [1]. 'Early' uraninites are typically small (10-100 µm) single uraninite grains containing higher concentrations of Pb and (REE+Y) (REY). The 'late' generation of uraninite exists as µm-sized grains to aphanitic varieties which form larger (up to mm-sized) aggregates and vein-fillings, and typically have lower Pb, but higher Ca ± Si contents compared to the 'early' generation.

'Early' uraninites represent single uraninite crystals which have been progressively chemically and texturally altered. 'Primary' uraninites have the simplest cubic euhedral morphology and often exhibit oscillatory and sectorial zonation of lattice-bound Pb and REY. The next class are the 'zoned' uraninites which are typically coarser, sub-euhedral grains and are often prismatic, containing an internal zonation pattern defined by distinct zones of high- and low- Pb and REY. The final and most altered class are the 'cob-web' uraninites which display the greatest heterogeneity in terms of variable hexagonal to octagonal morphologies, varying degrees of rounding, and rhythmic intergrowths of uraninite with Cu-(Fe)-sulphides ± fluorite from core to margin. Brannerite is classified into four texturally distinct types. Type 1 brannerite includes discrete bands of needle-like to bladed brannerite commonly intergrown with sericite, chlorite, fluorite and quartz. It also occurs within hematite and rutile and ranges in composition from what is effectively a uraniferous rutile to stoichiometric brannerite. Type 2 brannerite typically appears as irregularly-shaped blebs within bornite and chalcocite, whereas type 3 brannerite is intimately associated with barite and REY-minerals (i.e., zircon, monazite). Type 4 brannerite also occurs as irregular blebs, but is commonly contained within hematite laths. Patches of bornite and TiO<sub>2</sub> (possibly anatase) are found within this type of brannerite; galena inclusions are abundant. Compositionally, brannerite of types 1-3 are similar and all contain elevated Fe, As, Na and K compared to type 4 brannerite. Type 4 brannerite is distinguished by elevated Pb, REY, Si and Nb.

Coffinite is always found on the margins of quartz, and displays a range of compositions, which can be differentiated by Y and Si content. It can be found in association with massive uraninite where it appears as colloform growths surrounding quartz, enveloped by massive uraninite. In some cases, colloform coffinite growths completely encompass quartz grains, whilst in others they appear as more discrete globules nucleating on Cu-(Fe)-sulphide grains. Several 'early' uraninites also display incipient coffinitisation at their rims. When coffinite is found with brannerite, it is either very finely intergrown with brannerite, or occurs on the edges of brannerite masses.

Based on textural observations, supported by chemical composition, it is clear that there were at least two main uraninite mineralising events. Coffinite and brannerite may represent secondary U-minerals which formed via repeated dissolution and reprecipitation of uraninite originally precipitated at the time of ore formation, or may represent the products of a later U-mineralising event.

[1] Macmillan et al. American Mineralogist (in press), <http://dx.doi.org/10.2138/am-2015-5411>.

## Trace Element Variation of Sulphide Mineralogy of the Mount Isa Copper System and Implications for Ore Genesis.

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The giant Mount Isa copper system (North West Queensland) has received a great deal of research over its 90+ year mine life, but the geochemical variation of the sulphide minerals (pyrite, chalcopyrite and pyrrhotite) has not been thoroughly investigated. This study will complete the first detailed geochemical characterisation of trace element geochemistry in the sulphide stages.

This project focusses on samples collected from a cross section through the X41 ore body and transects from basement (greenstone) volcanics through a faulted contact into variably brecciated and mineralised Urquhart shales. Samples for this study fall into three main groups:

- \_) Fine-grained shale with folding, faulting and variable abundances of fine grained pyrite.
- \_) Brecciated and partly recrystallised shales with secondary quartz-carbonate infill commonly with chalcopyrite mineralisation and occasionally pyrrhotite.
- \_) Chlorite-altered sheared and brecciated metasediment or metavolcanic rock with quartz, pyrrhotite and traces of chalcopyrite and pyrite.

The sulphides display a consistent paragenetic sequence in all the samples, with a fine-grained diagenetic pyrite (Pyrite-1) followed by coarse-grained hydrothermal pyrite (Pyrite-2) that commonly forms euhedral crystals (0.5-1.5mm in diameter). Later pyrrhotite and chalcopyrite, which appear to have co-precipitated during additional brecciation and infill events, is the last infill stage recorded.

Research methods include drill core inspection and sampling, paragenesis studies using optical microscopy, secondary electron microscopy (SEM) and compositional analysis using electron microprobe and LA-ICP-MS. Establishing the differences in trace element geochemistry for this transect will enable small-scale geochemical variation within the ore body to be established.

## Inferring lithological information from multi-element soil geochemistry

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Multi-element soil geochemical surveys are a common feature of continental, regional, and prospect-scale exploration and environmental programs. They contain a wealth of useful lithogeochemical information, often under-utilised in favour of subjectively selected single-element investigations and contoured maps. In part this may be due to the problem of providing an illustrative, concise statistical outcome when up to 50 elements are analysed. The aim of the Degree of Geochemical Similarity (DOGS) methodology is to provide a simple, objective and comparative analysis of samples in any geochemical database.

The methodology comprises six steps: (1) Transformation of the elemental concentrations (ppm) to  $\log_{10}$  units and ordering of the elements in alphabetical order; (2) Removal of those elements with (say) >40% of censored data (below the lower limit of detection or above the upper limit of detection); (3) Selection of a key “reference” sample of known or sought provenance against which to compare other samples in the database; (4) Plotting bar diagrams of the “fingerprint” of the reference sample and of the “difference” between any sample and the reference; (5) Calculation of a correlation factor which quantifies the affinity of any sample with the chosen reference sample; and (6) Mapping this correlation factor as the DOGS of all samples to the reference sample, using percentile-based exploratory data analysis (EDA) symbols. Application of the DOGS methodology to the 1190 sample National Geochemical Survey of Australia (NGSA) Mobile Metal Ion (MMI) database, using the Pearson least squares correlation coefficient at step (5) above, shows the following. The geochemical data (42 elements remaining after step (2) above) contains elemental information suggesting high affinity between some samples in the Proterozoic Albany Fraser belt and the Archaean Yilgarn Craton granitoid (Beverley granite reference). A high DOGS is also apparent on an EDA map for some Albany Fraser belt catchment outlet sediments (soils) with a Yilgarn Craton sample from a mafic rock dominated catchment (the Kalgoorlie greenstone reference). Soil samples collected over marine carbonates are distinguished from those containing abundant secondary carbonate (calcrete) by their geochemical signatures after application of DOGS methodology using a reference soil sample on the Nullarbor limestone. The choice of a catchment outlet sediment reference sample north of Mt Isa/Cloncurry provides a means of highlighting on an EDA map other areas in Australia potentially prospective for similar mineral endowment. Application of the methodology to a separate 48 sample prospect-scale MMI survey in northern Queensland illustrates its potential to identify and map mineral-hosting lithologies from background lithologies. Substitution of other correlation techniques (e.g. Spearman Rank correlation) at step (5) above produces very similar results, demonstrating the robustness of the methodology, but more importantly the inherent diagnostic capability of multi-element soil geochemistry to delineate underlying lithology.

## **Archaean High Pressure Metamorphism in the Coorg Block, SW India.**

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The Coorg Block of southwest India contains some of the oldest protoliths in India with crystallisation ages stretching back to ca. 3.4 Ga. The ‘block’ is delineated by the Moyar shear zone to the south, which separates it from the Neoarchaean Nilgiri Block, and the less well defined Mercara shear zone to the north that forms the boundary with the bulk of the Western Dharwar craton. Rocks within the Coorg Block consist of orthogenesis and charnockites along with garnet+cpx mafic granulites and metapelites that include kyanite+cordierite+garnet paragneisses. These lithologies appear quite interleaved through the region between the Mercara and the Moyar shear zones and may represent an ancient accretionary system.

The presence of garnet+kyanite paragneisses and garnet+pyroxene mafic gneisses suggests that these rocks may have experienced high pressure granulite facies conditions. In addition, U-Pb data published over the last few years suggests that these relatively high-pressure assemblages date from the Archaean, and may stretch back into the Mesoarchaean, which would make these amongst the oldest high pressure assemblages in the rock record.

Here we present new field data and the initial results of a metamorphic study of these rocks, coupled with U-Pb monazite data targeted to constrain the age of the high-pressure assemblages and test the hypothesis that these rocks represent the oldest high pressure granulites known.

## **Ice-sheet collapse, oceanic feedback, and interhemispheric climate change at the end of an ice age**

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Ice-age cycles are major reorganizations of the ocean-atmosphere-cryosphere system that consist of gradual global cooling and ice-volume build-up during glacial periods, followed by rapid temperature rise and ice-sheet melting during glacial terminations. While there is general consensus on the importance of insolation forcing in these cycles, more debated is the role of the superimposed feedbacks, such as the varying concentration of CO<sub>2</sub> in the atmosphere and the global redistribution of heat, salt, and freshwater by ocean currents. It has been argued that these feedbacks were particularly important during glacial terminations, which occurred way too rapidly to be explained by a (linear) response to insolation forcing alone.

Because of the rapid ice-volume, ocean, and climate reorganizations during glacial terminations, a robust chronological control is mandatory to investigate the processes that bring ice ages to an end. Absolute dating of palaeoclimate archives from polar ice sheets, ocean basins, and land can be directly obtained only for the last glacial termination, Termination I (T-I), which has been historically used as a template to understand previous terminations. We challenge this view by developing an equally robust, radiometrically constrained chronological framework for key Northern and Southern Hemisphere records of ocean and climate change that span the penultimate glacial termination, Termination II (T-II), and last interglacial period. By determining in detail the sequence of climate events that characterized T-II, we demonstrate that the relationship between rapid melting of the circum-North-Atlantic ice-sheets and interhemispheric climate change differed fundamentally from that of T-I. The large-scale meltwater input into the North Atlantic during T-II coincided with enhanced Indian-to-Atlantic transport of saline waters through the Agulhas Leakage (South of Africa), with the attendant strengthening of the ocean circulation and of its associated redistribution of heat and freshwater. We will discuss how these findings advance the debate on the timing, nature, and magnitude of the ice-volume, ocean, and climate changes that characterize the ice age cycles of the Pleistocene Epoch.

## Identifying a magmatic source for the Pacific-Gondwana association: Zircon Hf evidence from the Paterson Orogen, Western Australia

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Ordovician to Neogene sediments of east Australia contain an anomalous Late Neoproterozoic zircon population that cannot be attributed to any local source rocks. The origin of these Pacific-Gondwana (PG) zircons is contentious, with the population extending from 650 to 550 Ma, pre-dating the earliest Terra-Australis magmatism. Most authors propose an Antarctic source for the grains, suggesting that a magmatic belt is hidden beneath the Antarctic ice sheet. Others argue that the population identifies an earlier inception of the Terra-Australis Orogen along the margin of Australia, with the magmatic source rocks now lost or buried. More recently, it has been suggested that the grains may have travelled eastward from the Petermann Orogen of central Australia, and represent related magmatic rocks that have since completely eroded. Nevertheless, no magmatic source for the 650-550 Ma population has been identified in outcrop.

If the source of the east Australian PG signature is indeed Antarctica, then this should be reflected by similar zircon ages and Hf signatures for each terrane. We compared a compilation of zircon Hf data from the Terra-Australis margin from both east Australia and Antarctica. The zircons from the Tasmanides revealed U-Pb age peaks at 594 and 566 Ma, but the data from Antarctic reveal noticeably younger U-Pb peaks of 544 and 524 Ma. Corresponding Hf data for Australia ranged from +7 to -40, with Hf model age of up to 3500 Ma, whilst for Antarctica the Hf range was just +5 to -20 with a Hf model age up to 2500 Ma. The Hf data from Australia highlighted significant contributions from evolved crust at ~550 Ma, with earlier, more juvenile contributions from ~650-600 Ma, whilst no similar evolutionary history could be inferred from the Antarctic data. The lack of correlation between U-Pb age peaks from east Australia and Antarctica, along with the significantly reduced range of Hf values, is inconsistent with an Antarctic source for the PG zircons in eastern Australian sediments. Further, the ~3.5 Ga Hf model ages from Tasmanide zircons demands sampling of a substantial volume of ancient Archean crust, which does not exist near the the east Australian margin, discounting an early Terra-Australis origin.

New zircon Lu-Hf data from both magmatic zircons of the Paterson Orogen and detrital samples of the Officer and Yeneena Basins of Western Australia, combined with GSWA data from the surrounding regions, provides an alternative source for the PG zircons. The Neoproterozoic grains from Western Australia closely resemble the PG signature of east Australia, clustering into two U-Pb peaks at 579 and 560 Ma and recording an Hf signature from +7 to -30, with crustal model ages up to ~3.1 Ga. Published data from the Lhasa terrane of Tibet records an almost identical Hf signature for Proterozoic zircons.

We propose that Hf data from Paterson Orogen granites provides strong evidence for the source of the ~650-600 Ma portion of the PG zircon population. The same PG signature is also identified in Cambro-Ordovician sediments across the Australian continent, from the Officer, Canning, Yeneena, Amadeus and Georgina basins. This information, along with easterly directed palaeocurrents in the Cambro-Ordovician Pacootta Sandstone in the Amadeus Basin, and the Cambro-Ordovician Wanna Formation of the Officer Basin, suggest that the 650-550 Ma PG zircons of eastern Australia were sourced in the Paterson Orogen and transported eastward through the Larapintine Seaway. The ~3100 Ma Hf model age indicates that the Paterson arc sampled Archean terrane of the West Australian Craton. The data presented also strengthens existing palaeogeographical models that link Western Australia and the Lhasa Terrane along the northern margin of Gondwana.

## Alteration at the Olympic Dam Iocg-U Deposit – Insights into Distal to Proximal Feldspar Chemistry From Infrared Reflectance Spectroscopy

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Twenty thousand metres of diamond drill core representing a 14 km cross section from weakly to intensely altered Roxby Downs Granite through the Olympic Dam Breccia Complex, host to the Olympic Dam iron-oxide-copper-gold-uranium (IOCGU) deposit in South Australia, were analysed using HyLogger (visible, shortwave and thermal infrared core scanner). Thermal and shortwave infrared spectroscopy results from 30 drill holes with an average depth of 950 m and a maximum depth of over 2 000 m provide insight into the spatial relationships of quartz, orthoclase-microcline, albite-oligoclase, and progressively changing sericite and chlorite compositions. Ancillary information of assays, density, and magnetic susceptibility supplement the hyperspectral information.

The relative proportions of quartz, orthoclase, microcline, albite and oligoclase were mapped with thermal infrared spectroscopy. Variations in the chemistry of sericite and chlorite were extracted by proxy from their shortwave infrared spectral response, together with their relative spatial distribution. HyLogger scanning has revealed four deposit-scale mineralogical trends, progressing from least-altered Roxby Downs Granite into mineralisation: 1) decreasing ratio of orthoclase to microcline, 2) slightly decreasing ratio of albite to oligoclase followed by plagioclase destruction prior to albite replacement, 3) a progressive Al-OH wavelength shift of 2205 nm to 2210nm for sericite, followed by a spatially rapid reversal, and 4) progressive Mg/Fe-OH wavelength shift of 2248 nm to 2252 nm reflecting an increase in the Fe:Mg ratio of chlorite.

The HyLogger feldspar results support recent petrographic evidence of hydrothermal albite and K-feldspar at Olympic Dam, not previously reported. The spectral results from continuous HyLogger scans also show that the microscopic observations and proposed feldspar replacement reactions are not locally isolated phenomena, but are applicable at the deposit scale. A QAP<sub>TIR</sub> diagram along with supporting abundance ratios of the orthoclase to microcline and albite to plagioclase and the wavelength shifts in characteristic absorption features for sericite and chlorite can be used as empirical vectors towards mineralisation at Olympic Dam, with potential application to other IOCG deposits.

## Pleistocene coastal terraces in northern Tasmania revisited; what do they tell us about landscape evolution and uplift rates?

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While extensive coastal terraces in northern Tasmania have long been documented, they remain poorly described and dated to this day. Early descriptions of terraces suggest they have similar elevations to those on mainland Australia and most workers agree that these features represent marine abrasion platforms and related fluvial base-levels and thus constrain sea-level high-stands. However, a small number of amino-acid racemization (AAR) dates published previously suggest that correlation is not simple across Bass Strait and conclude that Tasmania has the highest neotectonic uplift rates in the Australian craton.

Recent mapping of these coastal features from Wynyard to the Tamar Estuary with the benefit of LiDAR derived digital elevation models (with sub metre vertical accuracy) has allowed us to map a series of terraces sets rising up to ~24m AHD. The preservation of these terraces are highly variable, and some are partially overlain by younger sediments, but there is sufficient evidence to indicate that they persist at similar elevations over a distance of ~150km. In the Tamar Estuary, the same features are preserved except that there are higher terraces and base-levels exceeding 100m AHD that are probably of fluvial origin.

If we ignore the AAR dates, the terraces can be readily correlated to the international sea-level curve derived from the Huon Peninsula (PNG) assuming a steady uplift rate that is similar to the adjacent Australian mainland. If this is true then the last interglacial terrace is at 5-7m AHD and the highest terraces date back to about 950ka with an average uplift rate of 0.025m/ka. However, if we accept the AAR dating and an average uplift rate of 0.17m/ka (an order of magnitude faster), then we are left with a number of terraces below the ~24m high last interglacial that do not fit the sea-level model and are difficult to explain.

A recent study of a well-known site near Hobart (Mary-Ann Bay) challenges the previous AAR dating and genesis of a shelly deposit ranging up to 30m elevation. Based on this and other dates to be presented we consider that the uplift rates and landscape age is under question and requires further work. Which-ever hypothesis is true, there are constraints in the landscape that constrain the total amount of uplift since the Early Neogene. The timing of the initiation of this uplift is sensitive to the adopted age of the terraces under question. The resolution of this problem also has significance in understanding landscape evolution rates, and in particular landslide likelihood.

## The Kalinjala Shear Zone: intracontinental shear zone or Palaeoproterozoic palaeosuture?

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Many models for the growth of the Australian continent in the Palaeoproterozoic invoke plate tectonic processes, based on the presence of magmatic suites with 'arc-like' geochemistry, the correlation of orogenic and magmatic events across cratons and continental-scale shear zone systems. A variety of geological tools are available for testing tectonic reconstruction models which invoke the suturing of different cratonic blocks, such as structural mapping, U-Pb geochronology, whole rock Nd and Hf zircon data, deep crustal seismics and magnetotellurics.

The major crustal feature formed during the Kimban Orogeny (1730-1690 Ma) is the Kalinjala Shear Zone (KSZ), a continental-scale transpressive high strain zone extending along eastern Eyre Peninsula. This structure juxtaposes two distinct lithostratigraphic domains; the Sleaford Complex (~2500 Ma) and Hutchison Group (~2000-1790 Ma) in the Cleve Domain to the W and the Donington Suite (~1850 Ma) in the Spencer Domain to the E.

This paper presents new observations on the crustal architecture of the Kimban Orogeny on northern Eyre Peninsula, where a system of N- to NW-trending faults and shear zones splay off the northern end of the KSZ. This fault and shear zone system formed late in the Kimban Orogeny, and cross-cuts earlier Kimban tectonic fabrics and juxtaposes lithostratigraphic blocks with differing metamorphic grades. In an inversion of the MT line transecting northern Eyre Peninsula, these shear zones are imaged as subvertical shallow crustal conductive features. The major Kimban crustal feature on northern Eyre Peninsula does not coincide with the magnetic discontinuity which divides the Cleve and Spencer domains, but is a west-dipping mid- to lower-crustal conductive feature which coincides with the boundary between Neoarchaean and Mesoarchaean basement sequences within the Spencer Domain.

The KSZ has been interpreted as a palaeosuture formed during the Kimban Orogeny or Cornian Orogeny (~1850 Ma) in a number of plate tectonic reconstruction models. However, recent geochronology and isotope data suggest that rather than forming a continental suture zone, the KSZ developed in an intracontinental setting. Nd isotopic values and inherited zircons in Mesoarchaean to Palaeoproterozoic (3150-2000 Ma) felsic igneous rocks across northern Eyre Peninsula indicate that these units have formed by a series of crustal melting events of the same underlying juvenile Mesoarchaean (~3400 Ma) crust. Similar detrital zircon spectra and Hf zircon values for Palaeoproterozoic sediments (1790-1750 Ma) across both sides of the KSZ indicate that they are part of a single eastward younging basin contiguous prior to the Kimban Orogeny, which was sourced from detritus from the southern Gawler Craton. Also, new geochronology of the Bosanquet Formation, a felsic igneous unit which occurs to the W of the KSZ gives an age of 1853-1855 Ma, within error of that of the Donington Suite to the E of the KSZ, suggesting that the Cleve and Spencer domains were contiguous before ~1850 Ma.

## **Will fossil fuels ever peak? The future global energy mix.**

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Throughout the last century there have been many predictions of an imminent peak in oil and natural gas production with an associated astronomic rise in prices. Predictions of peak coal production began even earlier with Stanley Jevons' publication of *The Coal Question* in 1865. Despite these predictions, the global production of coal, oil and gas has continued to rise. The combined production of the three fossil fuels has increased by 37% since the year 2000 and in early 2016 the prices of these commodities were at their lowest this century. Predictions of fossil fuel production using Hubbert curve analysis were flawed because the total amount of available resource was unknown. The amount of perceived resource available grows with the application of new technologies and new geologic concepts. The global proved reserves of both oil and gas have more than doubled in the last 40 years despite the vast volumes that have been produced. Recent advances including the development of unconventional resources and deepwater resources suggest that this trend could continue for many years in the future. Peak production of fossil fuels within the next few decades is only likely to occur because cheaper substitutes become available – not because the resources are being depleted. Renewable energy has made substantial inroads into the power generation sector in the last 10 years in several countries and this trend is likely to continue as solar and wind energy become cost competitive. Better batteries are making renewable energy sources more viable and the recent growth in production of plug-in electric cars has the potential to substantially modify demand for oil in the transport sector over the coming decades. However, despite recent rapid rises in production, renewable energy (excluding hydro) still only accounts for 2.5% of global energy consumption. Demand for energy is likely to double by 2050 and it seems unlikely that the growth of renewable energy will result in peak fossil fuel production within the foreseeable future, at least from a global perspective.

## **Thick- and thin-skinned contraction – Inversion in orogenic systems**

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Convergent orogenic systems formed by subduction and collision are typically doubly-vergent and flanked by pro-wedge and retro-wedge basins infilled with syntectonic sediments. The flanking basins are commonly incorporated into the thrust belts of the orogen and exhibit both thin-skinned low-angle thrust systems detached above basement, as well as basement-involved high-angle inverted fault systems. Inversion of pre-existing, pre-contractional extensional fault systems is common in both pro- and retro-wedge thrust belts. Inversion in orogens such as the Andes is fundamental in controlling the emplacement of the giant porphyry copper systems of Chile, whereas inversion structures in the frontal sub-Andean basins form the traps that host numerous petroleum accumulations. This presentation examines the characteristic geometries and mechanics of these orogenic thrust and fold systems utilizing studies from the Pyrenees, New Zealand, the Zagros fold belt and from the Andes. Field data are integrated with seismic data, remote sensing studies as well as scaled physical models of inversion and thrust systems in order to develop evolutionary models for thick- and thin-skinned contraction in these terranes.

## The origins of Palaeoproterozoic tungsten (and copper) mineralisation in the eastern Aileron Province, Arunta Region, central Australia

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Tungsten is a critical metal to society yet it is relatively rare and immobile in most geologic settings. However in the Palaeoproterozoic eastern Aileron Province of the Arunta Region, central Australia, tungsten occurrences are unusually widespread and associated with a variety of different mineralisation styles. Tungsten occurs as (i) W-Mo skarn mineralisation (eg Molyhil deposit); (ii) vein-style W mineralisation commonly associated with Cu (eg Jericho and Samarkand prospects); and (iii) W mineralisation spatially associated with syngenetic Cu-Ag(Pb-Zn) massive sulfide mineralisation (eg the Jervois mineral field). Scheelite is hosted in calc-silicate and skarnoid rock of the Bonya Metamorphics and commonly located at contacts with granite, pegmatite and related quartz-tourmaline veins. Some of these granitoid intrusions and veins also contain tungsten.

Despite some geologic understanding of individual scheelite prospects, broad regional comprehension of the geological processes, timing and genesis of this tungsten mineralisation are lacking. Potential links between epigenetic skarn, vein and purportedly syngenetic tungsten mineralisation styles, and regional base metal mineralisation are not well understood. Similarly how this mineralisation relates to regional deformation, metamorphism and magmatism and broader tectonic processes remains poorly constrained.

A new regional genetic model for tungsten mineralisation in the eastern Aileron Province is proposed using a combination of reconnaissance mapping, drillcore logging, whole rock geochemistry, petrology, LA-ICPMS U-Pb zircon and apatite dating and <sup>34</sup>S and <sup>11</sup>B isotopic analyses of sulfides and tourmaline from mineralisation and associated veining. These results are integrated with new regional 1:100000-scale geological mapping by the NTGS and historical datasets.

The new results suggest that the epigenetic W and Cu mineralisation formed at ca 1730-1690 Ma after high-*T*, low-*P* regional metamorphism. This tungsten mineralisation event relates to the emplacement of felsic intrusions and associated fluid flow within a likely inverted back-arc basin setting along the convergent southern margin of the North Australian Craton. The possibility remains that some tungsten, along with boron, was introduced earlier at ca 1790 Ma related to continental back-arc magmatism and syngenetic base metal mineralisation in an extensional basin setting. Nonetheless significant tungsten mineralisation is only found where tungsten has been concentrated by later epigenetic processes.

Given that calc-silicate rocks host most tungsten mineralisation regionally, carbonate-bearing sediments appear to be a key lithological control on mineralisation, and there remains good potential for further skarn discoveries in carbonate-bearing host rocks. However the observation of granite- and pegmatite-hosted tungsten also warrants future exploration for vein and porphyry style mineralisation in other lithologies. On a tectonic scale, tungsten metallogeny in the Aileron Province between ca 1730-1690 Ma is probably related to granite emplacement within an inverted basin inboard from the plate margin. Significant tungsten mineralisation is also reported in other contiguous Australian terranes between ca 1820-1670 Ma (eg Davenport and Curnamona provinces). These occurrences appear to be associated with incompatible-enriched melts emplaced into extensional basin settings or their inverted equivalents at various crustal depths.

## Scientific accomplishments of Reginald Claude Sprigg

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Sprigg had vast enthusiasm for all natural history and could frame powerful questions in feedback with geological mapping; and he securely grasped the interplay between geo-structure and geo-history. By 1954 at 35 he had changed the culture of South Australian geology.

**Adelaide Geosyncline.** In the difficult mapping and structural and geomorphic analysis of the Adelaide region, he achieved the most comprehensive advance in its geology in 150 years. The Mawson-Sprigg Adelaide System was actually vintage Sprigg. He recognised the Adelaide miogeosyncline as a fossil continental terrace, much older than any known; Bruno Campana and he showed that the Kanmantoo eugeosynclinal trough initiated the Palaeozoic Tasman Geosyncline of eastern Australia.

**Ediacaran biota.** With prepared mind and deliberate search, Sprigg found the fossils of the Ediacaran assemblage of animals of latest Precambrian age. He described and named 17 species of pelagic coelenterates ("jellyfish") of which about one-third survived as recognized taxa, some as higher animals. He saw himself as much biologist as geologist, and his handling of the comparative morphology, taphonomy and reconstruction, taxonomy and biological inferences, was confident and secure, and assisted by his skills in drawing.

**Late Neogene in southern Australia.** Sprigg perceived the late uplift as part of the uplift of the SE Australian highlands, and he sustained this view of neotectonic activity when it was unfashionable in petroleum exploration in Mesozoic-Cenozoic sedimentary basins. Meanwhile, he found strong indications of a cyclical pattern in the regular lateral succession of fossil beaches in south-eastern South Australia and took the intuitive leap of explaining this regional pattern with the Milankovitch theory of ice ages, itself still to be integrated with the geohistorical record. Geomagnetic and oxygen-isotopic stratigraphy in due course would confirm his 1940s theory that the aeolianites record a punctuated succession of high sea levels (i.e., interglacials). Sprigg with S.A. Shepherd systematically sampled the benthic faunas of Gulf St Vincent and Investigator Strait, their map becoming a benchmark for monitoring subsequent degrading of the local marine environment and for insights into generating bryozoan carbonates.

**Overview.** Sprigg's science had two strong strands, historicist and structural. His historicism (from Walter Howchin) equipped him to tackle problems at all geological scales with less than ideal chronological control. He lifted South Australian historical geology to a new level in three steps: total immersion in the geology of the Adelaide district; strong response to M.F. Glaessner's new rigour in stratigraphic thinking; and a general reinvigoration of his thinking in petroleum geology. Structurally (from Lockhart Jack), his focus on lineaments, the deep-seated discontinuities acting as geosynclinal and basinal controls, survived his embracing continental drift and plate tectonics. Balancing the structural with the historicist, Sprigg could resist such explorational simplicities of the times as: Find me an anticline and I will drill it, or, find me a geochemical anomaly and I will drill it.

Sprigg was uniquely versatile and inspiring in the natural sciences of Australia. A small selection exemplifies his sheer range: *Spriggina*, Sprigg Canyon, Sprigg Orogeny.

## Magnetic Nanofluid for Rare Earth Extraction from Geothermal Fluids

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Rare earth metals are critical materials in a wide variety of applications in generating and storing renewable energy and in designing more energy efficient devices. Extracting rare earth metals from geothermal brines is a very challenging problem due to the low (ppb) concentrations of these elements and engineering challenges (pressure drop, parasitic pumping power losses) with traditional chemical separations methods involving packed sorbent beds or membranes that would impede large volumetric flow rates (>6000 gal/min for a 20 MWe plant) of geothermal fluids transitioning through the plant. In addition, to achieve reasonable brine residence times, the packed bed or membrane systems would be very large and so pose significant challenges in fitting within an existing geothermal plant footprint and would have very high capital and operating costs. To overcome these challenges, a simple and highly cost-effective nanofluid-based method for extracting rare earth metals from geothermal brines is being developed. Core-shell composite nanoparticles are produced that contain a magnetic iron oxide core surrounded by a shell made of metal organic framework (MOF) sorbent functionalized with chelating ligands selective for the rare earth elements. By introducing the nanoparticles at low concentration ( 0.05 wt%) into the geothermal brine after it passes through the plant heat exchanger, the brine is exposed to a very high concentration of chelating sites on the nanoparticles without need to pass through a large and costly traditional packed bed or membrane system where pressure drop and parasitic pumping power losses are significant issues. Instead, after a short residence time flowing with the brine, the particles are effectively separated out with an electromagnet and standard extraction methods are then applied to strip the rare earth metals from the nanoparticles, which are then recycled back to the geothermal plant. Recovery efficiency for the rare earths have now been measured with several MOF sorbents functionalized with a variety of chelating ligands and the results used to conduct a preliminary but detailed techno-economic performance analysis of an extraction system. Production cost estimates confirm potential to produce REEs at less than half the present commodity market value for these metals generating an internal rate of return >20%, clearly indicating promise for commercialization of this technology.

## Climate-carbon cycle feedbacks during the Palaeocene-Eocene Thermal Maximum

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The Palaeocene-Eocene Thermal Maximum (PETM, 56 Ma) was a period of abrupt and extreme global warming driven by a massive release of organic carbon. This event represents an opportunity to examine carbon cycle feedbacks that can be difficult to quantify in the modern day, but are critical to anticipating future carbon cycle changes. Soil respiration is the largest carbon flux from land to the atmosphere and acts as an important carbon cycle feedback: CO<sub>2</sub>-induced warming drives increased soil respiration, releasing more CO<sub>2</sub>, driving more warming. However, quantifying the sensitivity of soil respiration to changes in temperature and precipitation in the modern has proven challenging. Here we examine terrestrial carbon, hydrogen and oxygen isotope records from across the PETM in the Bighorn Basin, Wyoming, US, to examine changes in rates of soil organic matter degradation in relationship to climate change.

During the PETM, the addition of organic, <sup>13</sup>C-depleted carbon to the ocean, atmosphere and biosphere caused a wholesale shift in carbon isotope ratios. This negative carbon isotope excursion (CIE) is the hallmark of the PETM, but details of the CIE vary between different archives and across the paleolandscape. In the southeastern Bighorn Basin, leaf wax *n*-alkanes record a larger and more sustained excursion than soil organic matter; within soil organic matter, CIEs differ widely in their shape and magnitude even within a restricted field area. We can exploit the discrepancy between the leaf wax and soil organic carbon CIEs, to model the effects of soil organic matter degradation and inputs of allochthonous fossil carbon. We calculate that the PETM warming of ~5°C was associated with a doubling of microbial degradation rates, and that the proportion of reworked fossil carbon increased to ~28–63%.

The hydrogen isotope signatures of leaf waxes reflect the combined influence of the isotope signature of meteoric water and transpirational D-enrichment that is driven by atmospheric relative humidity. By first constraining the shifts in hydrogen isotope ratios of precipitation in the southeastern Bighorn Basin, we are able to use leaf wax hydrogen isotope ratios to estimate changes in relative humidity across the PETM. We use oxygen isotope ratio of *Coryphodon* tooth enamel and the global meteoric water line to estimate the hydrogen isotope ratios of precipitation across the PETM. We use a modified Craig-Gordon model to estimate the relative humidity required to generate the observed trends. We find that growing season relative humidity increased during the PETM, which contrasts with soil indices that indicate decreased moisture. However, these seemingly contradictory records together suggest increased seasonality of precipitation during the PETM: plant growth occurred during a more humid season, in spite of an overall decrease in available moisture.

The doubling of soil respiration during the PETM represents an important positive feedback on warming, and the increase in reworked organic matter suggests increased erosion and redeposition that is consistent with the reconstructed increased seasonality of precipitation. These results highlight the importance of periods of past climate change in characterising carbon-cycle feedbacks that are relevant to anticipating future climate change scenarios.

## **U-Th-Pb-He Geothermochronology: Principles, Techniques and Applications in Reconstructing the Thermal History of the Earth's Crust**

**McInnes, Brent I.A.**, Danisik, Martin, Evans, Noreen J., and McDonald, Brad J.

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$^{4}\text{He}$  is a natural radioactive decay product of the U, Th and Sm contained within the Earth's crust. These elements are largely contained within accessory minerals such as zircon, apatite, titanite, monazite and fluorite.  $^{4}\text{He}$ , like the radiogenic isotopes of Pb, is quantitatively retained in these minerals at surface temperatures and can be used as a geochronometer to determine the formation age of low temperature mineral systems such as supergene Zn-Pb carbonate and Fe oxide ore deposits.

With the smallest atomic radii of any element, the chemically inert He atom is prone to diffusion outside its mineral host in response to elevated temperatures. The differing crystallographic structure of each host mineral is a controlling factor in helium diffusion and therefore each mineral species has the potential to act as a unique chronometer through an effective temperature range of 60°C to 220°C. In a continental geothermal gradient, these temperatures correspond to depths ranging from 2 to 10 km in the Earth's crust, and thus (U-Th-Sm)/He dating is referred to as a thermochronometric technique. At higher temperatures, He diffuses out of its mineral host and into the surrounding rock interstices as fast as it is produced – and these fluxes can potentially accumulate in natural gas reservoirs in sedimentary basins.

Over the last two decades, Australian research institutions have played a leading role in the development and application of (U-Th)/He thermochronometry techniques and applications. Measurement methods have evolved from the analysis of bulk mineral separates to single grains and now to *in situ* laser ablation techniques with the advent of the RESOchron™ U-Th-Pb-He instrument, the product of collaboration between Australian Scientific Instruments and Curtin University. By enabling the *in situ* measurement of both the U-Pb and (U-Th)/He isotopic systems in a single mineral, the RESOchron instrument provides a unique geothermochronology tool. An early benefit of investigating the U-Th-Pb-He system has been the discovery that kimberlite pipes produce unique thermal signatures in zircons, and that zircon geothermochronology can be used in the exploration for diamond deposits.

The RESOchron instrument also allows the creation of high-resolution (~10  $\mu\text{m}$  scale) 2D images of He distribution in grain mounts and rock sections. Helium mapping, when used in combination with information from other imaging techniques (e.g., cathodoluminescence, Raman spectroscopy and LA-ICPMS elemental maps) has the potential to enable the reconstruction of the thermal history of a rock sample by allowing direct measurement of He diffusional profiles in its constituent minerals.

## An eResearch System for Managing and Distributing Publicly Funded Geochemical Data in a Collaborative Environment

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Publicly funded laboratories have a responsibility to generate, archive and disseminate analytical data to the research community. Laboratory managers know however, that a long tail of analytical effort rarely escapes researchers' thumb drives once they leave the lab. This paper reports on an eResearch data management project (the Digital Mineralogy Library or 'DML') where integrated information technology systems automatically archive and deliver analytical data and metadata to institutional repositories and thus to community data portals. The scientific objective of the DML project was to quantify the modal abundance of heavy minerals extracted from key lithological units in Western Australia. The analytical platform used in this pilot system was a TESCAN Integrated Mineral Analyser (TIMA) that uses EDS-based mineral classification software to image and quantify mineral abundance and grain size at micron scale resolution.

The analytical workflow used a bespoke laboratory information management system (LIMS) to orchestrate: (1) the preparation of grain mounts with embedded QR codes that serve as enduring links between physical samples and analytical data, (2) the assignment of an International Geo Sample Number (IGSN) and Digital Object Identifier (DOI) to each grain mount via the System for Earth Sample Registry (SESAR), (3) the assignment of a DOI to instrument data via Research Data Australia, (4) the delivery of TIMA analytical outputs, including spatially registered mineralogy images and mineral abundance data, to an institutionally-based data management server, and (5) the downstream delivery of a final data product via a map interface, on the AuScope Discovery Portal (e.g., <http://portal.auscope.org/portal/gmap.html>). Researchers can now search the JdLC Mineralogy Library for minerals of interest (e.g., biotite for Ar-Ar geochronology), request access to the physical grain mount for further testing, and download the mineral classification image for targeting *in situ* microanalysis.

The modular design of the system permits extension to multiple instruments within a single site or multiple collaborating research institutions. The potential benefits of the widespread adoption of this approach in geochemistry data are significant: surveys conducted in 2015 have reported that ~40% of Australian researchers openly share data, while university laboratories report that less than 25% of analyses conducted make it into publications in the open literature.

Sharing analytical data provides new opportunities for the geochemistry community. However, the creation of an open data network requires: (1) the adoption of open data reporting standards and conventions, and licenses, (2) instrument manufacturers and software developers to deliver and process data in formats compatible with open standards, and (3) public funding agencies to incentivize researchers, laboratories and institutions to make their data open and accessible to the community after a specified embargo period.

This project received funding from the National Collaboration Research Infrastructure Scheme (via the AuScope Earth Composition and Evolution Program and the Australian National Data Service Major Open Data Collections Program), the Australian Research Council (ARC LE 1400100150), and was conducted in cooperation with the Geological Survey of Western Australia. A pilot study was supported by a grant from iVEC through the eResearch Capability Fund.

## **Scientific drilling opportunities in the SW Pacific and Antarctica with the International Ocean Discovery Program.**

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The International Ocean Discovery Program (IODP) is the latest iteration of 45 years of scientific ocean drilling, and is the world's largest international scientific geoscience program, with an operational budget of \$US180 million p.a. and 27 participating nations, including Australia and New Zealand. IODP is a wide-ranging international program that provides access to marine science infrastructure well beyond what is generally available at a national level. IODP deploys two large drilling vessels and other special-purpose drilling platforms (e.g., operation in shallow waters, heavy sea-ice cover) on expeditions that take continuous deep sea cores to address global scientific problems in the fields of climate and oceanographic change, the evolution of biota, planetary dynamics and natural hazards.

The Earth Science community has also benefitted from the forerunner programs (Deep Sea Drilling Project and Ocean Drilling Program, DSDP and ODP), with access to deep stratigraphic cores from the Tasman Sea, Canterbury Basin, for example.

In the next 5 years there is likely to be unprecedented IODP activity in Australia and New Zealand's waters as well as Antarctica. This talk will focus on five accepted proposals awaiting scheduling for the east coast of New Zealand as well as in Antarctica.

- 1) Unlocking the secrets of slow slip plate boundary behaviour by drilling at the northern Hikurangi subduction margin, New Zealand: Riserless drilling to sample and monitor the forearc and subducting plate.
- 2) Creeping Gas Hydrate Slides: Slow Deformation of Submarine Landslides on the Hikurangi Margin.
- 3) Gateway to the Sub-Arc Mantle: Volatile Flux.
- 4) Subduction Initiation and Paleogene Climate (SIPC) in the Tasman Frontier, Southwest Pacific
- 5) West Antarctic Ice Sheet.

## **UNESCO Global Geoparks**

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Since 2004, UNESCO has endorsed areas of international geological heritage significance with a sustainable economic development plan through the Global Geoparks label. However in November 2015, the 38<sup>th</sup> session of the General Conference of UNESCO, by acclamation, adopted the new designation of UNESCO Global Geoparks and agreed to adopt all pre-existing Global Geoparks as new UNESCO Global Geoparks. This marks the first time since the ratification of the Convention concerning the protection of the World Natural and Cultural Heritage in 1972 (which allowed for the creation of World Heritage Sites) that UNESCO has created a new site-designation of this kind and the first time it has adopted a series of pre-existing sites.

While world heritage sites focus on the fulfilment of one of 10 criteria that demonstrates outstanding universal value, UNESCO Global Geoparks have the concept of community empowerment and sustainable development at their core through appreciation of geological heritage of international value and its link to other aspects of natural, cultural and intangible heritage. Using examples, this presentation will present examples of UNESCO Global Geoparks, explain the concept behind them and discuss the various changes that have resulted from the recent decision by UNESCO.

## Tracing salt cycling in a small endorheic basin using chloride/bromide ratios and stable halogen isotopes

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Continental saline lakes are unique environmental features that are investigated for their importance in understanding geochemical cycling, salinity regulation and palaeoenvironmental records. These lakes are generally the focus of drainage in endorheic basins, where the only water discharge is via evaporation and salts are continuously accumulated. Depending on local environmental factors such as groundwater/surface water dynamics, solute transport and erosion, these salts can be redistributed within the catchment or into adjacent ones. Therefore, understanding these pathways and rates of salt redistribution around saline lakes is of great importance for local water and mineral resources, and Earth's geochemical cycling.

Geochemical techniques such as element or ion ratios, and stable isotope geochemistry have become popular in investigating salt movement around saline lakes. These techniques are able to directly trace the geochemical interactions of specific elements or trace closely related proxy elements. In saline environments, chloride and bromide are particularly useful because of their high solubilities, weak-affinity for sorbing to mineral surfaces, stable behaviour in a wide range of redox conditions and variations in their individual geochemistries. Chloride/bromide ratios are particularly useful in environments where the precipitation and/or dissolution of chloride-bearing evaporites occur, such as saline lake basins. More recently, studies investigating the stable isotope ratios of chlorine and bromine have found that they are useful in saline environments because they can trace diffusion rates where large porewater salinity gradients exist (e.g. between saline porewater and fresh aquifers), and identify evaporite precipitation/dissolution.

We have measured chloride/bromide ratios and stable halogen isotope ratios of various waters (i.e. rain, surface and subsurface waters) around the Lake George Basin to better understand salt cycling. Lake George is an ephemeral saline lake that occupies the centre of a small endorheic catchment. The clayey lakebed sediments contain saline porewater that may be slowly diffusing into contiguous fresh-brackish aquifers. Although, the lake does not receive enough saline groundwater discharge to develop significant evaporite deposits, during dry phases (i.e. during most summers over the last decade) thin salt crusts form and are subsequently eroded by persistent westerly winds. The eroded salt is potentially redistributed into the surrounding creek valleys and nearby catchments. The diffusion of salt from the lakebed and the erosion of salt from the lake surface both have the potential to impact on the local water resources that are used for water supply.

Systematic variations of chloride/bromide ratios and stable halogen isotope ratios, combined with other ionic/elemental compositions, have been able to support hypothesised geochemical pathways and throw light upon the impact of the palaeoenvironmental conditions. Firstly, chloride/bromide ratios suggest that the wind erosion is indeed redistributing evaporites from the lake surface into the creek valleys and removing salts from the catchment. Secondly, chloride/bromide ratios have provided evidence that saline lake porewater has diffused into, and is slowly increasing the overall salinity of a contiguous water supply aquifer. Lastly, stable halogen isotope ratios have been able to constrain the direction and rate of movement of solutes as a result of the recession of an ancient mega-lake.

## Characteristics, origin and significance of Mesoproterozoic bedded clastic facies at the Olympic Dam Cu-U-Au-Ag deposit, South Australia

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Bedded clastic facies occur in the Olympic Dam Breccia Complex (ODBC) which hosts the Olympic Dam Cu-U-Au-Ag deposit, South Australia. The bedded clastic facies stand out markedly from the rest of the ODBC because they are well bedded and dominated by fine grain sizes (mainly <2 mm). The rest of the ODBC lacks consistent bedding and is dominated by coarser grain sizes (fragments commonly >1 cm). Contacts of the bedded clastic facies with breccia of the ODBC are faulted and/or brecciated; fragments of the bedded clastic facies occur in the breccia complex.

Five facies associations defined on the basis of colour, components, grain size and bedding characteristics are present: interbedded sandstone and red mudstone, well-sorted quartz-rich sandstone, green sandstone and mudstone, polymictic volcanic-clast conglomerate, and thinly bedded green and red mudstone. Four of the five facies associations are interbedded and form mappable units. Major sources of detritus were felsic and mafic volcanic units of the Gawler Range Volcanics and granitoids of the Hiltaba suite. The siliceous mudstone, ironstone and barite laminae in the thinly bedded green and red mudstone facies association possibly consist of chemical and/or hydrothermal components. The felsic tuffaceous mudstone facies in this association contains well-preserved bubble-wall shards and sparse quartz crystal fragments, typical of distal (tens of km from source) pyroclastic fall deposits from contemporaneous rhyolitic explosive eruptions. Archean and Paleoproterozoic zircons in well-sorted quartz-rich sandstone indicate that older Gawler Craton basement successions also contributed sediment to the bedded clastic facies.

The dominant facies (laminated or thinly bedded mudstone) of the bedded clastic facies indicates a predominantly low-energy, below wave base subaqueous depositional setting. The polymictic volcanic-clast conglomerate and some cross-bedded sandstone beds are consistent with such a setting but reflect much higher energy depositional event(s). This setting extended across the area now occupied by the bedded clastic facies in the southern mine area at Olympic Dam and probably extended farther because the contacts of the bedded clastic facies with the ODBC are faults and the top is the unconformity with the overlying Neoproterozoic sedimentary formations.

Folds of variable size and shape are evident in many logged intervals of the bedded clastic facies. Because no cleavage is present, even in mudstones, the folds probably formed prior to final lithification. Bedding data obtained from oriented drill core indicate that the folds have a reasonably consistent gentle plunge to the northeast. Given the evidence for the deformation being pre-lithification, the trend of the fold axes could be defining the northeasterly strike of the original depositional slope, down which unstable portions of the bedded clastic facies eventually slid; the dip direction (northwest or southeast) is unknown. The depocenter in which these facies accumulated may have been bounded by a combination of northeast-striking and northwest-striking faults known to have been active at the time.

Because the bedded clastic facies occur at the top of the ODBC and contributed clasts to it, the fault-controlled sedimentary basin was in place when the breccia complex and the Olympic Dam ore deposit formed.

## Active submarine caldera mapped with remotely operated and autonomous underwater vehicles

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Havre volcano is a totally submerged active caldera in the Kermadec Arc. The caldera floor lies at ~1516 m bsl and the caldera rim is 950 to 600 m bsl. The volcano was the source of an extensive pumice raft and a weak steam plume, first observed on 18<sup>th</sup> July 2012. Here we present an analysis of the 2012 eruption, compiled using high-resolution data obtained by remotely operated (ROV, "Jason") and autonomous underwater (AUV, "Sentry") vehicles deployed 3 years after the eruption. The AUV provided a bathymetric map with a resolution of ~1 m, revealing the morphology of seafloor features with unprecedented clarity. The AUV map provided a foundation for sampling, photography and stratigraphic analysis along carefully chosen traverses using the ROV.

Because the witnessed events involved a plume and pumice raft, the eruption was assumed to have been predominantly explosive. However, on the seafloor and hidden from view, we found 9 rhyolite domes and 5 rhyolite lavas, an extensive layer of giant pumice clasts, debris avalanche and rockslide deposits from collapse of the caldera wall, and intracaldera sediment deformed during the eruption.

One of the earliest events was partial collapse of the southwestern caldera margin, generating a debris avalanche that formed a hummocky terrain on the caldera floor. Eruption of two intracaldera lavas followed, from vents part way up the southwestern caldera wall. The mass eruption rate then escalated with the production of the layer of giant pumice clasts. The giant pumice clasts have blocky, equant or tabular shapes and many have preserved quench fractures on their surfaces. This layer is an important marker that separates the two early lavas from the later lavas and domes. Similarities between the giant pumice and pumice recovered from the raft suggest that the giant pumice clast layer on the seafloor was produced on July 18-19, 2012, and that it correlates with the observed pumice raft and weak plume.

The only pyroclastic unit recognised with confidence among the 2012 products is a relatively thin (everywhere < 1? m) pumice lapilli and ash layer that becomes thinner and finer away from its inferred source on the southern caldera rim. Another partial collapse of the southwestern caldera wall occurred around the same time as the pumice lapilli and ash layer, or shortly before. The pumice lapilli and ash layer was erupted after most of the rhyolite lavas and domes, and after the giant pumice clast layer. The two largest domes produced during the eruption followed, and occupy the vent used by the pumice lapilli and ash layer.

Our survey indicates that a significant proportion (>80 %) of the erupted volume was transported away from the volcano in the form of the pumice raft and giant pumice clast layer, reflecting the special complications that arise for eruption into water versus air. The unprecedented resolution of the Havre data shows that even relatively small-volume eruptions involve complex coupling between eruption dynamics and the submarine environment, with surprising results.

## **Reaching new audiences — the evolving role of geological surveys**

**Meakin, Simone**

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Historically, geological surveys have focussed on collecting and archiving data, mapping, and developing tectonic and mineralisation models to aid the mineral and energy resource industry. In recent years however there has been an increasing shift to appeal to a broader audience due to several factors including population increase, land-use conflict and the evolution of new technologies, particularly social media. Also, negative portrayal of mining by the mainstream media has led to a distrust of explorers, miners and geoscientists in general. Government is increasingly being held to account for its activities, and struggles to retain public trust. Outreach activities are seen as a small but critical role of many scientific organisations — to promote understanding of science, the role of industry in society and to inspire the next generation of scientists.

The Geological Survey of New South Wales (GSNSW) has been increasingly active in this space, developing new types of products to appeal to a wider market. High quality geoscience maps and images can now be loaded onto phones and mobile devices. New geotourism maps and brochures are proving to be very popular in the community. A map of NSW renewable energy resources will soon be released. The web portal *Common Ground* has resulted from collaboration between community, industry and the NSW Government. It provides a simple reference for resource industry activity in the state and clearly explains the roles of community and government in the decision-making process for resource exploration and production activities.

Though outreach budgets are typically tight, collaboration with other organisations is a valuable way to access expertise, equipment, events, funding and publicity for our messages and products. The GSNSW has developed relationships with the Geological Society of Australia (especially the geotourism and geological heritage subcommittees), several universities, schools, museums, libraries, other government agencies, amateur geological societies, historical societies, Cartoscope, tourism offices and the local science hubs. This has led to involvement in several earth science displays, public talks, school and university visits and the Hunter Earth Sciences Discussion Group. The highly successful Newcastle Time Walk was run for National Science Week 2015 and partly funded by the *Inspiring Australia* initiative, a national science engagement strategy. Another successful attempt to capture the imagination of the public was a competition to name the new NSW State Fossil Emblem *Mandageria fairfaxi*, now known as "Fred". The GSNSW also supports other organisations' geotourism and geoheritage events by providing expertise or information.

The field of science communication has grown in the recent decade, addressing the need to better deliver science to the public without losing the message. Geoscientists must learn to engage community members, who generally view science in terms of how it affects their lives and have a tendency to distrust information and advice that they do not understand. Geological surveys are uniquely placed to comment on public issues that relate to geoscience and to advise and educate the community. Through outreach activities, we can enhance community interest in geoscience, and assist industry by providing balanced commentary in support of responsible exploration and mining.

## Detrital Zircons in the Modern Environment: What You Expect Versus What You Get

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Detrital zircon sampling from modern stream sediments is a technique that has been growing in popularity around the world over the last decade. The idea behind this sampling technique is that a sample of stream or river sediment will provide an average zircon population for the catchment area of the stream or river sampled, allowing for large scale assessment of the zircon U-Pb age record with minimal sampling and less sample bias than single rock techniques.

This method of sampling was undertaken in the Broken Hill area with the intention of assessing the Hf isotope record of the Willyama Supergroup (WSG). Previous studies have shown the WSG to have a zircon record of detrital zircons as old as 3500 Ma and syn-depositional magmatic zircon between 1720 and 1640 Ma, with 1600 Ma metamorphic overprints associated with the Olarian Orogeny. No zircons younger than this should occur in the detritus shed by outcrops of the Willyama supergroup. Previous stream sediment samples from Broken Hill presented by Condie et al. (2005) show a population of 1630 Ma juvenile zircon.

Analysis of detrital zircons in river and creek sediment samples from across the Broken Hill area showed large populations of 1300-1000 Ma and 600-100 Ma aged zircons, together averaging 30% of the analysed zircons in each sample. The post-1600 Ma zircons were present in every sample regardless of catchment size, however catchments which contained more alluvial and colluvial regolith showed a larger proportion of the younger than expected zircons. No significant population of 1630 Ma juvenile zircon was identified.

In order to identify the source of these younger than expected zircons, samples of dune sands were taken from the south eastern Strzelecki desert, approximately 120 km north of Broken Hill. The zircons from these aeolian sands showed dominant age populations of 600-100 Ma and 1300-1000 Ma, which overlap with the observed younger than expected zircon ages from the Broken Hill area. Thus it is interpreted that the 1300-100 Ma zircons in the modern environment in Broken Hill are the result of Aeolian deposition. The dune sands also contained a notable portion (~20%) of zircons aged 1600 Ma or older, many of which overlap in age with that expected from the WSG. This casts further doubt onto the origin of zircons of the expected age range from the Broken Hill samples, as these may have also been deposited as aeolian detritus. While most zircons of the expected ages are likely to come from the bedrock within the catchment area of each stream, the origin of individual grains cannot be assigned with certainty, and thus must be considered unreliable.

Conclusions drawn from detrital zircon U-Pb-Hf isotopic compositions with respect to basement outcrop should be treated with extreme caution in any arid area with aeolian deposits, such as much of Australia and other mid latitude deserts around the world.

CONDIE K. C., et al. 2005 U-Pb isotopic ages and Hf isotopic composition of single zircons: The search for juvenile Precambrian continental crust, *Precambrian Research*, vol. 139, no. 1–2, pp. 42-100.

## Proterozoic evolution of the Barossa Complex, SE Gawler Craton, South Australia

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The Barossa Complex is an underexplored Paleo-Mesoproterozoic region located on the south eastern reworked margin of the Gawler Craton, South Australia, and forms part of the basement to the Neoproterozoic Adelaide Rift Complex. Mapping of the northernmost of the inliers has revealed a stratigraphic succession of calc-silicate gneisses, quartzo-feldspathic gneisses, psammopelites, and metapelites. This succession of sedimentary protoliths is suggestive of a deepening basin.

Detrital zircons indicate that deposition commenced after 1740 Ma and potentially continued until the onset of metamorphism at 1630 Ma. The dominant detrital zircon age peaks in the Barossa Complex range from 1850 Ma to 1730 Ma, which are suggestive of an eastern Gawler Craton source region. Hf isotope data show a strong similarity to data obtained from metasedimentary rocks on the eastern Eyre Peninsula (Szpunar et al. 2011).

A granitic intrusion occurred in the Northern Barossa Complex at approximately 1718 Ma, indicating some deposition had occurred by this point. One detrital zircon sample has shown an essentially unimodal peak at approximately 1700, suggesting that deposition continued after the intrusion of the granite. The depositional timing of the protoliths to the Barossa Complex overlap with the onset of deposition in the lower Willyama Supergroup in the Curnamona Province, and it is possible that the Barossa Complex is an equivalent or a continuation of the basin system. This timing also coincides with the development of the Kimban Orogen within the Gawler Craton, which is a likely source region for the Barossa Complex sediments.

Three distinct Proterozoic deformation phases are observed in the northern Barossa Complex. A high grade sill-gt bearing gneissosity (S1) was developed early in the deformational history, at relatively low P – high T conditions of approximately 800–850°C and 8–9 Kbar (Morrissey et al. 2013). The S1 fabric is at a low angle to the relict sedimentary layering in the metasediments. This fabric was subsequently deformed by open to tight N-S plunging F2 folds, which are further deformed by large open east plunging F3 folds. These events potentially correspond to the published metamorphic ages of 1630 Ma (D1), 1590 Ma (D2), and 1560 Ma (D3) but have yet to be directly linked. This metamorphism is synchronous with the Olarian Orogeny in the nearby Curnamona Province, and the Hiltaba and Wartarken Events in the Gawler Craton, however it is unclear whether the 1630–1560 Ma metamorphic ages represent a continuous or punctuated metamorphic event.

MORRISSEY L. J., et al. 2013 Early Mesoproterozoic metamorphism in the Barossa Complex, South Australia: links with the eastern margin of Proterozoic Australia, *Australian Journal of Earth Sciences*, vol. 60, no. 8, pp. 769–795.

SZPUNAR M., et al. 2011 Isotopic and geochemical constraints on the Paleoproterozoic Hutchison Group, southern Australia: Implications for Paleoproterozoic continental reconstructions, *Precambrian Research*, vol. 187, no. 1–2, pp. 99–126.

## Twofold origin of Cenozoic magmatism in Tasmania

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Cenozoic volcanism in Tasmania forms the southern insular end of the extensive Cenozoic magmatic province in eastern Australia. This province extends parallel to the eastern Australian margin and stretches from northern Queensland to Tasmania and westwards along the southern margin, into Victoria and as far west as Mt Gambier in South Australia. Cenozoic volcanism in Tasmania was widespread, is entirely basaltic and ranges from highly undersaturated olivine nephelinite to tholeiite. A number of hypotheses have been proposed to explain the Tasmanian volcanic activity, such as passive upwelling of hot asthenospheric mantle as a delayed effect of opening of the Tasman Sea or the Southern Ocean and/ or as a result of several hotspot tracks. However, none of these hypotheses fully explain the composition of all of the igneous rocks present in Tasmania.

Preliminary research based on plate reconstruction models and geochemical analyses show that the Cenozoic Tasmanian volcanism has a twofold origin. This comprises two main sources; a deep (asthenospheric) mantle source which has been stationary over time and which has caused magmatism in Queensland, New South Wales, Victoria and Tasmania, and a second, shallow source that is moving northwards with the Australian plate, and which is compositionally similar to the source that was also responsible for widespread Jurassic magmatism in Tasmania. Although many authors have suggested models of hotspot magmatism and deep plumes for Tasmanian magmatic activity before, the link with the Jurassic magmatism is new. This link has been demonstrated by modelling of trace elements and Sr, Nd and Pb isotopes of endmembers of both the geochemically distinct Cenozoic and Jurassic magmatism in Tasmania. This modelling shows that part of the Cenozoic magmatic rocks are a result of mixing between a MORB-like source, which is reflected in the most primitive samples in Tasmania, and the source responsible for the Jurassic magmatism. As this Jurassic source is still present in Tasmania, it has been stationary with respect to the Australian plate, so we conclude this source must be shallow enough to travel along with the plate. Based on major, trace element and isotopic analyses of Jurassic igneous rocks in Tasmania, it has previously been suggested that the Jurassic source consists of a depleted harzburgite which has been contaminated with a small fraction of upper crustal sediment during Cambrian subduction or lithospheric delamination at the end of the Cambro-Ordovician Delamerian-Ross Orogeny. This interpretation therefore agrees well with our theory of a shallow source, which travels along with the Australian plate.

## Hydration is the key for metal transport in vapour fluids

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In recent years there has been considerable speculation that low-density vapour fluids may play an important role in metal transport in magmatic-hydrothermal systems. A number of experiments have been carried out to investigate metal solubilities in vapour phase and the partitioning of metal species between liquid/vapour/melt. Metal solubility in vapour fluids is a consequence of the complexation by ligands such as H<sub>2</sub>O, H<sub>2</sub>S, Cl<sup>-</sup>; and increasing evidence of the abundance of water-poor, CO<sub>2</sub> rich fluids inclusions in orogenic gold deposits indicates that volatile-rich fluids may have played a role in deposit formation. The knowledge of identity, stoichiometry and thermodynamic properties of metal complexes is essential for modelling the dissolution, transport and deposition of metals in vapour fluids. In this study, we combined solubility experiments and molecular dynamics (MD) simulations to investigate the complexation, geometries and thermodynamic properties of gold and copper complexation from liquid to vapour fluids and gold speciation in CO<sub>2</sub>-rich fluids with different CO<sub>2</sub> fraction.

We have conducted *ab initio* MD simulations of Au-Cl and Cu-Cl complexes in aqueous fluids at a wide range of T-P and fluid density (0.02 - 1.18 g/cm<sup>3</sup>, 25–1000°C, 1–5000bar). The simulation results show that the hydration numbers of Cu<sup>+</sup>/Au<sup>+</sup>/Na<sup>+</sup>/Cl<sup>-</sup> ions decrease linearly with the decreasing of fluid density, which supports empirical thermodynamic models that correlate the stability constants of complexation reactions with solvent density. This correlation indicates the changes in hydration linked by H-bonds contributes to the change of metal solubility in low-density fluids, the same as suggested by solubility experiments.

The gold solubility experiments were conducted at 340 °C in 0.01 m HCl vapour fluids with CO<sub>2</sub> mole fraction (CO<sub>2</sub>/(H<sub>2</sub>O+CO<sub>2</sub>)) of 0.4- 0.84, and complemented by *ab initio* MD simulations of AuCl complex in H<sub>2</sub>O-CO<sub>2</sub> mixture fluids at densities between 0.78-0.15 g/cm<sup>3</sup> and CO<sub>2</sub> mole fraction of 0.1-0.98. The experimental results show that gold solubility has a negative correlation to the CO<sub>2</sub> content in the fluids, i.e., decreasing with decreasing water fugacity. The MD simulations indicate that the number of hydration water and H-bonds near the AuCl complex decreases systematically with increasing CO<sub>2</sub> mole fraction.

These consistent results from *ab initio* MD and solubility experiments suggest that as a polarized molecule H<sub>2</sub>O plays a key role in metal transport in vapour fluids by forming metal complexation from hydrated ions of metals and ligands. The hydrated speciation of Au and Cu complexation should be considered in the geochemical modeling in further studies.

## **Geo-Tipping Point – Impact of a Humble Carbonate on Microfracture, Gold Remobilisation and the Generation of a World-Class Gold Deposit**

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It is shown that gold can be remobilised from the crystal lattice of sulphides via infiltration of only small volumes of fluid, and that ankerite potentially plays a critical role in this process and in the style of coeval deformation. The world-class Obuasi gold deposit, Ghana, has ankerite alteration spatially associated with ore shoots of gold-rich arsenopyrites and gold-rich microfractures in the hinge zones of folded quartz veins. Remarkably there is little or no quartz infilling the gold-rich microfractures. Using a combination of quantitative electron backscatter diffraction analysis, ion microprobe imaging, and synchrotron XFM mapping the gold-rich arsenopyrites are shown to have undergone partial replacement (~15%) by gold-poor, nickel-rich arsenopyrite. The replacement reaction and removal of gold to the hydrothermal fluid phase occurred during intragranular microfracture, localised crystal-plastic deformation of the arsenopyrites and metamorphism (340°-460°C, 2 kbars). Microfracture and fluid infiltration was coeval with the precipitation of ankerite, which removed CO<sub>2</sub> from the fluid and had a two-fold impact; (1) buffering pH toward conditions optimal for gold solubility, and (2) generation of a silica undersaturated fluid. The development of silica undersaturated fluid would have inhibited quartz cementation and facilitated fluid ingress, as well as potentially enabling dissolution. Therefore, we suggest that precipitation of the humble ankerite has an impact on fluid chemistry and a significant feedback on how deformation proceeds within rock. Similar dynamics could occur in earthquake swarm events during H<sub>2</sub>O-CO<sub>2</sub> fluid phase separation, or in systems where hydrothermal graphite is forming.

## **Sequence Stratigraphic Analysis of the Epsilon Formation, Merrimelia Ridge, Cooper Basin, South Australia**

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The majority of successful gas fields within the Cooper Basin have historically been associated with four-way dip, intra-basin highs. This conventional model will have to be challenged in order for future exploration and field development to continue to be successful within the Cooper Basin.

The mid-Permian fluvio-deltaic Epsilon Formation has complex geomorphologies and is largely considered to be transgressive. This study integrated a wide variety of datasets including; seismic, wireline, core and image logs that identified two sequences (described as Tu95 and Tu35) within the Epsilon Formation. Their associated sequence boundaries and systems tracts were interpreted onto 26 wells covering 5 traverses over the study area. Image logs and core confirmed typical lowstand and highstand lithofacies assemblages supporting the wireline sequence and electrofacies interpretations, producing paleogeographic maps indicating a dominant south-east paleoflow. Previous empirical studies and measurements from potential modern analogues suggest that channel belts were up to 2500m wide. These results highlighted the potential of low stand systems tract (LST) sandstones as hydrocarbon reservoirs.

The Tu95 LST has been hypothesised to be a forced regressive deposit (FRD) as it exhibited sharp log signatures frequently associated with unconformities, thickening intra-formational isopach trends and an absence of the Roseneath Shale in the NW. This combined could also be evidence of basin tilting towards the SE. A period of a renewed tectonic activity, just prior to the Daralingie uplift event, may have caused additional sub-aerial exposure and basin tilting. This would support the weakly positive gradient assumed to be leading into the Nappamerri Trough at the time of deposition, which could have resulted in a substantially faster lowstand lake level retreat and FRD's.

Detailed seismic mapping of the Epsilon Formation identified eight 'sub-horizons' that generally relate to separate onlapping transgression events. As a result it was determined that an onlap fairway, represented by the Epsi\_00 sub-horizon, could hold potential for stratigraphic trapping. Seismic onlap versus truncation geometries also suggested a combination of non-deposition and post-depositional erosion is the likely reason for the lack of Epsilon Formation that is observed on the Gidgealpa-Merrimelia-Innaminka structural lineaments today.

Repeat formation pressure test and production perforation data found that the Tc90 and Tc20 Epsilon Sands within the Swan Lake field area were potentially isolated, whereas the Tc90 sands in the Meranji field were possibly connected. Shoreface, mouthbar and distributary channel facies were found to have the highest porosity and permeability.

After considering all the factors of the sequence stratigraphic architecture, paleogeography, reservoir connectivity and reservoir quality; the fluvial-deltaic sands associated with the Tu95 Low Stand System Tract were identified to be the most prospective and hold the greatest chance of technical success.

## **An explanation of ultrahigh-pressure metamorphism**

**Ross N. Mitchell, Grant M. Cox, William J. Collins, Bradley R. Hacker**

Ultrahigh-pressure metamorphism is thought to require the presence of a continental lower plate in collisional orogens, however a complete understanding of its genesis at depth and its preservation at crustal levels remains elusive. Here we show that UHP metamorphism occurs almost exclusively in mountain belts internal to the formation of supercontinent Pangea and are lacking in external, circum-Pacific orogens. Furthermore, peaks in UHP metamorphism correlate with the generation of S-type granites and correlate inversely with peaks in zircon production associated with arc magmatism. We propose a model of UHP metamorphism that initiates at closure of an oceanic basin, reaches peak conditions during crustal thickening along with the emplacement of S-type granite, and retrogrades and is exhumed as a consequence of slab breakoff.

## Ribbon tectonics in VanDieland

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VanDieland can be described as a series of up to seven continental crustal ribbons (King Island, Rocky Cape, Burnie, Tyennan, Pedder, Glomar, Wings, and Sorell-Badger Head) each with its own distinct geological history and with defined boundaries. Some boundaries are well known, like the Arthur Complex that separates the Rocky Cape and Burnie zones. Others are more cryptic as they are within high grade metamorphic complexes, like that between the Pedder and Tyennan zones, or are largely covered, like the boundary between the Tyennan and Sorell-Badger Head zones. The westernmost ribbons, the King Island, Rocky Cape and Burnie zones, can be traced north from Tasmania across Bass Strait into the Selwyn Block in Victoria where, together with the east South Tasman Rise and the South Tasman Plateau, they form the VanDieland microcontinent. The correlation between western Tasmania and the Selwyn Block is evidenced by the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios,  $_{\text{Nd}}$  values and calc-silicate xenoliths in central Victorian Late Devonian granites, and by quartzite- and basalt-derived conglomerates in Lower Devonian units and Cambrian volcanic rocks seen in the eastern Melbourne Zone.

VanDieland came together in the Tyennan Orogeny as the result of the aggregation of the different continental ribbons. These had formed between approximately 770 Ma and 580 Ma, in the breakup of the 'southwest' Laurentian and East Antarctic parts of Rodinia. Thereafter, they drifted 'north' in the proto-Pacific Ocean from the present-day East Antarctica until, at approximately 520 Ma, they began to interact with the subduction system that lay outboard of east Gondwana. Rather than subducting, the ribbons aggregated in the upper plate above this west-dipping subduction zone. Mostly, transitional oceanic crust had loosely held the ribbons together. In shortening, large parts of these thinned regions were consumed, but some are preserved as slivers of mafic-ultramafic complexes and slices of basalt and mafic volcanoclastic sandstone. This happened along the east-dipping Burnie-Pedder boundary, giving rise to the Heazlewood River and associated mafic-ultramafic complexes and the allochthonous Cleveland-Waratah association. On the western margin of the Wings subzone, it gave rise to the Adamsfield Ultramafic Complex and the Ragged Basin Complex. Where they had previously been sufficiently far apart to form intervening back-arc basins (as between the King Island and Rocky Cape zones) secondary east-dipping subduction zones briefly formed. Here, subsequent slab-break-off generated the Mount Read Volcanics and equivalents. These collisions also gave rise to the many high-pressure metamorphic complexes seen in Tasmania.

## **Investigating causes of river avulsion: a case study from the Magdalena River, Colombia. Insights for fluvial petroleum reservoirs.**

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Improvements in interpretation, characterization and modelling of fluvial reservoirs are needed to unlock the vast amounts of hydrocarbons hosted in fluvial reservoirs. The lateral continuity of sand-bodies as well as sandstone and mudstone distributions are often hard to predict, especially when channel bodies are below seismic resolution. In such cases, reliance on depositional models and scaling relationships are essential. The understanding of avulsion events offers a process-based approach for unraveling controls in facies distribution and stratigraphic architecture in fluvial systems. However, very few studies include observations from avulsion events taking place or soon after their occurrence. Here, we investigate the causes that generated a 2007 avulsion event that took place in one of the anabranching reaches of the tropical Magdalena River, Colombia. This analogue is particularly relevant for the fluvial reservoirs of the Mungaroo Formation, which hosts vast resources of hydrocarbons in the North West Shelf of Australia.

Based on a collection of satellite images we established that the avulsion event took place via the formation of a crevasse splay followed by maintenance and expansion of one crevasse channel, in-filling of a lake and development of a network of new channels. We also provide topographic, bathymetric, sedimentologic and discharge data to elucidate the possible causes of this avulsion event and provide deposit facies descriptions. On a regional scale, the location of the avulsion node is related to changes in gradient caused by a fault, while on a reach scale it is linked to the location of the channel's thalweg, which is up against the bank where the avulsion node is located. We also show that levee height is not closely scaled to channel depth and therefore normalized superelevation does not play a role in the setup for avulsion in this site. The trigger of the avulsion and maintenance of the newly avulsed channels can be ascribed to high discharge magnitudes related to the 2007 -2008 and 2010-2011 extreme La Niña events.

## The Windmill Islands, east Antarctica: a window into the poorly exposed margin of the Albany–Fraser Orogen

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The Windmill Islands are a series of outcropping islands and mainland peninsulas on the coast of Wilkes Land, east Antarctica. Together with the Bunger Hills, they form part of an extensive Mesoproterozoic orogenic belt that includes the Albany–Fraser Orogen in Western Australia and extends to the Musgrave Province and southern Warumpi Province in central Australia. This orogen was at least ~5000 km long and occupies a pivotal location in the architecture of the formerly contiguous Australian–Antarctic continent. However, the paucity of exposure has hindered attempts to understand the links between each of these regions.

The Windmill Islands, Albany–Fraser Orogen and Musgrave Province are characterised by a two-stage tectono-metamorphic evolution. Stage I occurred between ca 1345–1290 Ma and Stage II occurred between ca 1220–1140 Ma. In all three regions, Stage II was associated with voluminous, high-temperature charnockitic magmatism. However, despite the temporal similarities in magmatism and orogenesis, recent work has suggested that Albany–Fraser Orogen and Musgrave Province evolved on different basement. The Albany–Fraser Orogen is built on the margin of the West Australian Craton, whereas the Musgrave Province is interpreted to have a juvenile basement that corresponds to the Madura Province to the south. The eastern margin of the Albany–Fraser Orogen is covered by younger sediments, and therefore the relationship to the juvenile Madura Province is poorly understood. The Windmill Islands provide an opportunity to assess links between the Albany–Fraser Orogen and the Madura Province. In addition, the Windmill Islands provide a unique opportunity to assess the conditions of both stages metamorphism.

Laser Ablation–Split-Stream U–Pb geochronology suggests that deposition of the metasedimentary rocks in the Windmill Islands occurred between 1350–1300 Ma, corresponding to the timing of deposition of sediments within the Albany–Fraser Orogen. Detritus was sourced from neighbouring terranes of the West Australian Craton, Musgrave and Madura Provinces.

In situ monazite U–Pb geochronology and calculated metamorphic phase diagrams suggest that deposition was shortly followed by regional, high thermal gradient metamorphism (M<sub>1</sub>) at ca 1320–1300 Ma. M<sub>1</sub> occurred at upper amphibolite facies, with pressures of 4–5 kbar and temperatures of 730–750 °C. The tectonic setting of M<sub>1</sub> metamorphism is not constrained, but the elevated thermal regime may have been inherited from a back-arc setting. The second phase of metamorphism (M<sub>2</sub>) occurred at ca 1200–1160 Ma and was related to intrusion of the Ardery Charnockite. The effects of M<sub>2</sub> are more localised and increase progressively to the south, to conditions of 4.5–5 kbar and temperatures >800 °C. The similarities in pressure between M<sub>1</sub> and M<sub>2</sub> suggest that the region was not significantly exhumed after M<sub>1</sub>.

## **CSG in the GAB - changing our understanding of basin hydrodynamics.**

**Andrew Moser<sup>1</sup>, Ryan Morris<sup>1</sup>, Thomas Flottmann<sup>1</sup>**

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The scale and pace of Coal Seam Gas development in Queensland's Surat Basin has been unprecedented in Australia. Widespread concurrent development by a relatively small number of operators, and a strong research agenda to satisfy regulatory, community and production optimisation issues has resulted in a uniquely intense learning opportunity. The sustained convergence of geoscientific and engineering disciplines rarely seen in the past has facilitated a rapid, though still infant evolution in our understanding of wider scale basin hydrodynamics.

This presentation will use learnings from the vast monitoring network, core studies, in-situ testing, aquifer injection operations, tracer studies, and modelling to examine:

- the necessity for, and dangers of simplistic conceptual models;
- how a formation can simultaneously be an aquifer and an aquitard;
- continuity of permeability at different scales;
- permeability sub regions;
- the overarching influence of structural setting;
- potential preservation of paleo pressure regimes; and,
- the big picture challenges of recharge and flow.

## Influence of dynamic topography on the evolution of the Australian landscape since the Late Jurassic

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Australia is an outstanding natural laboratory to study the influence of dynamic topography on landscape evolution, having been largely unaffected by tectonic deformation since the Jurassic. For instance, the sedimentary deposits of the Eromanga inland sea that covered a third of Australia between 130 and 100 million years ago were laid down because of flow deep within the Earth. We developed a new numerical framework to quantify the fundamental feedbacks between mantle flow, landscape dynamics and associated sediment transport at continental scale. The approach relies on the soft coupling between *CitcomS* (a finite element code designed to solve thermochemical convection of the Earth's mantle) and *Badlands* (a finite volume code built to simulate geomorphological evolution and stratigraphic record under various climatic and tectonic forcings). Here we present how this new framework can be used to quantify the impact of dynamic topography on Australian landscape evolution over the last 150 Ma.

We use a mantle flow model to reconstruct the evolution of Australian dynamic topography since the Late Jurassic. The model predicts that Australia was tilted down to the east 150 Myr ago because of longlived subduction along the eastern border of the continent. At around 100 Ma, subduction ceased and Australia migrated eastward over sinking ancient Gondwanaland slabs, causing Eastern Australia to rebound from being drawn down. After some time of absolute plate motion stagnation, a renewed uplift of the eastern highlands happened during the Cenozoic period, as the Australian plate progressively migrated over the Pacific Superswell.

We used this predicted evolution of dynamic topography as forcing conditions of *Badlands* models, in addition to a history of varying climate and longterm sealevel. The *Badlands* models quantify the time dependence of erosion and deposition, as well as the evolution of catchment dynamics, drainage capture and drainage network reorganisation. The models show that the motion of the Australian plate has resulted in significant changes in river drainage, intercontinental erosion and sedimentation. In particular, the models reproduce the erosion and formation of the transcontinental Ceduna River, feeding sediment into the Ceduna Delta during the Lower Cretaceous, before the flooding of central Australia. The predicted denudation rates and drainage evolution are compared to thermochronology data and paleodrainage from paleogeography and sedimentary record in the Eromanga and Great Australian Bight regions. We show that the results are in good firstorder agreement with published uplift models derived from river profiles and the stratigraphic record (progradational patterns and deposit thicknesses) from the Ceduna Basin.

Despite the model limitations, this coupling approach shows promising results that reflect the fundamental link between dynamic uplift, fluvial erosion and depositional pulses in basins distal to passive margin highlands.

## Pygplates – a GPlates python library for data analysis through geological time and space

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Plate tectonics is unique to the Earth in the Solar System, and a key to the origin and sustainability of life, not least human life - most mineral and energy resources formed at geologically energetic tectonic boundaries. An understanding of plate boundary evolution through deep time is therefore a critical step in locating new resources. The well-established GPlates software is a paleo-geographic information system that allows geoscientists to combine a wide variety of geodata and examine them within tectonic reconstructions through time. The availability of such powerful tools also brings new challenges – we want to learn something about the key associations between geodynamic processes and resource formation and preservation, but the high-dimensional parameter space is hard for a human being to visually comprehend and quantify these associations. To achieve true spatio-temporal data-mining, new tools are needed. Motivated by these issues, we have developed *pygplates*, a Python library that enables access to GPlates functionality via Python scripting. The advent of *pygplates* opens the door for connecting spatio-temporal data analysis to “big data” on the cloud. The well-established ecosystem of open-source python-based tools for data-mining, statistics and machine learning can now be linked to *pygplates*, allowing spatial data to be seamlessly analysed in space and geological “deep time”, and with the ability to spread large computations across multiple processors. Example applications range from basic data query and filtering capabilities; to the reconstruction of ocean crust in now destroyed ocean basins; analysing the proximity of subduction zones and mantle plumes through time; and predicting past Large Igneous Province eruptions sites and where their products are most likely to have accreted at subduction zones. Efficiently extracting subduction zone characteristics for age-coded ore deposits allows us to unravel the tectonic environments of Pacific-rim porphyry copper-gold deposits. *pygplates* is also designed to facilitate linking tectonic surface boundary conditions contained within plate tectonic reconstructions (plate boundary configurations and plate velocities) to thermo-mechanical models of lithospheric deformation and mantle convection. The *pygplates* code-base is already being used to build various applications and visualisations within the GPlates portal ([portal.gplates.org](http://portal.gplates.org)). A paleomapmaker allows users to export publication-quality figures using datasets and reconstructions contained within the portal data store or uploaded directly by users. Over time, the establishment of RESTful web services will migrate additional functionality of the desktop GPlates software into the Cloud. Future *pygplates* applications will integrate tectonic reconstructions with ultra-high-resolution high-performance computer simulations for improving our understanding of the engine that drives Earth’s evolution and the development of the experimental planet. A unique system of this linked technology has the potential to reveal the big picture of how surface and deep-Earth processes interact, and thus the intricate pathways in the planet’s geological development. Key questions involved are: how can we understand the dynamics of Earth’s mantle and its interaction with the components of Earth above it and how does lithosphere dynamics depend on mantle processes and feed back into deeper mantle dynamics? An efficient framework for quantitative plate tectonic analysis is a key ingredient in answering these questions.

## The eastern Australian record of continental travel, dynamic topography and landscape evolution since Pangaea breakup

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The large-scale structure of the Earth's lower mantle is dominated by the African and Pacific large low shear velocity provinces (LLSVP), which are both associated with geoid highs, reflecting anomalous temperature, possibly chemistry, and large-scale upward mantle flow. Australia is unique amongst continents formed during the breakup of Pangaea in that it has travelled from the edge of the African LLSVP in the Late Jurassic to the edge of the Pacific LLSVP in the Cenozoic, crossing the East Gondwanaland slab burial ground. The plate tectonic history has had major consequences for the evolution of Australia's dynamic topography, exhumation, erosion and depositional systems through time. In the Late Jurassic at 150 Ma, Australia was tilted to the east, while the western part of the continent was proximal to the African LLSVP and the continent's eastern border was marked by long-lived subduction. Around 100 Ma subduction became extinct while Australia had migrated east to a position far away from large upwellings. Eastern Australia's rebound from being drawn down by sinking Gondwanaland slab material followed subduction cessation and slab breakoff, leading to pronounced uplift of the eastern highlands of Australia, erosion and formation of the transcontinental Ceduna River, feeding sediment into the Ceduna Delta. After some period of absolute plate motion stagnation, Australia's fast Cenozoic north-northeastward brought its eastern perimeter into the reach of the Pacific LLSVP, leading to renewed uplift of the eastern highlands, and a second pulse of sediment deposition in the Ceduna Delta. We couple these dynamic topography predictions with a continental-scale surface process model that we use to compute 150 Myr of landscape evolution from a history of varying climate, sea level and mantle flow-driven dynamic topography. The model predicts the time dependence of erosion and drainage patterns that we compare to denudation rates and paleo-drainage from paleogeography and the sedimentary record in key basins. We find that the motion of the Australian plate from the African to the Pacific LLSVP domains has resulted in significant shifts in river drainage, intracontinental erosion and sedimentation as a result of the interplay between large-scale mantle convection and tectonic forcing with surface processes. Our results are in good agreement with published uplift models derived from river profiles and the sediment influx into the Ceduna Basin offshore southeast Australia, reflecting the fundamental link between dynamic uplift, fluvial erosion and depositional pulses in basins distal to passive margin highlands.

## The GPlates Portal: Cloud-based interactive 3D visualization of global geophysical and geological data in a web browser

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The pace of scientific discovery is being transformed by the availability of ‘big data’ and open access, open source software tools. These innovations open up new avenues for how scientists communicate and share data and ideas with each other, and with the general public. Here, we describe our efforts to bring to life our studies of the Earth system, both at present day and through deep geological time. The GPlates Portal ([portal.gplates.org](http://portal.gplates.org)) is a gateway to a series of virtual globes based on the Cesium Javascript library. The portal allows fast interactive visualization of global geophysical and geological data sets, draped over digital terrain models. The globes use WebGL for hardware-accelerated graphics and are cross-platform and cross-browser compatible with complete camera control. The globes include a visualization of a high-resolution global digital elevation model and the vertical gradient of the global gravity field, highlighting small-scale seafloor fabric such as abyssal hills, fracture zones and seamounts in unprecedented detail. The portal also features globes portraying seafloor geology and a global data set of marine magnetic anomaly identifications. The portal is specifically designed to visualize models of the Earth through geological time. These space-time globes include tectonic reconstructions of the Earth’s gravity and magnetic fields, and several models of long-wavelength surface dynamic topography through time, including the interactive plotting of vertical motion histories at selected locations. The portal has been visited more than 300,000 times since its inception in October 2015, as tracked by google analytics, and the globes have been featured in numerous media articles around the world. They have helped illustrate online articles on published research papers by media either providing links to a given virtual globe or by embedding a globe in their own web page. In this way the globes have started playing a significant role in helping to communicate research to the public. Their popularity demonstrates the demand for fast visualization of global spatial big data, both for the present-day as well as through geological time. The cloud-based Cesium globes offer many future opportunities for providing additional functionality, especially on-the-fly big data analytics. Future functionality will include making big data mining workflows accessible as services on the Cloud. The establishment of RESTful web services will migrate some functionality of the desktop GPlates software into the Cloud. The portal already includes a prototype for a paleomapmaker, designed to allow users to export publication-quality figures using datasets and reconstructions contained within the portal data store or uploaded directly by users. The globes put the on-the-fly visualization of massive data sets at the fingertips of end-users to stimulate teaching and learning and novel avenues of inquiry.

## The Future of Mineral Exploration in the Cloud

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The global mining industry seeks reduction in the cost and risk in its search for new mineral resources – the intelligent use of geoscience big data to drive discovery of buried objects. A Mineral Exploration Cloud Laboratory is a vision for a future virtual laboratory in ‘big data’ science that will directly support these needs, advancing the integration of physical, chemical and dynamic properties of the Earth needed by the Exploration Industry and Research sectors. The opportunity is to connect five frontier developments into a breakthrough, low-cost cloud-based technology designed for Australian and global mineral prospecting (1) Seeing beyond what the eye can see using high-resolution geophysical images reflecting physical properties beneath the Earth’s surface; (2) Big Data technologies to interrogate Petascale data; (3) Automatic image analysis: deep Earth objects can be detected automatically by linking currently-dispersed collections of satellite and airborne-survey images, trained with “ground-truth” data and advanced machine learning. (4) Spatial-temporal data analysis: combined spatial-temporal analysis of big, time-dependent geoscience data will drive the search for undiscovered ore bodies beneath the surface. (5) Online services: inexpensive services would give users the ability to analyse data in the cloud across entire data collections. Mineral Exploration in a Cloud Laboratory could aggregate global geoscience imaging data sets, initiate new ones, and build a large scale cloud-data collection for use in Mineral Exploration and Geoscience Research. It could offer a series of web-based services that offer derivative products such as ore-targeting maps derived from cloud-held big data. Dramatically reduced costs and increased capabilities, from affordable remote sensing and big data in the cloud, will enable advanced and affordable online services.

We illustrate this concept with a “small data” case study for South American subduction-related porphyry ore deposits, using an iPython Notebook running on the cloud-based GPlates Portal ([portal.gplates.org](http://portal.gplates.org)). Using the recently released pygplates software ([www.gplates.org](http://www.gplates.org)), we apply spatio-temporal analysis to age-dated ore deposits to isolate the tectono-magmatic parameters leading to the formation of metalliferous copper deposits during subduction. We focus our analysis on plate convergence rates and directions, the age of the downgoing plate through time and ore deposit proximity to the plate boundary. We test two machine learning techniques, the ‘random-forest’ ensemble and ‘support vector machine’ classification methods to identify and quantify tectonic parameters that are robust predictors of Andean ore deposit formation. We find that a combination of rapid convergence rates (~100 km/Myr), subduction obliquity of ~15°, a subducting plate age between ~25-70 Myr old, and a location far (>2000 km) from the boundary of a subducting trench represent favorable conditions for porphyry magmatism and related ore deposits to occur. This allows us to broadly predict where and when ore deposits may have likely formed along the Andes, creating a foundation for predicting ore deposits along other (paleo-) subduction zones. The ideas outlined here represent an opportunity for a future Virtual Geophysics Laboratory, building on previous investments by AuScope, Nectar, NCI and a SIEF-funded Big Data Knowledge Discovery project.

## Uncovering the groundwater resource potential of Murchison Region of Western Australia through targeted application of airborne electromagnetics

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Access to water is identified a key infrastructure need for mining, energy and industry development. However it is generally accepted that in many parts of regional Australia there is an inadequate knowledge of these resources and their capacity to meet the emerging water requirements for industry. In Western Australia, the scale of planned developments linked to current mineral exploration and mining is set to generate significant economic value for the State, but its realisation is dependent on ensuring access to groundwater. There are significant knowledge gaps about groundwater recharge, safe limits of abstraction, and water quality characteristics. To address these issues, The WA Government Department of Water (DoW) has embarked on a series of groundwater investigations to identify and establish long-term water resources in regional areas where agriculture and mining opportunities have the potential for development. The Murchison in northern WA was identified as one of six key priority areas for this initiative. In this region, the mining industry is currently the largest user of groundwater. Until recently there are more than 30 operating mines using groundwater for mine development and ore processing, with numerous known mineral deposits having potential for development. Locating and securing adequate, long-term water supply is a critical consideration for this to happen. While it is known that there are significant groundwater resources in the region, at present these are generally poorly understood.

Of particular importance are the palaeovalley aquifers which are known (locally) to contain a significant resource, but which are relatively poorly characterised. A better understanding of these systems will underpin future groundwater management decisions in the region. As part of a collaborative study an airborne electromagnetic (AEM) survey has been flown in the Murchison over an area covering over 180 000 square kms. Covering such a large region required a novel approach to survey design to maximize the information relating to palaeovalley thickness and variability. Prior studies indicated that the palaeovalleys in the region were most likely to be near-coincident with contemporary valley systems developed in a granite/gneiss-greenstone basement. Therefore we used a terrain index (MrVBF) to define the extent of contemporary valleys, and the extent of the AEM survey area. Flight lines were planned to minimize the cost of an AEM survey covering such a vast region. This approach allowed survey acquisition costs to be kept to around a third of the cost of flying a more "traditional" survey over the entire area. It also allowed for the acquisition of data with a closer line spacing than would have been possible otherwise, therefore capturing more of the spatial variability associated with the palaeovalley systems - the main storage areas for groundwater. Pilot investigations also determined the most appropriate system to use for acquisition. The results have demonstrated the validity of the strategy adopted and have shown that in the absence of conventional hydrogeological information, geophysical methods are demonstrably a cost and time effective approach to upscaling local hydrogeological information, thereby fast tracking groundwater resource assessments that would otherwise take decades to complete.

## **Working with the minerals industry in facilitating outback water solutions for remote parts of South Australia – The Goyder Long-Term Outback Water Solutions (G-FLOWS) Eyre Peninsula Project.**

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Mining and energy development in South Australia's remote regions is set to have significant consequences for the water resources of the State. These industry sectors are of important economic and social value to the State and their support remains a priority for Government. The scale of potential developments from current exploration programs, facilitated in part by the SA Governments' Plan for Accelerating Exploration (PACE) Program, will result in an increase in infrastructure requirements, including access to water resources to support mines and minerals processing. However, the increased demand for water, particularly groundwater, is compromised by the limited information we have about these resources. There is a recognised need to expand this knowledge so that water availability is not a limiting factor to development.

One such area is the Northern Eyre Peninsula, a priority area for PACE investment given its mineral endowment and potential, coupled with its agricultural resource base. For large parts of this region non-prescribed groundwater resources are poorly understood. Much of the limited groundwater infrastructure is dilapidated, and hydrogeological and piezometric head data very sparse. The Goyder Institute's Long-Term Outback Water Solutions (G-FLOWS) Northern Eyre Peninsula Project was established to help address these issues. In a partnership with State agencies, the Project worked with junior exploration companies and employed exploration geophysical data sets, including local scale airborne electromagnetic, regional scale airborne magnetic and contemporary terrain data to develop an enhanced understanding of the groundwater resource potential in key parts of the region.

The geologically diverse Cleve Hills, prospective for graphite, uranium and iron ore, located in the eastern part of the Eyre Peninsula was one of those areas. The groundwater resources, scale and nature of the flow systems, the vertical connectivity between aquifers and ecosystems at the surface and the sources of salinity were investigated through a combination of the analysis of data from government and industry, the acquisition of new piezometric head and environmental tracer data, and the re-interpretation of exploration geophysical datasets. Interpretation of surface geology, subsurface lithology and airborne geophysics indicate that the Cleve Hills and adjacent valleys have diverse hydrogeological settings including, unconfined fractured rock and sedimentary aquifers respectively. Variations in piezometric head influenced by undulating topography and shallow depths to impermeable bedrock along hydrogeological transects indicate predominantly localised flow systems. Similarly, environmental tracer concentrations in groundwater suggest timescales for these flow systems is a few hundred years at most. Strontium and stable isotopic compositions suggest groundwater salinity is caused by the concentration of vadose zone soil water by evapotranspiration. The project provided specific recommendations for future groundwater monitoring and the basis for investigation of valley-system aquifers. The G-FLOWS approach provides a basis for understanding aquifer hydrodynamics and upscaling the resource potential. It also provides an investigative framework for assessing likely socioeconomic and environmental impacts under future development scenarios, with potential for application in other parts of the country.

## Uncovering the depths in minerals exploration – Advancing geophysics is a critical element to this goal

Munday, Tim

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The need for a new toolkit suite to “see” through Australia’s cover is recognised as being one of the highest priorities for the mineral exploration industry, and is described as such in the **UNCOVER** vision, recently published by Australian Academy of Sciences, and the **AMIRA Industry Roadmap** for UNCOVER which was launched in 2015. Geophysical technologies are a central part of this suite, particularly as Australia’s future mineral wealth lies in uncovering the highly prospective and potentially well-endowed geological settings that are obscured by an extensive post-mineralisation veneer of regolith and sedimentary rocks of varying thickness and age. Exploration through these materials, is increasing reliant on the geophysics and recognition of its challenges is encouraging considerable innovation in geophysical hardware and software. This is observed in airborne, surface and sub-surface methods. In part this has been aided by advances in electronics, computational power, and data processing, but also by an enhanced understanding of how to interpret an observed geophysical response against geological and geochemical information.

With airborne methods, particularly airborne electromagnetics, contractors continue to develop their systems to see more subtle targets at greater depths. Increasing dipole moments for greater depth penetration have been commonplace in TDEM systems. The lowering of noise levels has been helped by the use of new receivers and it has also encouraged the use of lower base frequencies. Higher moment, low noise, systems have resulted in advances in the recognition, processing and modelling of airborne IP effects. We still need to better explain their causes and their relevance to exploration. A similar story is apparent with suppliers of airborne gravity systems with advances in hardware, software, data processing workflows and data acquisition technologies leading to significant improvements in spatial resolution and the accuracy of measured signal. The development of UAV technologies through miniaturization of geophysical hardware is gaining traction and new magnetic gradiometer drones are likely to see increased use in Australia in the future.

Advances in ground geophysical technologies have paralleled those made with airborne systems. High powered 3D resistivity/IP systems are now routinely employed at the camp scale to resolve attributes of mineral systems to depths of greater than 500m. Developments in 2 and 3D inversion of these data are helping geologists understand the geometry of mineral systems at scales and detail not seen previously. Wider deployment of MT technologies (e.g. AusLAMP) has become a key part of helping us understand the whole-of-lithosphere architectural framework for mineral systems exploration. Similar developments have been witnessed with passive seismic methods with relatively cheap arrays of portable broadband seismometers coupled new processing methods can be used to map the thickness and seismic velocity structure of sedimentary cover overlying a prospective basement terrane. In drillhole geophysics, innovation is seeing geophysical sensor packages that are being undertaken as part of the drilling process. Concepts involving autonomous shuttles and logging while drilling are being developed by the DETCRC, for example, to provide the geologist/geophysicist with information to inform exploration while the drill rig is on-site.

## From amino acids to changing sea levels and the movements of continents

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This presentation examines the geological application of amino acids (amino acid racemisation - AAR) in determining the age of geological successions younger than 2.5 million years. Several case studies are briefly illustrated that show how the AAR method has been used in documenting rates of relative sea-level changes, long-term patterns of coastal evolution, and vertical crustal movements of parts of the Australian continent. Based on the degree of racemization of amino acids preserved within the biominerals of fossil molluscs and other marine invertebrates, geochronological frameworks have delineated rates of long-term coastal evolution, relative sea-level changes and neotectonism. The AAR method has been applied to a wide selection of fossil molluscs from sedimentary successions ranging from late Pliocene to latest Holocene age. Holocene coastal successions have been dated using the fast racemizing amino acid, aspartic acid to assign numeric ages to fossils that would otherwise have been problematic to date using the radiocarbon method, particularly for fossil remains younger than 1000 years. The research has provided a novel approach to derive geochronological frameworks to subdivide Quaternary time and is innovative in creating new opportunities to delineate the age of sedimentary successions that could not previously be dated. It has fostered several new avenues of investigative research such as evaluating the taphonomic integrity of sedimentary deposits (time-averaging and spatial fidelity), confidently undertaking stratigraphical correlation and relative age assessments over wide geographical areas, assigning ages to biostratigraphically significant fossils (e.g. *Anadara trapezia*, *Marginopora vertebralis*), "whole-rock" dating of aeolianites and quantifying rates of coastal evolution and neotectonism. The work has confirmed that southern Australia preserves one of the world's best preserved and most geographically extensive temperate carbonate shoreline successions of last interglacial age (128 to 118 ka). At this time relative sea level was at least 2 m above present sea level as shown from peritidal facies on Eyre Peninsula, South Australia. The research has also revealed, based on studies of the last interglacial shoreline that Australia, although a highly stable continent, continues to experience subtle neotectonic movements. These findings have modified the general perception concerning the tectonic stability of the Australian continent, and have reinvigorated an interest in the neotectonic histories of passive continental margins. Differential shoreline elevations of last interglacial deposits relate directly to their pre-Quaternary geotectonic setting and highlight the contrasting stabilities of these geotectonic domains over longer temporal scales. An enhanced understanding of the nature of the stratigraphical record preserved within marginal marine settings, the preservation potential of coastal successions in the longer Quaternary geological record and the spatial and temporal distribution of biostratigraphically significant taxa for the Quaternary represent further outcomes of this body of research.

## Fluids, faults and foliation at the Izu rear-arc – their rock magnetic signal

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IODP Expedition 350 cored Izu rear-arc site U1437, and recovered a 1320 m thick distal sequence dominated by tuffaceous mud and subordinate fine tephra, overlying a more proximal volcaniclastic sequence extending to the base of coring at 1800 mbsf. A continuous magnetostratigraphy was recovered from the muds of the distal sequence, despite challenges presented by downhole alteration. Magnetostratigraphy, biostratigraphy, and post-cruise zircon dating all indicate a younger than expected, post-middle Miocene age for the cored sequence. The surprisingly uniform, mud-dominated lithology of much of the sequence makes Site U1437 an instructive setting to examine influences of fluid flow on the iron oxide and sulphide mineralogy, revealed by rock magnetism. Shipboard studies of magnetic susceptibility ( $k$ ), saturation isothermal remanence (SIRM), demagnetisation behaviour, acquisition of partial anhysteretic remanence (pARM) and anisotropy of magnetic susceptibility (AMS) have been supplemented by additional shore-based measurements and complemented by post-cruise studies of hysteresis, low-temperature demagnetisation, and anisotropy of AMS. Rock magnetic parameters that track diagenesis and alteration of magnetic iron oxides and sulphides (SIRM/ $k$ , SIRM after 0.3 T demagnetisation [ $S_{-0.3T}$ ] and the hysteresis parameter  $D_{JH}$ ) exhibit a background downhole trend towards increasingly mature pyritisation that is surprisingly similar to patterns seen in ODP sites drilled in hemipelagic sediments with much lower volcanogenic input. Superimposed on this trend are excursions which parallel features in pore-water geochemistry and physical properties, apparently marking fluid migration and diffusion at depth. Diffusion upwards from a deep fluid source at about 275 mbsf produces an inverted deep sulfate reduction profile that is expressed magnetically as scattered low values of  $S_{-0.3T}$  and higher values of  $D_{JH}$ , which typically indicate production of the magnetic sulphide greigite. SIRM/ $k$  and  $D_{JH}$  reach local maxima at about 460–480 mbsf, matching an offset in foliation development in AMS (anisotropy of magnetic susceptibility), and corresponding to the position of the highest value in the sulfate profile (reaching seawater concentration), inflections in Li, Mg and other species, and an increase in lithification marked by a break in the porosity profile. A second fluid source at this depth, perhaps along the lithification front, seems indicated. Methanogenesis between about 850 and 1000 mbsf is accompanied by decreases in SIRM and susceptibility, suggesting loss of iron oxides, and scattered high  $D_{JH}$  and low  $S_{-0.3T}$ , which we interpret as growth of greigite, the combined processes being driven by anaerobic oxidation of methane. Interruption to otherwise continuous magnetostratigraphy across the break between coring in Holes U437D and U1437E suggests the presence of a normal fault. A sudden change in  $D_{JH}$ , a shift to multidomain-dominated magnetic mineralogy below the break between holes, and the equally sudden appearance of ethane in headspace gas, suggest a contrasting fluid circulation environment in the foot and hanging walls.

## The Macquarie Arc: what is it, and where did it come from? A geophysical perspective

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Models for the nature and tectonic history of the Ordovician Macquarie calc-alkaline volcanic province in the eastern Lachlan Orogen have multiplied in recent years. Viewed by most workers as the product of a suprasubduction zone setting, the Macquarie Arc has usually been seen as an intraoceanic feature developed on an oceanic crust substrate, in either an episodically retreating setting above a west-dipping subduction system facing the palae-Pacific, or as an allochthonous arc accreted to the Gondwana margin in the late Ordovician Benambran Orogeny. The Lachlan Orocline model modifies the simple retreating orogeny model by considering the response to congestion of the subduction zone by collision with a continental sliver (the Selwyn Block), leading to rapid roll-back of the unpinned subduction zone and the consequent clockwise rotation, extension, and transcurrent displacement of the upper plate, including the Macquarie Arc, during the Silurian. An earlier phase of anticlockwise rotation of the arc has also been proposed as part of a mechanism to explain the distribution of Ordovician quartz turbidites on both sides of the arc. Alternatively, the volcanic suite has been re-interpreted as a marginal basin rift sequence, substantially west of the locus of active subduction.

Of these competing scenarios, only the Lachlan Orocline model has been constructed around a geophysical framework. Deep focussed filtering of aeromagnetic data defines the oroclinal curvature, and palaeomagnetic data from the Macquarie Arc are consistent with a Silurian phase of oroclinal rotation. Numerical models of congested subduction mimic the evolution of the Lachlan Orocline.

Further geophysical constraints are available. Reconsideration of existing palaeomagnetic data from NSW, and a new pilot study from Victoria, not only support a late Silurian–early Devonian phase of clockwise motion, but suggest a preceding anticlockwise phase beginning in the late Ordovician. Long-wavelength low aeromagnetic anomalies characterise the Macquarie Arc and its along-strike extension into the eastern Thomson Orogen, and contrast with a long-wavelength high across the western Lachlan Orogen and western Thomson Orogen. Comparatively low s-wave velocities likewise characterise the middle crust below the Macquarie Arc. Together, the geophysical characteristics are incompatible with the magnetic susceptibility and seismic velocity that would be expected of the simple oceanic crust basement previously postulated for the Macquarie Arc. Likewise, a marginal basin rift origin can be eliminated. Instead, the arc appears either to have been constructed on a continental sliver (as suggested for Vanuatu), and/or to have a thick, mature, evolved basement, like that of the Izu rear-arc, with which it shares geochemical features and a history of extension. The two phases of rotation have displaced the Macquarie Arc from an initial position close to – and perhaps rifted off – the Gondwana margin; Pb isotope signatures thought to reflect the substrate of the Macquarie Arc closely match those of the Cambrian Ponto Group from the Koonenberry Belt, the Cambrian convergent margin of Gondwana.

## **Insights from unique calcification processes of modern coralline algae may aid understanding the mechanism of Neoproterozoic cap carbonate formation**

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The mechanism for the formation of Neoproterozoic cap carbonates is widely debated. Without an understanding of how these carbonates formed, a reliable interpretation of past environments from the cap carbonate morphological features and their stable isotopes is elusive. Here evidence is presented supporting the possibility that portions of the cap carbonates could have been substantially formed by ancestral species of the modern coralline algae. While there has been an increase in the study of physiological responses of coralline algae to ocean acidification and warming scenarios, to date little work has been undertaken to understand in detail how modern corallines form their carbonate skeletons. A detailed study of their cellular-scale calcification features reveals previously undescribed unique properties that exercise unexpected controls on calcification responses to environmental prompts. Temperature is not always the dominant control on Mg uptake as has previously been thought. The typically Mg-calcite corallines can switch to using dolomite for primary skeletal growth depending on the growth mode. Conversely, localized changes in environmental conditions can completely inhibit the formation of dolomite where it is otherwise abundant. If these and other unique calcification properties were present in predecessor calcifying red algal species, then these organisms could feasibly have formed or provided the carbonates for much of the Neoproterozoic cap carbonates. Furthermore, the possibility that Neoproterozoic cap carbonates may be originally biogenic carbonates raises the issue of stable isotope interpretation. In association with the biologically-driven changes in mineral composition, there are substantial changes in isotope composition of the modern coralline algae. Interpretation of ancient dolomite-derived carbon isotopes is premised on the proposal that there is no biological influence and therefore no adjustment for vital effects is required. These results show a substantial influence of biology on isotope values indicating that if the ancient carbonates are biogenic, then adjustments for vital effects are needed before drawing conclusions about past climate and the carbon cycle. In addition, by understanding how the modern corallines change calcification in response to their environment, together with observations from ancient carbonates formed through periods of extreme climate changes, in combination this information may help us anticipate how carbonate structures may change in the future with rising temperature and atmospheric  $p\text{CO}_2$ .

## **Tourism Earth Science: An emerging discipline generating new opportunities for earth scientists**

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Earth Science is the study of the Earth and its neighbours in space. Earth scientists apply their knowledge in locating and developing energy and mineral resources, studying the impact of human activities on environment and designing methods to protect the planet. They also use their knowledge about Earth processes such as volcanic activities, earthquakes, tsunamis and hurricanes to plan and warn communities to avoid or adapt to these natural hazards. Their knowledge are rarely applied in planning, promoting and developing tourism despite the fact that tourism generates 277 million jobs worldwide and contributes US\$7.6 trillion or 9.8% of the total world's GDP in 2014. This paper introduces an emerging academic discipline within the scope of Earth Science which start growing since the mid 1980's in China. The academic discipline has been named by Chinese earth scientists as Tourism Earth Science. It is a new, multi-disciplinary, applied geoscience involving geology, geography and tourism. It studies and addresses all earth science related tourism issues by applying earth science theories and methods. It helps to locate, identify, classify and evaluate both natural and cultural tourism resources for better understanding, efficient and sustainable uses of them. Results of its research are important for strategic planning and development of local, regional and national tourism strategies. It provides strong, continual supports and lays strong foundation for the establishment and development of the current 241 national geoparks (among which 33 with UNESCO Global Geopark status), 72 national mining parks, 660 wetland parks, 135 national science popularisation centres (with geological museums), 84 field scientific observation and research centres and a few hundreds of provincial geoparks and mining parks, 'Class A' scenic attractions with significant geological and geomorphological features, world natural heritages, biodiversity protection areas, national forest parks, national parks and national water conservancy attractions. The number of jobs directly created by Tourism Earth Science in China is over 1.5 million in 2014 with a forecast of growing to 3 million in 2025. Tourism Earth Science enhances the important contribution of Earth Science to the economic well-being of the society. It is particularly effective in revitalising poor, remote communities where mineral and agricultural resources are lacking. Through identification of interesting geological heritage with tourism value, followed by appropriate tourism planning, development and promotion, livelihood of these communities could be improved. While most Earth scientists focus their attention on the exploration of mineral and energy resources, protection of the environment and the prevention of natural disasters, the potential of Tourism Earth Science in generating tremendous new opportunities for them should not be ignored.

Keywords: Tourism Earth Science, tourism, mineral exploration, geoparks, geological heritage

## Cisuralian stratigraphy, biostratigraphy and interbasin correlation, eastern Australia: implications for exploration

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Recovery of ashfall tuffs from palynologically-controlled samples in the Galilee and Gunnedah basins provide new age control on Cisuralian sediments and palynomorph zones and correlation to the Southern-Urals/Russian type sections and zonations. Zircon ages in both regions have been obtained using chemical-abrasion isotope-dilution thermal-ionisation mass spectrometry (CA-IDTIMS).

CA-IDTIMS dating of the Edie Tuff Member (ETM: Jochmus Formation) in GSQ Muttaburra 1, 1254 – 1256 m, and OCE Glue Pot Creek 1 (GPC1), 824.6 – 824.8 m, in the Galilee Basin, have been dated as 294.80 – 294.91 My and 296.09 My respectively. These samples are associated with the *Pseudoreticulatispora pseudoreticulata* zone (APP2.1). The Muttaburra samples came from below the member's top and the GPC1 sample from 14 m above its base.

In the Gunnedah Basin, a thin ashfall tuff, dated as 291.62 My, from the Goonbri Formation in Santos Bibblewindi 11c, 1034.86 – 1034.99 m, is also associated with the zone. It extends over ~100 m in Muttaburra 1, having a minimum age range of 4.4 My. Younger Cisuralian dates (282.41, 282.72 My) have been obtained therein from the Aramac Coal Measures (ACM) at 1096 – 1101 m; they are associated with the *Granulatisporites trisinus* zone (APP2.2). As the *Phaselisporites cicaticosus* zone (APP3.1) has been recorded ~30 m higher, the *trisinus* zone has a minimum-age span of 7.4 My over 126 m.

CA-IDTIMS dates from the Usolka (Krasnousolsky) section, Southern Urals, have provided control points that can be applied to Australia. Sample 01DES-212 from upper Bed 18 in the Kurkin Formation, dated as  $296.69 \pm 0.16$  My, is considered to be late Asselian. This compares closely with the date of  $296.09 \pm 0.07$  My from the Edie Tuff in GPC1 (824.6 – 824.8 m), placing this sample near the top of the Asselian. Similarly, a sample from the same Urals section (97USO-91 0), dated as  $290.50 \pm 0.17$  My, is considered to be Sakmarian, suggesting that the Goonbri-Formation sample ( $291.62 \pm 0.18$  My) is Sakmarian.

The two Edie-Tuff samples (Muttaburra 1), must lie near the Asselian–Sakmarian Boundary, at 295 My. This suggests the member and the *pseudoreticulata* zone span the Boundary. In the Southern Urals, dates of  $288.36 \pm 0.17$  My (DTR905) and  $288.21 \pm 0.15$  My (01DES-403), from the Dal'ny Tulkas roadcut section, have been assigned an Artinskian age and are the youngest-dated tuff beds from there. This implies that the ACM samples (Muttaburra 1:  $282.41 \pm 0.08$  My,  $282.72 \pm 0.07$  My) could represent the Artinskian or the Kungurian. The Artinskian–Kungurian Boundary has been variously placed at 279.3, 282 or  $283.5 \pm 0.6$  My, indicating that these samples (in the *trisinus* zone/APP2.2) are latest Artinskian or earliest Kungurian. No published radiometric dates exist between 288 My (Artinskian) and 265 My (Capitanian).

## **Ultrafine soil fractions: sizeable benefits to improve our ability to explore through cover**

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As mineral exploration moves into regions dominated by transported cover, conventional techniques may not be applicable and thus increasingly there is a requirement for new innovative approaches to geochemical exploration. Some quite simple procedural changes from standard size fraction analysis could have pronounced effects on the exploration industry. Commonly, <250 µm or <180 µm soil fractions are used for geochemical digestion and analysis. However, use of smaller size fractions has the benefits of greater concentrations of pathfinder metals, better contrast and improved reproducibility. A few in the exploration industry have pursued selecting a silt particle size fraction for analysis (<50 µm), with some research studies showing the value of clay sized (<2 µm) geochemical analysis. The benefits of fine fraction analysis is most pronounced for gold, particularly with respect to reproducibility and nugget effects. Experimental and observational data have revealed many populations of different sizes of small gold particles (<2 µm) in regolith, many of which make up economic deposits or near surface signatures of deeper primary deposits. These micro (<2 µm) and nanoparticulate (<0.2 µm) gold in soils and regolith are highly mobile and able to move through cover. A method to quantify gold in the micro and nanoparticulate fractions was tested using wet sieving and centrifugation of fourteen soil samples from Western Australia. Five fractions were separated and subject to aqua regia digestion and analysis by an ICP-MS. Although the soils tend to be dominated by the coarse (>250 µm), quartz-rich, soil fraction in these transported soils, the analysis on all the size fractions shows that the majority of the gold is small and hosted in the <2 µm fraction. The gold associated with the bulk, coarse fraction dominated materials is less than 2%. Analysing the nanoparticulate gold fractions via particle size separation results in concentrations of gold of three orders of magnitude (100s to 1000s ppb gold). The benefits are obvious for Au, but there is no loss in using this technique for base metals exploration. Examples will be shown of fine gold, the rapid mobility of metals in field experiments through cover and finally the value of using fine fractions for gold and base metals to improve regional geochemistry. This study has demonstrated the method to quantify gold in these very small size fractions and ties into current research using site and regional scale studies to improve our ability to explore through cover.

## Central Australia, an island paradise: Were the Musgrave Province and Arunta Region exposed during Neoproterozoic sedimentation in the Amadeus Basin?

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Detrital zircon U-Pb-Hf isotopic provenance analysis of the Neoproterozoic Amadeus Basin succession has revealed that sediments were sourced from both the adjacent Paleoproterozoic Arunta Region and Mesoproterozoic Musgrave Province. This provenance study has enabled a synthesis of the major depositional controls on basin architecture with shorter-term and more localised influences. For example, the dominant sediment source region fluctuates during the Neoproterozoic depositional history, but the dominant source region for a formation may vary with the proximity of a sample to a basement terrane. Comparison with published U-Pb-Hf isotopic data for rocks of the Musgrave Province and Arunta Region allow some specific likely sediment sources within these basement terranes to be identified.

An overview of the newly acquired data for the Neoproterozoic succession indicates that the Arunta Region to the north of the basin was generally the dominant sediment source. The Musgrave Province to the south is generally also represented. The data also indicates that immediately following the two major Neoproterozoic glacial episodes (Sturtian; 700- 690 Ma and Elatina; 640-580 Ma), the Musgrave Province formed the dominant source region for a period.

Some source components have been identified within the Arunta Region. Zircon grains with ages within the range of two tectono-thermal events; the Strangways Event (1735 – 1690 Ma) and the Chewings Orogeny (1590 – 1560 Ma), have been identified in all of the sedimentary units analysed. Magmatism related to these two events occurs in the adjacent parts of the southern Aileron Province of the Arunta Region. Zircon grains have been interpreted to have formed during magmatism associated with the Musgrave Orogeny (1220 – 1150 Ma) in sedimentary units that pre-date the Elatina Glaciation suggest that at least the northwestern Musgrave Province was exposed prior to ca. 640-580 Ma.

These detrital zircon provenance data suggest that both terranes were at least partially and/or periodically exposed throughout the Neoproterozoic. This is at variance with the generally accepted model of the Centralian Superbasin where present day, remnant component basins (which include the Amadeus Basin) were contiguous during the Neoproterozoic. Currently exposed basement areas were interpreted to be sites of deposition rather than erosion at least until the superbasin was reconfigured immediately following the Petermann Orogeny (580 – 5300 Ma).

It is interpreted that the basement terranes were exposed as a series of 'island chains' in the Neoproterozoic in central Australia. The effects of the Sturtian and Elatina glaciations, particularly glacial scouring during the Sturtian glaciation (720 – 660 Ma), likely enhanced sediment supply from the basement terranes, as well as possibly temporarily influencing basin palaeogeography.

## **Understanding landscape evolution for better targeted undercover exploration: A palaeogeographic reconstruction of the late Palaeozoic sediments covering the northwestern and southern margins of the Gawler Craton.**

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Late Palaeozoic sediments are associated with some of the areas of deepest sedimentary cover in South Australia. The late Palaeozoic sedimentary cover has, therefore, been a frustrating mineral exploration impediment, especially as it covers parts of highly prospective mineral provinces, such as the northwestern and southern margins of the IOCGU-Olympic Domain of the Gawler Craton. Understanding the palaeogeography and consequently, the depositional and erosional history of the cover sequence, allows for better constrained physical dispersion characteristics and vectors for potential mineralisation indicators in the cover sequence. We present a holistic model that accounts for changes in the depositional environments and gives an improved understanding of the palaeogeographic movement of the late Palaeozoic sediments, their potential source regions, and the direction of ice flow using field observations, sedimentology and U- Pb isotope detrital zircon provenance studies.

Glaciofluvial and glaciomarine sequences from the Permo-Carboniferous glaciation preserve evidence of the tectonics, eustacy, isostacy and drastic climate changes that occurred during this time. The sediments of the Arckaringa and Troubridge basins investigated in this study are an excellent example of how the sedimentology and inferred depositional settings of an isolated area can provide an indication of the overall climate and depositional conditions occurring across the broader basin, and in some cases, continental-scale climate and depositional environments can be deduced. An understanding of the historical evidence these sediments support can then provide a better understanding of the coal measures, shale gas, oil, and aquifers within the basin succession as well as the provide possible dispersion vectors of mineralisation through cover sequences. The depositional history of the late Palaeozoic sediments of South Australia can be attributed to 3 stages; 1) maximum glaciation; 2) maximum marine transgression; and 3) during the fresh water conditions that occurred at the end of glaciation. The majority of late Palaeozoic sediments across South Australia were deposited during the glacial maximum. Differing diamictite properties reveal the primary glaciation of the area; continental ice sheet, ice tongue or valley glaciers were all present during the glaciation. Small, isolated marine sediments and the absence in some basins indicates that the marine transgression did not completely inundate South Australia. The absence of sediments in the northeast of the state suggest at maximum transgression the sea reached as far north as the Arckaringa Basin. Detrital zircon provenance studies suggest that the transgression began in the west and was impeded from further migration to the east by the uplifted Neoproterozoic Peake and Denison Ranges. Freshwater deposited sediments are restricted to the northern Arckaringa Basin. It is likely that the fresh water conditions were initiated by the melting of valley glaciers in highlands to the north of the basin and fluvial systems transported the sediments into the Arckaringa Basin.

## **Structural and Geochemical Controls on the Formation of the ‘Inter-lens’ at the Ernest Henry Mine, Queensland**

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The ~1530Ma Ernest Henry Iron Oxide Copper Gold (IOCG) deposit is located 35km north-east of the township of Cloncurry in North West Queensland and is the most significant Cu-Au deposit in the Cloncurry Mineral System. The pipe-like Ernest Henry ore body is hosted in brecciated and K-feldspar altered Mount Fort Constantine (intermediate) volcanics (~1740Ma) and dips ~40° towards the SSE. The ore body is structurally controlled by a series of sub-parallel shear zones and is ~250m thick, ~300m wide with a down-plunge length of over 1km and is open at depth. The ore assemblage is dominated by magnetite, chalcopyrite, pyrite, carbonate, quartz and apatite. The deposit is enriched in Fe, Cu, Au, K, Ba, S, Co, As, U, LREE, Mo, W, F and Ca and has geochemical similarities to other IOCG deposits in the Cloncurry area including E1 and Monakoff.

Recent exploration drilling and underground development has identified an area within the ore-body known as the ‘Inter-lens’, represented by a zone of (ductile) shearing within the main ore zone. This weakly mineralised structure appears to have formed synchronously with ore deposition and provides important information relating to potential depth extensions to the ore body.

This project has used underground mapping and detailed core logging to measure kinematic indicators for structural modelling. 3D Leapfrog modelling based on existing and newly collected data will define the location and extent of the feature and provide geological constraints to structural controls and depth extensions to the ore body. Petrography, SEM and MLA techniques have also been used to define the mineralogy and distribution of trace metals and the geochemical signature of the Inter-lens and how these relate to the structural conditions present at the time of ore formation.

## Development of the northern Yilgarn margin between 2200 and 1960 Ma — as recorded in the volcano-sedimentary record

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Volcano-sedimentary successions that formed over the northern Yilgarn Craton between 2200 and 1950 Ma have been variably described as rift, sag and retro-arc foreland basins. These successions have been interpreted as discrete depocentres — the Yerrida, Bryah, Padbury and Earaheedy Basins — and thought to have formed in that order. However, our review of this region has found that apparent disparate successions formed during the same periods of lithospheric extension or compression along the northern Yilgarn margin. For example, the Yerrida Basin is probably much more extensive than first realised, and covers much of the northern margin of the Yilgarn Craton; parts of the stratigraphy previously assigned to the Bryah Basin more likely belong to deeper facies of the Yerrida Basin. Volcano-sedimentary rocks of the Windplain, Bryah and Mooloogool Groups that were deposited in this large basin record a history of shallow to deep rifting, separated in both space and time. Carbonate sedimentation, dated at c. 2200 - 2100 Ma, was followed by the onset of volcanism in the northern part of the region. Increased rifting in the northern part of the basin led to basin deepening resulting in the onset of voluminous, mainly mafic, volcanism at c. 2035 Ma in the Bryah Group. These rocks were deposited within a spatially restricted rectilinear area that may represent a fault-bounded trough or failed rift. Concurrently over shallower parts of the basin the Mooloogool Group was deposited, which also contains mafic volcanic and intrusive rocks. Rifting of the northern Yilgarn Craton margin ceased by about c. 2000 Ma, following deposition of felsic volcanic and siliciclastic rocks, and was followed by a hiatus of at least 10 to 20 million years prior to development of the Earaheedy and Padbury Basins, respectively, in the east and west. The Earaheedy Basin, which contains carbonate and siliciclastic sedimentary rocks and granular iron formation, has been described as a rift basin. The Padbury Basin contains carbonate and siliciclastic rocks and banded iron formation, and has been interpreted as a retro-arc foreland basin. A review of the regional tectonics operating during development of these two basins indicates that siliciclastic rocks at the base of the Padbury Basin must have been deposited in a peripheral foreland basin (i.e., over the down-going plate) at 1990–1960 Ma during the Glenburgh Orogeny. These sedimentary rocks, which form the Labouchere and Wilthorpe Formations formed close to the forebulge of the basin. To the west, sedimentary rocks deposited in the basin foredeep may be the protoliths to high-grade paragneiss of the Camel Hills Metamorphics that contain similar maximum depositional ages. Additionally, banded iron formation of the Padbury Group and granular iron formation of the Earaheedy Group, may have formed contemporaneously within the same basin that deepened from east to west.

## **Regional structural interpretation and depositional history of the Bresnahan Group, Capricorn Orogen, Western Australia**

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Despite significant work elsewhere in the Capricorn Orogen, the structure and stratigraphy of the 1700-1600 Ma Paleoproterozoic Bresnahan Basin has not been addressed for 25 years. New magnetic, gravity, electromagnetic and remotely sensed data (airborne hyperspectral, Landsat 8, radiometrics and ASTER) are being used to investigate the Bresnahan Group, in particular the primary tectonic structures that potentially controlled basin fill deposition.

Analysis of remote sensing datasets allows a better understanding of Bresnahan Group composition that have not been previously mapped. For example, hyperspectral datasets highlight differences in the proportions of mica and montmorillonite (i.e. variations in AlOH and FeO), and radiometric data indicate changes in the proportion of Th, U and K noted along distinct stratigraphic horizons. These are supported by petrographic observations of field samples. Possible explanations for the compositional differences include depositional changes up the stratigraphic column that may represent surfaces with sequence stratigraphic significance, or are lateral changes within time equivalent intervals. Additional fieldwork and detrital geochronology are required to constraint the interpretation further. A new structural interpretation for the basin shows that a significant north-west trending structure appears to be a major syn-depositional fault along the eastern basin margin. The feature is interpreted to be a reactivated structure that may have been present before and/or during the deposition and tectonic development of the older Hamersley Basin. The Bresnahan Basin is bound in the north by a west-trending strike-slip fault, which is likely a reactivated structure that controlled the deposition of the underlying Ashburton Basin. Only fieldwork will determine whether there are syn-depositional faults to the west and within the Bresnahan Group. Linking together the compositional variations and structural interpretations suggest areas of syn-depositional faulting that was in part controlled by pre-existing structures.

## Translating mineral systems analyses into a sensible workflow for ground selection and targeting

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Mineral systems analysis has moved on from the “source-pathway-trap” approach adapted from the oil and gas industry, recognizing that understanding geodynamic processes, fluid transport mechanisms and drivers, and depositional traps or sites are critical in finding locations which host and preserve ore deposits. Critical controls on the formation and preservation of mineral deposits also include continental-scale processes such as the Earth’s secular evolution, lithospheric controls on mineral enrichment, and geodynamic drivers. Of these, lithospheric enrichment and geodynamic drivers are directly linked to plate tectonics and the kinematics of plate motion, which are related to the supercontinent cycle. Lithospheric- or crustal-scale architecture that form conduits, and hosts to mineralization can be mapped through integration of geological and geophysical datasets. At a smaller scale, identifying traps related to mineralization are also important. The current-day level of crustal exposure can be used as a proxy for preservation of different styles of mineralization.

By using a mineral systems approach in exploration targeting, the factors leading to prospectivity for disparate commodities can be considered in combination, and search spaces significantly reduced for mineral explorers. For data-driven analyses, the location of particular commodities or commodity groups is required in the form of known deposits. However, a mineral systems approach to targeting is knowledge-driven, non-prescriptive, flexible and allows multi-commodity analyses to be performed. It is a workflow that can target commodities indiscriminately as data points are not required. The challenge with mineral systems analyses is translating critical elements from concepts, or interpreted data into prospectivity models. As knowledge-driven processes are subjective, models are often non-repeatable. A workflow, specifically developed for multi-commodity mineral systems analyses, uses an approach of defining and mapping proxies for tectonic triggers, fertility, depositional site, deep crustal-scale structures and preservation zones. The workflow has been tested on the Halls Creek Orogen in the east Kimberley and the resulting prospectivity models and maps were produced using a knowledge based GIS system. A tool was simultaneously developed as an add-on in ArcGIS which allows this process to be repeated as the steps of data processing and modelling are recorded. Validation of the modelling performed on the Halls Creek Orogen confirms that known ore deposits were located. More importantly, all the prospectivity maps reduce the exploration search space to less than 0.04% of the total area for most commodities, except for Au and Sn-W-Mo for which the search space was reduced to less than 0.5%. In geographic terms, the area of ground required for exploration at the camp is ~25 km<sup>3</sup> (REE, Cu-Au-Mo, diamonds, Ni-Cu-PGE-V-Ti, Pb-Zn) and less than 350 km<sup>3</sup> (Au and Sn-W-Mo) in the region.

## Combined slow and rapid mineral precipitation in lode gold and IOCG deposits

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Average fluid flow rates generated by metamorphic devolatilization, and by thermally driven circulation in broad hydrothermal systems, are in the range  $10^{-2}$  to  $10^1$  m/year. However, flow rates in shear zones ( $10^1$  to  $10^{2.5}$ ) and fault zones (up to  $10^4$  or more), although short-lived, are several orders of magnitude faster. Despite these directly and indirectly determined fluid flow rates, ore genesis models for lode gold and IOCG systems commonly appeal to combinations of these styles of flow, apparent mostly in widespread alteration systems surrounding orebodies in which rapidly cemented breccias may form a significant, or bonanza, contribution to the metal endowment. The ~ 2.65 Ga Sunrise Dam Gold Mine (SDGM) in the Laverton Belt of the Eastern Goldfields in Western Australia is dominated by gold-bearing quartz-carbonate vein stockworks with surrounding sericite-carbonate-pyrite alteration extending penetratively shear zone fabrics, and patchily through less deformed rocks. At m- to 10m-scales in the 'normal' (1 to 4g/t Au) lodes, calculated metasomatic volume expansion of up to 10% accompanying the alteration appears to have choked porosity, increased fluid pressure and thereby developed repeated banding in gold-bearing 'crack-seal' veins. This feedback between chemical reaction and veining most likely occurs in the time frame of inter-seismic and moderate magnitude seismic events, e.g. months to thousands of years. The ~ 1.53 Ga Ernest Henry IOCG deposit in the Cloncurry District of northern Queensland is surrounded regionally by long lived (~ 100 m.y.) sodic alteration and more proximally by strong, shear-zone related biotite-magnetite alteration. Although the duration of the event(s) that produced the Fe-K alteration is poorly known, the scale and association with ductile shearing are not dissimilar to 'classic' metasomatic shear zones in lode gold systems. At SDGM, there are steep, shear-zone discordant lodes with 'bonanza' Au grades, commonly associated with elevated Sb and Te, dominated by discordant carbonate-matrix mosaic breccias that grade locally into chaotic, fluidized breccias with matrix of sulphide microclasts and carbonates. Similar shoots are also found in the Golden Mile, and are notably deficient in smaller (< 2 MOz) lode gold deposits in the Eastern Goldfields. At Ernest Henry, the orebody is defined by mosaic breccias with abundant carbonate-sulphide-magnetite infill and some replacement, sitting within the bounding shear zone. Near the bottom of the exposed parts of this system, discordant breccia sheets and pipes, cm to metres wide, contain fluidized magnetite, calcite, sulphides and elevated copper grades, with sulphides locally occurring as abraded clasts. In both these ore systems, the association of high and/or bonanza grades and locally anomalous metal associations with carbonate-bearing fluidized breccias implies rapid, CO<sub>2</sub>-driven fluid pulses at very high velocities (> 100m/s). Recrystallization in shear zones may serve to obscure similar pulses occurring earlier in the paragenesis. A substantial contribution of magmatic CO<sub>2</sub> and metals from crystallizing mafic magmas, with extreme velocities driven by supra-lithostatic fluid pressures potentially generated in magmatic carapaces, is apparent in both these styles of ore systems, despite regional long-lived circulation of metamorphic and/or basinal fluids, which themselves produced mineralisation via fluid flow in shear zones.

## Paleovolcanology of a northwest Australian Large Igneous Province: outpouring of the c. 1795 Ma Carson Volcanics.

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The Hart-Carson Large Igneous Province (LIP) is the northwestern Australian portion of the large Australia-wide c. 1790 Ma Hart mafic igneous event. At c. 1795 Ma mafic magmatism led to the intrusion of the Hart Dolerite into the Speewah Basin and the developing lower Kimberley Basin. Some tholeiitic mafic magma reached the surface and flooded the shallow marine to emergent Kimberley Basin to form the Carson Volcanics. The volume of the Hart-Carson LIP is comparable to the Columbia River Basalt Province. The Carson Volcanics comprise 17% by volume of the LIP.

The Carson Volcanics are widespread and flat lying to gently dipping across much of the Kimberley region, but are deformed and metamorphosed on the westernmost Yampi Peninsula and along the upturned margins of the King Leopold and Halls Creek Orogens. The thickness of the unit roughly varies between 80–200 m thick in the northeast to 300–800 m thick on the Yampi Peninsula.

The Carson Volcanics share features characteristics of flood basalt provinces. Widespread tabular basalt units forming layer cake stratigraphy interspersed with elongate lenses of sedimentary units and a few palagonite-pillow facies associations. In the north, around Kalumburu and the Mitchell Plateau, three to six basalt units are intercalated with sandstone and siltstone. Basalt units 20–40 m thick can be traced up to 250 km along strike. Massive and amygdaloidal basalt commonly display polygonal to subhorizontal and rare vertical columnar jointing. Ropy lava tops, toe lobes and basal pipe vesicles are consistent with fluidal pahoehoe lavas. In marked contrast, the 800 m-thick succession in the southwest on the Yampi Peninsula comprises up to 100m-thick units of volcaniclastic rocks, polymictic breccia and conglomerate with subordinate intercalated basalt flows and rare pillow basalt. Breccias are matrix-supported with a greywacke matrix. Clasts include pebble- to boulder-sized silicified sandstone, amygdaloidal basalt and massive basalt. Clasts in some breccias are variably vesicular basalt and some near the top of the succession contain angular, elongate and irregular-shaped clasts of vesicular basalt. These vesicular basalt clasts are delicate and could not have been extensively reworked, but may have been entrained in debris flows. Many mafic clasts may have formed by quenching or phreatomagmatic eruptions where water was able to enter vents.

Lithofacies of the Carson Volcanics are consistent with their deposition in a shallow to emergent shelfal environment with an overall gentle south to south west dip. The change in volcanic lithofacies in the Yampi Peninsula to thick clastic and volcaniclastic units may be due to a deeper depocentre in this area.

## **Past, present and future monitoring of subsidence due to groundwater abstraction using InSAR in the Perth Basin, Western Australia**

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Vertical land motion, due principally to groundwater abstraction, is observed throughout the globe including Perth, Western Australia, where small magnitude (~2-6 mm/yr) subsidence has been recorded since the 1970s. Measuring and monitoring such deformation has previously been achieved using repeat levelling or continuous-occupation GPS, but space-based InSAR (Interferometric Synthetic Aperture Radar) is becoming an increasingly popular tool, providing measurements of ground displacements at unparalleled spatial resolution (up to 1 m) over large (up to 200 km) regions.

In the Perth Basin, there is now a >20 year archive of InSAR data, with sensors covering different time-periods and operating at different wavelengths (X-, C-, L-band). These data complement ground-based surveys and aid in characterising the full spatial extent of subsidence. Using L-band ALOS InSAR data, we have identified localised deformation in rural areas and wetlands outside of the metropolitan area. By comparing ALOS time-series of subsidence with water levels measured at artesian monitoring bores, we evaluate whether non-linear vertical land motion reflects changing water levels in subsurface aquifers.

SAR coverage of the Perth Basin is ongoing and is to be complemented by a ground network of corner reflectors co-located with continuous GPS. These provide consistent bright reflections for the high resolution X-band TerraSAR-X satellite and can be tracked between satellite images. Data is also being acquired by the recently launched European Space Agency satellite Sentinel-1A. Regular coverage and high coherence of this imagery has enabled us to produce some of the first Sentinel interferograms in Australia. The ongoing collection of these and other ground-based geodetic data means that we are now well placed to measure and monitor vertical land motion across more of the Perth basin than can be measured by ground-based techniques alone.

## **Edgeworth David geologist in war and peace**

**Passmore, Virginia**

*Canberra, Australia*

When Britain recognised the need for a geological advisor on military mining during the First World War it appointed the experienced and world renowned Australian geologist Edgeworth David to the British Expeditionary Forces in 1916.

Born in Wales in 1858, Edgeworth David immigrated to Australia in 1882 to take up a position as a geological surveyor with the New South Wales Geological Survey. The discovery of the Hunter Valley coal fields during his surveys and public talks on the state's resources brought him to public attention. In 1891 he was appointed Professor of Geology at the University of Sydney. During his tenure at the university he undertook expeditions to Funafuti Island and in 1907 joined Shackleton's Expedition to the Antarctic. These geological expeditions gained him world-wide repute and election as a Fellow of the Royal Society of London.

David was a strong supporter of the First World War who joined a local militia unit and spoke at recruitment rallies, Nevertheless in 1914 at a time of strong anti-German feeling he also spoke up for German scientists who were attending a scientific meeting in Australia. In 1915 he encouraged the formation of a military force of geologists and miners to undertake wartime tunnelling activities. In October at the age of 57 he enlisted in the AIF and was commissioned a Major in the Mining Battalion. He embarked for France in February 1916 taking with him the first three units of the Australian Mining Corps. Once in France the British appointed David as geological technical advisor to the Controller of Mines of the British Expeditionary Forces to undertake geological investigations and to advise on defensive mining for dugouts and trenches and on offensive tunnelling in Belgium and northern France. From detailed field investigation, test bores and existing water well data he determined the stratigraphy and subsurface strata of the Western Front as well as seasonal variations in the water level of Cretaceous chalks used for dugouts. His most notable service was the identification of two clay units suitable for mining and tunnelling in the Messines region, one unit of which lay beneath the German fortifications. In 1917 he was attached to the Inspector of Mines, General Headquarters where he continued his geological investigations and produced colored maps and vertical sections of the region, the first environmental engineering maps. He also worked with and advised Americans geologists in the latter year of the war. Returning to Australia and the university in 1919 he began work on his major project the Geology of Australia, completing a Geological Map of the Commonwealth of Australia and Explanatory Notes before his death in 1934.

Edgeworth David's wartime service was recognised by King and country. He was awarded a DSO and promoted to Lieutenant Colonel in 1918 and post-war was given a KBE in 1920. His work also received scientific recognition in Australia and overseas and he was given a state funeral and several posthumous memorials.

## Starra & SWAN – Same, same, but different: a petrophysical analysis of two contrasting IOCG deposits in the Selwyn–Mt. Dore region, Queensland.

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The Uncover Cloncurry project was launched with the aim of providing useful research to aid future mineral exploration beneath the extensive cover sequences of Australia. As part of the project petrophysical analysis was undertaken on the SWAN and Starra deposits in the Selwyn region approximately 100 km South of Cloncurry. The Starra deposits are relatively high grade, low tonnage whereas SWAN has a lower grade but greater tonnage. The petrophysical analysis included measurements of density (ρ), magnetic susceptibility (K) and remanent magnetisation (J) on over 75 drill core samples. In addition, anisotropy of magnetic susceptibility (AMS) analysis was undertaken to establish the existence of any magnetic fabric in the samples.

Mineralisation at Starra is hosted in magnetite-rich ironstones west of the Starra shear which has been reactivated multiple times during the region's long-lived deformation history. The petrophysical properties of the sampled Starra drill hole are generally modest with the exception of the chalcopyrite-magnetite-rich ironstones at the bottom of the hole. The majority of magnetic susceptibility values are less than 0.2 SI and densities less than 3.0 g/cm<sup>3</sup>. Comparatively, the mineralised ironstones have K values up to 1.9 SI and densities up to 4.4 g/cm<sup>3</sup>. There is some debate regarding the timing of magnetite in the area with some work suggesting that iron oxide enrichment happened late in the deformation history (post D<sub>4</sub>) whilst others conclude that the magnetite-hematite ironstones at Starra were present early on (pre-syn D<sub>2</sub>). AMS analysis provided remarkable evidence to support the latter with excellent clustering of the three elongation axis (K1 = long axis, K2 = intermediate axis and K3 = short axis). K3 orientation of magnetite in host rocks at Starra indicates an early shortening direction of ESE-WNW with maximum elongation in an astonishingly similar orientation to the axis of F<sub>2</sub> folds (dipping steeply between NE and ENE).

SWAN is situated adjacent to the contact between the Stavely Formation and Soldiers Cap Group with economic mineralisation hosted in large breccia bodies. The petrophysical characteristics of SWAN are highly variable with densities ranging from 2.5 – 4.4 g/cm<sup>3</sup> and K values of 2.4 × 10<sup>-6</sup> SI to 1.9 SI. The correlation of high remanent magnetisation with high susceptibility values is consistent with the coarse grained magnetite enrichment visible in hand specimen. AMS results from SWAN are somewhat less conclusive than Starra with no contiguous magnetic fabric down-hole. However, a group of metasomatised magnetite enriched samples cluster well and suggest a shortening direction of NE-SW with grain elongation (long and intermediate axis) scattered about a NW-SE girdle. This is orthogonal to the SE-NW shortening at Starra only ~15 km away. We suggest that the locally rotated fabric may be a result of the emplacement of the Squirrel Hills Granite at ca 1510 Ma.

IOCG systems within the Cloncurry region are often considered part of a regionally linked system. This may well be the case; however the results from the petrophysical and magnetic analysis of this study illustrate the stark differences in characteristics between mineral occurrences that are relatively proximal.

## Balance of precious metals in the Paris silver deposit, South Australia

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The Paris silver deposit, Northern Eyre Peninsula, is hosted by rocks of the 1,600 Ma Gawler Range Volcanics (GRV) deposited upon the Katunga dolomitic marble of the Paleoproterozoic Hutchison Group. Together with several other prospects, Paris occurs in the Uno Province, a region of Ag-base metal mineralization located along the Uno Fault, marking the southern boundary of the GRV. Mineralization is hosted within intensely clay-altered polymict volcanic breccias and an upper, oxidised zone of the Katunga dolomite. Paris contains an inferred resource of 33 Moz silver (IVR 2015).

The dolomite is intruded by narrow northwest dykes of granite, which have yet to be dated; but were originally considered to be of Hiltaba (~1.59 Ga) age (IVR 2013a). Genetic relationships between mineralisation and these intrusions remains inadequately constrained. In addition, the dolomite is host to narrow, discontinuous, deformed magnetite- and sulphide-bearing veins, which contain comparable assemblages to sulphide-rich clasts in the breccias. As such, they have been interpreted as a potential source (IVR 2013a). An oxidised interface is present between the dolomite and the breccias, potentially representing the pre-eruption paleosurface. This zone, in addition to the upper, altered dolomite form the base of the ore zone at Paris. At depth, magnesian skarn assemblages, dominated by forsterite but also containing spinel and retrograde assemblages of chlorite, pyrite and secondary carbonates (calcite and kutnohorite), prevail across the footwall to the silver deposit.

Ore assemblages in both dolomite and breccia clasts are characterized by galena, arsenopyrite, pyrite, sphalerite and chalcopyrite. Silver is primarily present as acanthite and native silver; however, significant amounts of refractory silver have been measured in pyrite, galena, arsenopyrite and sphalerite. While preliminary metallurgical testing indicated positive recovery results (IVR 2013b), the contribution of refractory silver to the overall silver balance may carry important implications for processing, and thus must be considered in order to optimize recovery.

To further evaluate the significance of refractory silver, and any potential variation in concentration across the lateral extent of the deposit, and in different lithologies, sulphides in 13 samples were analysed by Laser Ablation Inductively-Coupled Plasma Mass Spectrometry (LA-ICP-MS).

Silver is contained within sulphides in solid solution (particularly in galena, sphalerite and arsenopyrite), and as inclusions a few µm in size extending down to the nanoscale. Porous, inclusion-rich pyrite from the sulphide-rich breccia clasts contain an average of >10,000 ppm Ag, whereas pyrite from magnetite/sulphide veins at depth contains mean concentrations of 80 ppm Ag. This suggests mineralised breccia clasts in Paris are likely coevally derived from within the Mesoproterozoic epithermal diatreme environment. Concentrations of other trace elements vary considerably with respect to texture. We conclude that refractory ores may make a significant contribution to the overall silver balance but that this contribution is subordinate to free-milling silver. Additionally, pyrite demonstrates significant variation in trace element chemistry between different sulphide-rich zones, indicating that the sulphide-rich breccia clasts may not all be sourced from the magnetite/sulphide veins at depth, as previously suggested.

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<http://www.investres.com.au/>

## Finding closure; multiple stages of Musgravian-aged deformation in the eastern Musgrave Province

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Recent work from the eastern Musgrave Province has revealed that two distinct foliations developed during the c. 1220–1120 Ma Musgravian Orogeny. The earliest fabric is locally preserved within domains that are characterised by moderately dipping to sub-horizontal foliations. In several places, shallowly dipping interlayered ortho- and paragneisses are folded into km-scale, open, upright synforms that plunge shallowly to the north and south.

The region is dominated by the second fabric, characterised by a steep, broadly NNE-striking foliation, corresponding to a pervasive aeromagnetic grain. This foliation is associated with lineations and upright tight to isoclinal folds that plunge shallowly along strike to the NNE and SSW, similar to the plunge of the km-scale synforms. The folded gneissosity often has axial planar leucosomes, and folded leucosomes can have an axial planar gneissosity. These hinges are often isolated by layer-parallel melt-filled shear zones that run along the sub-vertical limbs, resulting in rootless isoclinal folds. The hinges of the outcrop-scale folds would correspond to the shallowly to moderately dipping foliation in the domains described above. Furthermore, the moderately dipping foliation in one of the km-scale folds is deflected and truncated by broadly north-striking, fanning zones with steep foliations, similar to a crenulation cleavage. The steep foliation is locally cut by melt-filled conjugate shear bands that are texturally continuous with the layer-parallel leucosomes. These field observations suggest apparent ESE-WNW-directed sub-horizontal shortening during development of the steep foliation.

Overprinting relations indicate that the shallow foliation formed first, before being folded into the NNE-striking, upright, shallowly plunging folds, resulting in a steep axial planar parallel foliation in the hinge and a composite foliation on the fold limbs. Furthermore, the folded and axial planar leucosomes can be texturally continuous, suggesting that the two foliation generations, leucosome injection and folding developed during the same metamorphic event.

New SHRIMP zircon geochronology supports the field relations. Zircons from rocks in the shallow domains have metamorphic overgrowths that are dated at c. 1170–1168 Ma, statistically distinct from metamorphic overgrowths within rocks with a steep foliation which are dated at c. 1160–1138 Ma. The youngest age was obtained from a metapelitic rock, which has been boudinaged and overprinted by compressional shear bands that are interpreted to have formed late in the shortening history.

This sequence of structural elements indicates several stages of deformation during the Musgravian Orogeny. The early stage involved horizontal transport and the development of the shallowly dipping foliation. Extensive regional UHT metamorphism and significant A-type magmatism at this time suggest a period of regional extension and crustal thinning, consistent with formation within a back arc or continental rift setting. This extensional phase was then affected by a period of WNW-ESE-directed shortening, which resulted in the dominant sub-vertical, NNE-striking trend in the eastern Musgrave Province.

## The Hiltaba-GRV Suite as a lithospheric probe: A reflection of lower crustal or upper mantle conditions?

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The Hiltaba Suite-Gawler Range Volcanics-Bennerie Ridge Volcanics-Ninnerie Supersuite felsic large igneous province in South Australia unquestionably provided the thermal input that drove the Olympic Dam-style IOCG mineralising systems along with a wide spectrum of associated deposit types (e.g. Au, Pb-Zn, Ag). However, it remains unclear how many of these deposit types also sourced their metals directly from the Hiltaba event magmatism. Budd (2006) outlined an apparent spatial correlation between granitoid geochemistry and broad deposit type (e.g. 'A-type' = IOCG, 'I-type'=Au-only) and suggested that granite types reflect varying litho-tectonothermal conditions and may be used as a guide for exploration. This work focuses on the isotopic variation of the Hiltaba event across the full extent of its expression in South Australia.

Hf isotope data collected from Hiltaba event rocks across South Australia show a marked spatial organisation that broadly correlates with the currently exposed, pre-existing geology. Magmatic zircons from igneous rocks within the eastern Gawler IOCG province are generally the most evolved within the event with  $\epsilon_{Hf}(t)$  values dominantly around -2 – -5. This is similar to results from intrusive rocks in the neighbouring Crocker's Well region in the south-western Curnamona Province, highlighting the potential similarity in lithological and thermal regimes in the two regions.  $\epsilon_{Hf}(t)$  zircon isotope data from the central Gawler Craton and central and northern Curnamona Province tend to cluster around 0.  $\epsilon_{Hf}(t)$  values from the western Gawler Craton are almost exclusively positive with values as high as +7.

Modelling of the data relative to the surrounding country rocks and mafic end-members does not suggest a systematic variation of mantle input into the magmas. Hence the isotopic data is interpreted to represent varying compositions of the lithospheric column below each region. It may prove to be the case that portions of the lithospheric mantle below the Gawler Craton have isotopic signatures that are more crustally evolved (i.e. -ve in epsilon space) than the neighbouring crust. That these isotopic signatures broadly correlate to mineralisation style provides further support for the concept that mineralisation styles can be linked to the state of the deep lithospheric column.

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## Diagenetic effects on the mineral structure and isotope geochemistry of biogenic silica: Implications for palaeoclimate research

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The siliceous microfossils of diatoms are abundant in many lake and ocean environments worldwide. Increasingly, oxygen isotope analysis of diatom (biogenic) silica ( $^{18}\text{O}_{\text{silica}}$ ) is used as a paleoclimate proxy. Implicit in the use of biogenic silica for this purpose is the assumption that during sedimentation, the structure of the silica skeleton and the outer hydrous layer remains constant. This assumption contrasts with observations that fossil diatoms contain markedly less  $\text{SiO}_3\text{OH}$  within their silica structure than their living counterparts. Condensation of  $\text{SiO}_3\text{OH}$  to  $\text{SiO}_4$  has also been observed to correlate with post-mortem changes in  $^{18}\text{O}_{\text{silica}}$ . The significance of these changes are not well understood but may have implications for both palaeoclimate research and for ocean biogeochemistry. In particular, little is understood regarding the rate and maximum extent of silica condensation, either within the natural environment or under experimental conditions (including sample pre-treatment). Here, we explore this phenomenon using experimental manipulation of pure, freshly cultured (but dead) diatom silica. A combination of oxygen isotope mass balance and infra red spectroscopy is used to examine the role of temperature on the rate of silica condensation. Preliminary data suggest that the silica condensation is a positive function of temperature within the range 0-80°C. By contrast, secondary silica-water oxygen isotope fractionation varies inversely with temperature, consistent with extrapolation of high temperature mineral-water calibrations.

## **Maximizing the immediate value of wireline log information in shale evaluation**

**Peyaud, Jean-Baptiste**

*Baker Hughes Incorporated*

The composition of a shale formation includes its organic content, the type of organic matter and its level of maturity, and the composition of the hydrocarbons contained in the formation (e.g., dryness of the gas, CO<sub>2</sub> content). The ability to stimulate a large enough volume of the formation is critical in determining the viability of the reservoir. Therefore it is necessary to understand the mechanical properties of the formation. A number of these parameters can only be assessed in the laboratory. Organic maturity, for instance, requires pyrolysis experiments; the fraction of gas adsorbed can only be assessed by desorption experiments. However, laboratory experiments take time, and it is sometimes month before the results are available. Conversely, operators often face important decisions regarding their wells, especially if they want to test them, locate one or several lateral extensions or stimulate the formation. In these circumstances, the log data must provide the information required for making operational decisions: estimate the amount of organic matter and its level of maturity, identify potential barriers and intra-formational reservoirs, characterize the variation of rock mechanical properties.

What type of information can be extracted from logs in shales? This is strongly related to the type of data acquired and the level of pre-existing knowledge. For instance, if no pre-existing information is available, the use of a spectroscopic tool will contribute to reliably characterize the variations of lithology and organic content in the target formation. A borehole image will reveal the sedimentological and structural features, such as the occurrence of erosion surfaces or the presence of faults, cemented horizons and nodules, thinly bedded intervals (high vertical anisotropy can have an impact during stimulation) or borehole damages. Considering what can be learnt about the geological evolution of the basin in the well and the well temperature, it is possible to estimate the type of organic matter and its level of maturity. Acoustic data, in conjunction with a borehole image, provides information on the orientation of the stress field and the elastic properties of the formations. The occurrence of hydrocarbons and their composition can be inferred from the mudlogs. Information extracted from log data allows thus to characterize the vertical variability of the formation, locate intervals of interest, identify potential barriers and determine the best orientation to drill lateral extensions and optimize the stimulation process.

This communication will present a workflow where relevant information can be extracted from logs to evaluate the potential of a formation within 5 to 10 days of completing the data acquisition. It will address the key questions of the value of information, and the importance of core data in log interpretation.

## Lake George: a sedimentary archive of the Quaternary Period

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Lake George, at an elevation of 675 m in the Southern Highlands of NSW, contains the longest known sedimentary archive of any Australian lake basin and one of the longest in the world. Drill cores obtained in the 1980's, by the Bureau of Mineral Resources (now Geoscience Australia), show that up to 165 m of sediment lies beneath the floor of the lake. A combination of magnetostratigraphy, biostratigraphy and cosmogenic nuclide burial dating indicates an age of ~4 million years (mid-Pliocene) for the base of the sedimentary sequence (Macphail *et al.* 2015).

At present, the lake is an internally draining basin with no outlet. However, dramatic water level fluctuations have occurred during the last 200 years, largely controlled by the balance between rainfall and evaporation. At times the lake has been up several metres deep and at other times, including this year, it has been completely dry. During the Late Pleistocene, gravelly shoreline deposits indicate that the lake reached depths of 35-40 m, at which time the lake may have overflowed to the west or north, into the headwaters of either the Murrumbidgee or Lachlan rivers.

The lake is impounded, on its western side, by the Lake George Fault. Quartz-rich fluvial gravels on the upthrown (western) side of the fault are more than 200 m higher than similar gravels in the base of drill holes on the downthrown side of the fault, indicating significant vertical displacement over the past 4 Ma.

Palynological results from sediments dated to ~3 Ma (late Pliocene), indicate a wetland dominated by the coral fern family, Gleicheniaceae, while the surrounding dryland vegetation was a mix of sclerophyll and temperate rainforest communities, the latter including trees and shrubs whose nearest living relatives are endemic to New Guinea, New Caledonia and Tasmania; mean annual rainfall is inferred to have been 2000-3000 mm (c.f. ~600-700 mm/year today). By ~2 Ma (Early Pleistocene), rainforest species had disappeared and the dryland vegetation was sclerophyll woodland, but differing from the modern vegetation in that eucalypts were very rare; mean annual rainfall was less than 1200-1300 mm/year. The transition from the Pliocene to the Pleistocene at Lake George was therefore marked by a significant decrease in mean annual rainfall.

In November 2015, we obtained a new drill core (Geary's Gap-1) from Lake George, to a depth of 77 m. Based on comparison with nearby BMR drill cores, the estimated basal age of the new core is ~2 Ma. We are undertaking detailed geochemical, mineralogical, geophysical, sedimentological, hydrological, geochronological and paleontological analyses on this core.

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## Ultra-high precision $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of volcanic rocks by multi-collector mass spectrometry

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The new generation of multi-collector mass spectrometers for noble gas (including  $^{40}\text{Ar}/^{39}\text{Ar}$ ) geochronology and geochemistry (e.g., Noblesse, ARGUSVI, HELIX-MC) offer unprecedented levels of analytical precision and have the potential to transform temporal constraints on volcanic events. In this presentation, we will document  $^{40}\text{Ar}/^{39}\text{Ar}$  ARGUSVI geochronology results obtained on sanidine from selected tuffs (including those used as  $^{40}\text{Ar}/^{39}\text{Ar}$  dating standards), anorthoclase megacrysts entrained in New Volcanic Province basalts (Victoria, Australia), as well as young (<0.5 Ma) basalts from the New Volcanic Province.

The  $^{40}\text{Ar}/^{39}\text{Ar}$  ages have been standardised against the A1 Tephra unit from the Faneromeni section, Crete, which has an astronomically tuned age of  $6.943 \pm 0.005$  Ma [1]. ARGUSVI  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses exhibit significantly enhanced precision levels (generally >10x), compared to previous mass spectrometer systems.

The high precision achievable using the ARGUSVI has permitted resolution of distinct age gradients in step-heating spectra for the sanidine standards [2], which are attributed to mass fractionation processes. This does not affect laser fusion results. For example, new  $^{40}\text{Ar}/^{39}\text{Ar}$  ages calculated for the Fish Canyon Tuff sanidine (FTCs) and Alder Creek Rhyolite sanidine (ACRs) are:  $28.126 \pm 0.016$  (0.057%) Ma (2□) and  $1.1811 \pm 0.0011$  (0.093%) (2□), respectively.

The ARGUSVI system is particularly well suited to high precision  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of young (<100 kyr) basalts. Typically, such basalts yield ages with uncertainty levels of <1% (2□). Higher precision ages are attainable from anorthoclase megacrysts in basalts, with new age data confirming these constituents as xenocrysts that formed just prior to basalt magmatism.

The significant improvement in analytical precision using the new multi-collector instruments presents new challenges, but also provides new insights into the chronology of volcanic rocks.

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## Sedimentary trends in Late Permian coal measure strata, Galilee Basin

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Three key wells (GSQ Tambo 1-1A, OCE Glue Pot Creek 1 and COI Montani 1) that intersect Late Permian coal measures of the Galilee Basin were chosen for sedimentary logging and facies analysis. These wells traverse the eastern margin of the Galilee Basin from south to north. In this region the coal-bearing Bandanna Formation (BF) and underlying Colinlea Sandstone (CS) are separated by the Black Alley Shale (BAS)/Peawaddy Formations (PF). Regional trends in thickness and lithology of these formations were generated from 1000 coal exploration wells.

On the Springsure Shelf (southernmost area) the CS was only partly intersected and contains a coal seam capped by a sequence that grades upward from wavy and flaser-bedded sandstone with horizontally bioturbated mud-drapes, to thick, clean, massive to low- and high-angle cross-bedded sandstone, interpreted as the drowning, rapid transgression and regression of lower and upper shoreface deposits over the coastal or deltaic peats. These facies are occasionally interrupted by sandy, matrix-supported conglomerate interpreted as storm deposits derived from reworking of fanglomerate sourced from the nearby Anakie Inlier.

Overlying the thick sandstone unit, ripple-laminated, horizontally burrowed mud-drapes and clean sandstone interbedded with minor conglomeratic units are observed again. These shoreface-derived facies, which represent the beginning of a transgression, are considered to be the PF. They are overlain by dark carbonaceous siltstones of the BAS, which also contain tuff horizons that can be correlated northward into the basin.

Using the sequence of tuffs in the BAS as marker horizons, the marine shoreface deposits of the PF either pinch or interfinger northward into the increasingly coal-bearing CS. The CS is composed of a series of fining-upward sequences capped by coal seams, with each cycle becoming thinner upward, an observation ascribed to avulsing fluvial channels. Northward, two fining-upward cycles are observed in the lower CS, however the cycles above have the addition of coarsening-up sequences and periods of silt-dominated interburden, suggesting sedimentation in ponded areas. To the north and south the CS is overlain by fine-grained siltstone representing the transgression of the BAS. The youngest coal in the CS is recognised regionally as the C-seam by its tuffaceous nature. In the centre of the basin it is overlain by an intensely bioturbated black siltstone that coarsens upward until capped by fine-grained, flat- to cross-laminated clean sandstone that is capped by the BF Coal Measures. These coarsening-upward sequences pinch to the north, where the correlative stratigraphic unit is a grey siltstone with siderite. Based on regionally correlated siltstone intervals within the coarsening-upward sequence, it is interpreted as a southerly prograding deltaic sequence, capped by wave- to tide-dominated top set beds that are overlain by the terrestrial coal measures.

The BF contains a second tuffaceous horizon persistent across the basin that is correlative southward with another tuffaceous horizon above the coarsening-upward sequence of the BAS on the Springsure Shelf. This relationship suggests that the BF is possibly misplaced stratigraphically, as it could be correlated with the younger, tuffaceous Burngrove Member of the Fort Cooper Coal Measures in the Bowen Basin.

## The National Rock Garden

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When completed, the National Rock Garden (NRG) will occupy a 5 hectare site on the western foreshore of Lake Burley Griffin, in Canberra. The site is close to the National Arboretum, the National Zoo & Aquarium and the Lindsay Pryor National Arboretum and just a few kilometres from the Australian National Botanic Gardens.

The vision for the National Rock Garden is to celebrate the geological heritage of Australia by displaying iconic rocks in a park-like setting and to provide a unique outdoor geosciences education facility, which can be utilised by the many school groups that visit Canberra. Initially, we envisaged a display consisting of at more than 100 large rock specimens from all around Australia, each weighing about 10-20 tonnes, and placed along meandering pathways with sympathetic plantings of native trees and shrubs. Each rock would have a plaque, to explain its significance and, where appropriate, a cut and polished face to reveal its features. A primary consideration, in choosing the rocks, was that they would tell interesting stories of national (and sometimes international) significance that would appeal to a wide public audience, especially school children.

The NRG project was launched at the AESC in July 2010, and formally gazetted as a national monument in April 2011. The first display, the Federation Rocks, was opened in October 2013 as part of Centenary of Canberra celebrations. The Federation Rocks consist of eight large rocks, one from each state and territory, each chosen for special significance to its state or territory of origin.

The Federation Rocks display has served to demonstrate two important principles:

1. People love big rocks, if they have an interesting story to tell and if they are visually appealing.
2. Informative signage is essential, with text that is both understandable and entertaining for the wider public.

The Federation Rocks have whetted people's appetite for more rocks and provide a way of enthusing would-be sponsors and donors, as we seek to raise a substantial amount of money to develop the whole 5 hectare site. To that end, in 2013, we engaged renowned landscape architects, Taylor Cullity Lethlean, to develop an NRG masterplan with a 'wow' factor to further excite people about rocks. That masterplan, which was released in November 2014, is available for download from the NRG website at <http://www.nationalrockgarden.org.au/>. Key elements of the masterplan include an entry structure (incorporating an education pavilion), rock gallery, amphitheatre, time wall, gorges, a geological walk along meandering paths and a work area for preparing rock exhibits.

Using a grant from the Australian Geoscience Council, a sketch design for the education pavilion has been prepared by prominent Sydney architects Tonkin Zulaikha Greer, together with indicative costing of that structure.

In 2015, the NRG received a grant from the National Cultural Heritage Account, through the Ministry of Arts, for the acquisition of two significant mining heritage rocks – a 7 tonne alunite-bearing rock from Bulahdelah, NSW, and a 16 tonne chrysoprase-bearing rock from Marlborough, Queensland – both currently in storage in Canberra.

## **Thermodynamic approach to the manganese deposits of the Lafaiete District, Minas Gerais, Brazil**

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The manganese deposits of the Lafaiete District in Minas Gerais State form a well defined approximately 50 km long and 5 km wide belt, distributed between Entre Rios de Minas deposits at the SW portion of the belt and the Morro da Mina and a myriad of deposits at the SE part of the belt. The Mn-deposits are confined in an Archean greenstone belt comprehended in gneisses and intrusive granite. The deposits have been described since the beginning of the last century with emphasis to the famous Morro da Mina Mine exploited by CMM-Companhia Meridional de Mineracao, subsidiary of U.S. Steel Corp., which received million tons of high-grade manganese ore to feed its steel industry. Initially Piquiri was discovered and exploited up to it almost exhaustion, followed by discovery of Morro da Mina. Rhodochrosite, spessartite, tephroite, rhodonite and tirodite are the main constituents of the Mn-protore represented in Mn-Si-Al-C-O-H systems, described as queluzite, in contrast with the siliceous quartz spessartite-tirodite protore defined in India as gondite studied in the Mn-Si-Al-O-H system. Both protores were later transformed through Tertiary weathering in an association of Mn-oxides, composed of pyrolusite, manganite, psilomelane and cryptomelane described locally as "bioxide ore". Subordinate pyrophanite, bementite, neotocite and mangan apatite have also been identified. Apparently a Mn-carbonate-rich rock with cherty portions was responsible for the metamorphic parageneses formed under medium-grade conditions as a result of several metamorphic reactions. Subsequent pegmatoid and strong hydrothermal activity modified the initial parageneses by the introduction of H<sub>2</sub>O and H<sub>2</sub>S combining with evolved CO<sub>2</sub> to generate large and beautiful rhodonite crystals, asbestosiform amphibole, well formed spessartite and sulfide minerals, mostly pyrite, pyrrhotite, chalcopyrite, bornite, siegenite and covellite. An ample discussion involving proposal of several investigators has been presented, in order to clarify the previous work and genetic approach was included as well as thermodynamic consideration to help a better understand of the formation condition.

## **1800-900 Ma global paleogeography: new insights**

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Precambrian paleogeography attracts a lot of attention of Earth scientists in various disciplines. This interest particularly caused by new hypothesis of supercontinental cycles and their relation with global geodynamic processes. Most workers agree about existence of at least two Precambrian supercontinents – Neoproterozoic Rodinia and Mesoproterozoic Nuna (aka Columbia). A number of various paleogeographic reconstructions of these supercontinents and some kinematic models of their assembly and breakup have been published in recent years. In this presentation I summarise newly published paleomagnetic, geological and geochronological data and propose a new kinematic model of the ca. 1800-900 Ma global paleogeography. In summary the following published data have been used for a modification of previous models: (i) new paleomagnetic and geochronological data from Mesoproterozoic and Early Neoproterozoic rocks in Baltica, North China, Sao Francisco, Amazonia, Australia; (ii) new discoveries of Large Igneous Provinces with ages between 1800 and 900 Ma in Siberia, North China, Sao Francisco and Congo; (iii) new geological and geochronological data from Europe and South America, which do not support the popular SAMBA model of long-lived connection between Baltica and Amazonia in late Paleoproterozoic and Mesoproterozoic. In a new model I tried to imply all these and some other new data. Some of these multi-disciplinary results are contradictive to each other, so some parts of new model are debatable and alternative versions of plate tectonic movements are proposed for further testing. New data support the hypothesis of ca. 300 m.y. connection between Siberia, Sao Francisco, Congo, North China, Amazonia and West Africa at 1800-1500 Ma. New model includes the enigmatic time interval between 1270 and 900 Ma – the time of breakup of Nuna and assembly of Rodinia. New paleomagnetic data support the closeness of Siberia and North China, proposed in IGCP 440 Rodinia reconstruction since ca. 1100 Ma, but not before. New ca. 920 Ma paleomagnetic data from Sao Francisco do not support the hypothesis that Congo/ Sao Francisco craton has been a part on Rodinia. The ca. 1120 Ma Salla Dyke pole from Baltica suggests unrealistically fast and long travel of this craton with respect to Laurentia, so a more realistic and geologically supported reconstruction of the Asgard Sea between Laurentia and Baltica has been used in the new model.

## Virtual and classical outcrop mapping for reservoir analogue modelling

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The Lower Jurassic Precipice Sandstone is an important reservoir for water, hydrocarbons and potentially geosequestration in the Surat Basin. It is the basal infill of the Surat Basin, and its commonly interpreted origin is a fluvial system that formed a thick belt of sandstone located in correspondence to the structural axis of the basin, the Mimosa Syncline.

The unit crops out along the northern margin of the basin, often forming laterally continuous cliffs that provide good conditions for 3D photogrammetry and classical 2D mapping and analysis of sedimentary architectures, bedding and facies. Photogrammetry is a measurement technique that builds 3D photorealistic virtual models in which every pixel on the image corresponds to a real 3D point in georeferenced space. This was used to measure surfaces, bed and body geometries for export to a reservoir modelling system, providing a bridge between the subsurface drilling data and the outcrop analogue.

The field survey mapped the lower, defined by the predominance of southeast-flowing planar and trough cross stratified sandstone (the braided stream facies), and upper Precipice, defined by a predominance of heterolithic, ripple and plane parallel stratification and slumps that transition upward into the Evergreen Formation mud-dominated unit. Sedimentary structures in outcrop suggest a northward flow on the eastern margin of the outcrop for the upper Precipice. The basin asymmetry, coincident with a major, meridional-trending fault system—the Goondiwindi-Moonie-Burunga system, and changes in upper and lower unit thickness suggest some syn-depositional control on the sedimentary architecture.

To assist with the identification and lateral continuity of fine grained units and their mineralogical composition within the Precipice, quantitative mineral maps derived from hyperspectral imagery acquired from a field-based platform were integrated with photogrammetry.. Clay mineral-rich layers can impact on both reservoir permeability and the reactivity with CO<sub>2</sub>. Iron and manganese oxides and hydroxides, phyllosilicates (clays) and carbonates can be detected by means of hyperspectral sensors measuring the visible near-infrared (VNIR) and short wave infrared (SWIR) spectral range. The integration of hyperspectral panoramic images with 3D photogrammetric data enabled different spectral signatures (indicative of changes in mineralogy) to be quantified, thus mapping the lateral continuity and thickness of layers on the exposed wall.

The preliminary field results particularly demonstrate that the gross clay mineralogical (e.g. kaolinite) and iron oxide changes follow the bulk changes in lithology (siltstone and sandstone), as do patterns of absorption by molecular water, but discrimination is poor where there are no sharp boundaries. Although the spatial resolution and mineralogical identification might be improved, this technique shows great promise because it highlights the distribution of siltstones beds and drapes that can potentially create baffles in the reservoir.

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## Across Australia and around the World in Millimetres

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In the geodetic space technique of Very Long Baseline Interferometry (VLBI) we make use of extra-galactic radio-waves to precisely determine relative distances on the Earth's surface, as well as the changing orientation and rotational speed of our planet. By measuring differences in arrival times at multiple radio telescopes, VLBI is a key technique to realise stable and highly accurate reference frames attached to the solid Earth. They are essential to measure and understand plate tectonics, sea level rise and the dynamics of the inner Earth.

AuScope has brought VLBI in Australia to a next level, both in globally leading the way of VLBI operations and technical development itself as well as in the scientific results: since the commencement of operations of the AuScope VLBI array in 2010, the accuracy of measured distances across the Australian/New Zealand continent has doubled, from the centimetre-level to a few millimetres.

In this presentation we show that the reasons for this improvement were our efforts in thorough simulation studies to improve observing schedules, i.e. determining in which direction the telescopes need to 'look' at a given time. The AUSTRAL observing program, organised by the VLBI group at the University of Tasmania, features high cadence observing of 24 h duration almost every second day. This is world-wide unique and offers exciting new possibilities for Australia. For example, the new time series allows for a much improved combination with data from Global Navigation Satellite Systems, predominantly GPS. Finally we show how AuScope has enabled the Southern Hemisphere to catch up with the Northern Hemisphere, which has traditionally dominated in the number of VLBI sites and precision of measurements. AuScope has provided an exciting tool to observe the deformation processes of Australia and the whole Earth at the mm-level on time scales of days to years.

## Trace element geochemistry of $\text{TiO}_2$ polymorphs in igneous rocks: an example from the igneous Moorarie Supersuite, Capricorn Orogen, Western Australia

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Rutile ( $\text{TiO}_2$ ) is a common rock-forming mineral that can be found in a variety of metamorphic, sedimentary and, to a lesser degree, igneous rocks. Research into the trace element composition of rutile has yielded a variety of valuable tools; notwithstanding the Nb vs. Cr discrimination plots for provenance studies, partition of HFSE (and in particular Nb and Ta) into rutile during subduction zone magmatism, Zr-in-rutile thermometry as well as increased concentrations (up to ~2 wt%) of elements such as V, W, Sn and Sb in rutile associated with mineralized ore systems. However, the common occurrence of other  $\text{TiO}_2$  polymorphs (anatase and brookite) has the potential to complicate the utilization of rutile as a provenance tracer and/or recognizing distal footprints of ore deposits.

To better characterize the variations in trace element chemistry between the  $\text{TiO}_2$  polymorphs (rutile, anatase and brookite), rocks from the same igneous suite were chosen in order to minimise chemical variations associated with different protoliths and/or metamorphic conditions. Four samples from the Moorarie Supersuite igneous suite were selected for analysis. The intrusion of the Moorarie Supersuite occurred in an intracratonic setting, coeval with the Capricorn Orogeny (ca. 1820 – 1780 Ma). All three polymorphs were identified in our samples, although not together in a single sample. Anatase and brookite were found in a single sample, while rutile alone was found in the remainder of the samples. The textural relationships were examined under the optical microscope and SEM/EDS, while polymorph characterization was carried out using the electron backscatter diffraction (EBSD).

Simultaneous acquisition of trace element geochemistry and U-Pb geochronology was carried out at the Laser Ablation Split Stream (LASS) petrochronology laboratory at the University of California, Santa Barbara — UCSB (Kylander-Clark et al., 2013). The igneous origin for rutile was confirmed by U-Pb geochronology (ca. 1813 – 1799 Ma), while anatase and brookite did not contain any uranium and yielded only common lead compositions. Although brookite was not observed in thin section (it was only present in the heavy mineral separates), anatase is commonly rimmed, or completely enclosed, by ilmenite and shows perfect euhedral crystal habits that we interpret to be of igneous origin.

Trace element compositions were found to be quite different between the  $\text{TiO}_2$  polymorphs, with greatest variations in Fe, Cr, Al, W, Sb, Sn, Zr and Nb. A positive correlation between pentavalent (Nb, Ta) and trivalent (Fe, Al) elements was observed for rutile only and most likely suggests a coupled substitution of  $\text{M}^{5+} + \text{M}^{3+}$   $\text{Ti}^{4+}$ . The discrimination between the  $\text{TiO}_2$  polymorphs was best represented by a combination of elements (Al, Fe, Sb, Cr and W) on a ternary diagram and applies not only to igneous rocks, but for the majority of the rock types (sedimentary and metamorphic). Additionally, as trace elements Fe, Cr, V, W and Sn are commonly used to discriminate rutile from the barren/unmineralized bedrock with that from the ore zones, it is important to recognize the importance of characterizing the type of  $\text{TiO}_2$  polymorph prior to using these ‘pathfinder’ elements to detect distal footprints of mineralized ore systems.

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## The Watershed tungsten deposit (NE Queensland, Australia): Scheelite vein mineralization, alteration and mineral chemistry

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The Watershed deposit is located in far north Queensland, about 100 km northwest of Cairns. It has a combined JORC resource of 49.32 Mt @ 0.14% WO<sub>3</sub> totalling 70,400 tonnes of WO<sub>3</sub>. Watershed lies within the Mossman Orogen, which comprises a folded sequence of Ordovician-Devonian metasediments intruded by Carboniferous-Permian granites of the Kennedy Province. Mineralization is hosted by a sequence of folded slates and, locally calcareous, psammites of the Hodgkinson Formation. In addition, multiple felsic dykes of the Permian S-type Whypalla Supersuite occur cutting the metasediments.

Veining, alteration and mineralization occur in mainly five stages. Stage 0 corresponds to strongly deformed quartz-calcite-mica veins cutting slate units. Stage 1 is a widespread red-green prograde skarn in psammitic units. It is comprise mainly of grossular-spessartine-almandine garnets of up to 2 mm and hedengbergitic-diopsidic pyroxene, and is overprinted by clinzoisite, actinolite-ferroactinolite-magnesiohornblende-tourmaline-biotite-scheelite-calcite retrograde alteration.

The first mineralization event occurred in Stage 2. Mineralisation is hosted in quartzite and fine-grained psammite as sinuous and/or deformed quartz+feldspar+biotite±scheelite±pyrrhotite veins and veinlets. In this stage, scheelite mineralization is not of economic significance. The main alteration mineral in the halo of such veins is biotite.

The most extensive scheelite mineralization occurred in Stage 3, in centimetric halos of quartz–feldspar–scheelite-pyrrhotite and minor arsenopyrite veins. This vein set, with <50 cm wide sinuous to planar E-W striking, S dipping veins, mostly cuts skarn altered psammite breccia, minor quartzite, and granitic dykes (LA-ICP-MS U-Pb zircon age of 300 ± 4 Ma). Additionally, in this stage minor scheelite occurs disseminated in skarn and as coarse grains in granitic dykes. At least six sub-stages are recognized in Stage 3: (3a) early quartz+oligoclase–scheelite assemblage as vein margins (<3 cm wide); (3b) grey quartz-scheelite occupying the centre of the veins. Stage 3c are white quartz veinlets, which cut across previous veins. It is locally cut by calcite stringers of Stage 3d. Stage 3e is defined by muscovite-sericite veins (muscovite <sup>40</sup>Ar/<sup>39</sup>Ar age of 252.9 ± 1.3 Ma) with minor siderite center line. Stage 3f post-dates all previous events, and corresponds to fracture-filling pyrrhotite-arsenopyrite veins.

The latest scheelite mineralization occurred in Stage 4 as quartz-oligoclase-scheelite-minor pyrrhotite veins/veinlets with ‘ladder’ texture. They are <3 cm wide, planar or rarely sinuous. Such veins are typically high-grade. New short-wavelength infra-red (SWIR) spectroscopy shows locally illite crystallinity values up to 8, indicating temperatures of ~350° - 420°C.

The new pre-mineral dyke age of ca. 300 Ma is somewhat 35 Ma older than reported ages for intrusions of the Whypalla Supersuite. Mineralization occurred close to ca. 253 Ma. Garnet compositions confirm the reduced nature of the alteration fluids, and together with the crystal size suggests a hydrothermal origin for the skarn. The illite crystallinity values suggest that high-grade greisen/skarn may be present below the current drilling levels at Watershed.

## Duration of tectonic processes constrained by Lu–Hf garnet geochronology—Insights from HP/LT oceanic rocks (Halilba ı Complex) and Barrovian-type mica-schist (Menderes Massif)

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Garnet has become a key target for geochronological studies. Technical and analytical advances in the past two decades have made garnet geochronology a powerful approach to constrain the evolution of metamorphic rocks. Not only may precise metamorphic dates be obtained from multi-point isochron diagrams but also the tempo of garnet growth can be explored taking account of the scatter in isotopic data or using micro-sampling of large crystals. We used Lu–Hf garnet geochronology to investigate the dynamics of transient tectonic environments related to the closure history of the Neotethys Ocean in western Anatolia.

We studied five garnet-bearing mafic samples from the Halilba ı Complex that record contrasting subduction-related metamorphic evolutions, including pristine lawsonite blueschist, lawsonite–epidote blueschist, lawsonite–epidote blueschist/eclogite, epidote eclogite, and garnet amphibolite (from the overlying subophiolitic metamorphic sole). For each sample, 3–4 garnet separates were analysed for Lu–Hf geochronology. In each sample, garnet batches generally yielded similar two-point matrix–garnet isochrons. In some case, one garnet plots slightly to significantly above the isochrons. We interpret the scatter to be geologically meaningful, reflecting minimal garnet growth intervals. Our results indicate that LP/HT metamorphism at the bottom of the ophiolite took place at 109–104 Ma; “warm” HP metamorphism (epidote eclogite facies) occurred at ~93 Ma; and “cold” HP metamorphism (prograde and retrograde lawsonite blueschist facies) followed from 89 to 86 Ma. Garnet dates thus reveal the progressive, active cooling of a former subduction interface, from its inception to a steady thermal state over ca. 15–20 Myr.

In addition, we studied cm-sized garnet crystals from a mica schist of the southern Menderes Massif. After major and trace element analysis, 4–6 sections along core-to-rim profiles of five crystals were sampled using a micro-saw and analysed for Lu–Hf geochronology. Outcropping conditions did not allow sampling of the matrix of the mica schist. We therefore relied on two-point garnet-only isochrons using the Lu-depleted garnet rims as the lower Lu/Hf point on isochrons. Micro-sampled sections yielded ages that consistently decrease from core to rim, and thus reveal a valuable record of the pace of garnet growth. Lu–Hf dating results indicate continuous growth during prograde metamorphism from  $42.6 \pm 1.9$  and  $34.8 \pm 3.1$  Ma. Extrapolating garnet growth rates suggests that the outer rims formed around  $31 \pm 6$  Ma. Two distinctly older dates ( $58.83 \pm 0.69$  and  $50.16 \pm 0.84$  Ma) were obtained for the core sections of two crystals and might point to early nucleation of these larger garnets. Prograde garnet growth during continental collision therefore occurred over several Myr, possibly >15 Myr.

The pace of tectonic processes was investigated using Lu–Hf garnet geochronology with two different approaches: (i) comparing complementary samples in a subduction complex, and (ii) applying micro-sampling on cm-sized garnet crystals. The active cooling of the subduction interface post-subduction inception, and heating of underplating continental crust in a collisional setting are inferred to last over long periods (likely >15 Myr), as required to allow drastic thermal changes.

## **Stable isotopes from mollusc shells: implications for reconstructing palaeoenvironment, human-environment interaction, and seasonal shellfish foraging**

**A. L. Prendergast**

Stable isotopes from mollusc shells can be used to reconstruct aspects of palaeoenvironment including sea surface temperature, rainfall, air temperature, and vegetation. However, inter and intra-species differences in growth rates, physiology, and environmental responses can cause variations in isotopic profiles. Before stable isotopes are used for palaeoenvironmental reconstruction, modern populations of the proxy species should be examined to understand how isotopic variation in shell carbonate correlates to local environmental conditions. In this paper we present modern calibration studies from eastern Mediterranean marine and terrestrial molluscs. The calibrated proxies are then applied to molluscan samples from eastern Mediterranean Palaeolithic archaeological sites to examine late Quaternary human-environment interaction. We find evidence for fluctuating sea surface temperature and rainfall regimes from MIS 3 to 1 that appear to be linked to northern hemisphere millennial-scale climate oscillations. Obtaining these records from archaeological mollusc shells enables the reconstruction of a more detailed picture of how humans responded to changing climatic regimes in the past.

## Comparisons and contrasts of detrital zircon U-Pb-Hf signatures for the northern and western margins of Neoproterozoic Siberia: tectonic implications for Rodinia break-up

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Siberia's position in Neoproterozoic continental reconstructions is problematic, largely because of a lack of geological data establishing its affinity to other continents. The northern and western margins of Siberia are surrounded by Neoproterozoic to Early Cambrian orogenic belts, but how they related geodynamically to each other and coeval orogenic belts of eastern Baltica and NE Laurentia remains enigmatic.

Neoproterozoic to Early Cambrian sediments of both western and northern Siberian margins reveal ca. 980-800 Ma and ca. 750-600 Ma zircon populations, broadly consistent with ages of the magmatic belts recognized within Taymyr (northern margin), Yenisey Ridge and East Sayan (western margin). To establish cratonic affinities of these coeval Neoproterozoic arc terranes, we compared detrital zircon signatures from pre-accretionary Mesoproterozoic to post-accretionary Neoproterozoic and Cambrian sediments on both sides of the Craton.

Each margin was surrounded by a continental arc at ca. 900-800 Ma, as evidenced by vertical Hf arrays extending Hf (T) values from ~+12 to -10, with the Hf model ages of up to 2.3-2.4 Ga. A peri-Siberian origin for the Early Neoproterozoic Taymyr arc also can be inferred from inheritance of 2.15-2.0 Ga juvenile zircon population, which is abundant in Mesoproterozoic pre-accretionary sedimentary units from the Anabar Shield. In the west, post-accretionary sediments from near Yenisey Ridge retain the 1.86 Ga peak in detrital age spectra that links the basement of the arc terrane to the Angara magmatic belt along the western cratonic edge.

Another accretionary event that occurred at ca. 600 Ma introduced a 750-600 Ma arc-related zircon population and an exotic Mesoproterozoic detrital signature to the platform cover of northern Siberia. The detrital signature of Siberia is significantly different from that of Laurentia and Baltica, because the Siberian cratonic basement incorporates Archean and Paleoproterozoic but not Mesoproterozoic crust. An exotic U-Pb-Hf detrital signature in post-600 Ma sediments of the northern Siberian margin has an affinity to the 750-550 Ma Timanian orogen of eastern Baltica, which locally incorporates metasedimentary basement derived from a Mesoproterozoic orogen. By contrast, along the western Siberian margin, post-accretionary Early Cambrian sediments retain persistent detrital zircon signatures of Siberian basement. eHf values of 750-600 Ma zircons that cluster between +12 and -4 provide an additional evidence that the 750-600 Ma arc was built on the Early Neoproterozoic peri-Siberian arc.

Integration of U-Pb-Hf detrital zircon data and geological records suggest that the northern and western margins of Siberia became active at ca. 970 Ma, likely as an extension of coeval Valhalla orogen that formed on the margin of NE Laurentia. Possibly, at ca. 800-750 Ma, subduction rollback along this margin of Rodinia promoted the rift and drift of Siberia from northern Laurentia and ultimately caused its collision with Baltica at ~600 Ma. By contrast, the western margin of Siberia remained a part of a peri-Siberian accretionary orogen at least until the Early Paleozoic.

## Insights to the geologic evolution of the Thomson Orogen and nature of the deeper crust from isotopic studies of magmatic and inherited zircons.

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Deep basement cores from petroleum and stratigraphic drill holes through central and southwest Queensland show that the subsurface Thomson Orogen is dominated by monotonous metasedimentary units but also includes scattered felsic volcanic rocks and more abundant (locally batholithic-scale) intrusions. These igneous rocks and small granitoid exposures along the Eulo Ridge provide means of probing the deeper crustal composition and the geological evolution of this vast area that is mostly covered by deep sedimentary basins.

In this area, the upper crust is dominated by metasedimentary rocks of the Thomson Orogen, but the composition of the lower crust is unknown. Current hypotheses originating from geophysical interpretation and modelling range from Neoproterozoic oceanic crust to extended Proterozoic continental crust (either the Mount Isa Province or an eastward extension of the Musgrave Province).

To evaluate these hypotheses and to investigate the long term evolution of magmatism in the Thomson Orogen, we used U-Pb, Lu-Hf and O isotopic studies of magmatic and inherited zircons in a collaborative effort between the Geological Survey of Queensland, Geoscience Australia and Queensland University of Technology.

Igneous rocks in this study range in age from mid Cambrian to Late Devonian. Many samples contain inherited zircons that cluster in the 500 – 650 Ma and 900 – 1300 Ma age brackets. These inherited age patterns accord with the main populations identified in detrital zircons from metasedimentary rocks of the Thomson Orogen. This highlights significant metasedimentary input to source magmas and is supported by elevated  $^{18}\text{O}$  values. It is likely that many of the magmas were sourced within or have incorporated varying amounts of Thomson Orogen metasedimentary material.

The few rocks that retain mantle-like  $^{18}\text{O}$  values and therefore may be expected to be reliable indicators of deeper crustal age/composition give two-stage Hf model ages (reflecting crustal growth through addition of juvenile material) of ~1.3 to ~1.4 Ga. This is younger than model ages of hypothesised continental material in the lower crust (e.g. Musgrave Province = ~1.9 Ga; Mount Isa Province = >2 Ga) and older than the suggested age of hypothesised oceanic material in the lower crust (Neoproterozoic to Cambrian). It should be noted however that this is calculated from a limited data set. Igneous rocks with more elevated  $^{18}\text{O}$  values give older model ages of ~1.8 Ga. Rather than reflecting a different lower crustal domain, these likely represent mixing of this 1.3-1.4 Ga age and the various model ages incorporated into the Thomson Orogen metasedimentary rocks.

Excluding the oldest sample (rhyolitic ignimbrite from Adria Downs 1, ~510 Ma), Hf(t) values for the igneous rocks broadly increase over time, trending to more juvenile compositions. We suggest that this trend reflects the dominance of repeated and widespread extension through the Thomson Orogen, the majority of which has remained spatially remote from orogenic zones since at least the Cambrian.

## **Integrated geological, hydrogeological and groundwater modelling assessment of potential impacts of coal seam gas activities: an example from the Clarence-Moreton bioregion**

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The Australian Government has commissioned the Bioregional Assessment (BA) Programme, a scientific analysis that provides a baseline level of information on the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas (CSG) and large coal mining development on water resources. The Clarence-Moreton bioregion (CMB), which covers an area of approximately 25,000 km<sup>2</sup> in north-eastern New South Wales and south-eastern Queensland, was selected as a priority region for the BA due to the presence of confirmed CSG resources. Within the CMB, Triassic to lower Cretaceous sedimentary sequences are present, including several major aquifer-aquitard systems and the Jurassic coal-bearing Walloon Coal Measures. Despite considerable exploration activity for CSG, the hydrodynamics and in particular the hydraulic relationships between aquifers and aquitards ('seals') remain poorly understood.

As part of the Bioregional Assessment Programme, we have developed the first basin-wide 3D geological model of the CMB including alluvial, volcanic and sedimentary bedrock aquifers. Using the 3D geological model, we have examined the major geological characteristics of the CMB, and assessed how these influence groundwater flow processes. The 3D geological model was then used as a framework to assess and visualise basin-wide groundwater recharge and hydrochemical processes, aiming to develop refined conceptual models of groundwater flow processes. This helped to improve the current conceptual understanding of how, and where, different components of the hydrological cycle are likely to interact in the Clarence-Moreton bioregion. Taken together, the 3D geological and hydrogeological conceptual model underpinned the development of a numerical groundwater flow model in a potential CSG development area within the CMB, and allowed an assessment of potential impacts of CSG activities to be undertaken. Furthermore, the 3D geological model provided the model structure for a six layer groundwater model of the Richmond river basin, the area where most recent CSG exploration has occurred.

The integration of 3D geology, hydrochemistry and recharge studies with groundwater numerical modelling in this project helped to remove some of the misconceptions surrounding the link between basin CSG resources and hydrodynamics. Furthermore, this multi-disciplinary approach allowed the reduction in conceptual uncertainties associated with predictions of potential impacts of CSG activities. This assessment will provide a framework for future groundwater modelling studies elsewhere within the CMB.

## The need for integration of ‘everything’: an example from the Condamine River catchment on how consideration of multiple lines of evidence benefits conceptual hydrogeological model development

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The significance of reliable conceptual hydrogeological models, which describe how a hydrogeological system or hydrological processes operate, is increasingly recognised as an integral part of any water resource investigation. Ideally, conceptual hydrogeological models are based on multiple lines of evidence including three-dimensional (3D) geological models, hydrochemistry, recharge assessments and potentiometric maps of key aquifers. However, misconceptions can result when they are based on poorly integrated data or individual lines of evidence. Even after integrating multiple data sources, multiple conceptual hydrogeological models honouring the available data may still be possible, particularly in data scarce areas or regions with complex geology. This will undoubtedly impact the reliability of any predictions or assessments based on a given conceptual hydrogeological model.

One of the major areas in Australia where research into the potential impacts of coal seam gas (CSG) operations on water resources is conducted is the Condamine River. In previous studies, multiple conceptual models considering different groundwater recharge processes and connectivity between alluvial and sedimentary bedrock aquifers have been proposed. Some of these conceptualizations, suggest that there is no or very limited connectivity between alluvial deposits and Walloon Coal Measures (the CSG target). These conceptual models, however, are often based on individual lines of evidence (such as the use of hydrochemistry) without adequate consideration of the broader geological framework, inferred flowpaths or the limitations posed by existing monitoring networks.

In this work, we apply an integrated approach which simultaneously uses multiple lines of evidence to further refine the conceptual understanding on aquifer recharge and connectivity between shallow and deeper aquifers within the Condamine River catchment. The techniques employed include development of a high-resolution 3D geological model, assessment of groundwater recharge, development of potentiometric surface and head gradient maps, and assessment of hydrochemistry.

This newly developed 3D geological model aims to more accurately represent the geometry of both shallow and deep aquifers, which differentiates it from previous model that often focussed on deeper sedimentary bedrock units. A groundwater recharge assessment was conducted using chloride mass balance for volcanic and sedimentary bedrock aquifers and the relationship between rainfall, soils and vegetation for the alluvial aquifers. This was further supplemented by potentiometric surface maps and head gradient maps. Considered together, the application of these different techniques allowed an initial assessment of where a high potential for vertical interaction between shallow and deep aquifers exists. This was then followed by evaluation of the spatial patterns of hydrochemistry to test if there is evidence for aquifer connectivity in these areas.

Overall, the integration of multiple techniques and the refinement of the understanding of aquifer geometry and interfaces between shallow and deep aquifers provided new insights into the connectivity between shallow alluvial and volcanic aquifers and the underlying sedimentary bedrock aquifers. New areas where such connectivity between shallow alluvial aquifers and sedimentary and volcanic bedrock occurs were identified particularly at the eastern margin of the Condamine alluvium. Furthermore, a significantly improved understanding of recharge processes and rates was achieved, which will provide valuable information for future groundwater resource investigations.

## Large discrepancies between garnet Lu-Hf and Sm-Nd isochron ages: the problem of inherited Hf

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A commonly observed phenomenon in garnet geochronology is that Lu-Hf isochron ages are consistently older than Sm-Nd ages from the same sample, a relationship explained by differences in closure temperature and REE zoning that are then used as the basis for constraining mineral growth and/or cooling rates. We report Lu-Hf and Sm-Nd age discrepancies of up to 40 Myr from three samples of garnet-chlorite-magnetite schist from the Walter-Oatalpa Shear Zone, Curnamona Province, South Australia. Lu-Hf and Sm-Nd isochron ages vary between 531-515 Ma and 500-479 Ma, respectively, spanning the entire duration of the 514-490 Ma Delamerian Orogeny. U-Pb monazite ages from matrix-hosted grains are within error of the youngest Sm-Nd ages (c. 480 Ma), whereas monazite inclusions in garnet return age estimates coeval with the oldest Sm-Nd age (c. 500 Ma). LA-ICP-MS trace element mapping reveals that Nd is strongly partitioned into garnet rims for samples with the youngest ages, suggesting that REE zoning biases these estimates towards the latter stages of garnet growth. Conversely, Lu-Hf ages largely reflect Hf distributions that are strongly concentrated in core domains, most likely representing the earlier timing of garnet nucleation in prograde zoned grains.

However, all samples contain zircon present either as a matrix accessory phase or as inclusions in garnet, often as micron-scale grains difficult to detect without detailed SEM/LA-ICP-MS imaging. This calls into question the implicit assumption that the Lu-Hf isochron has an initial gradient of zero, i.e. that the  $^{176}\text{Hf}/^{177}\text{Hf}$  ratio of newly grown garnet is in equilibrium with the whole rock composition. We demonstrate that this assumption is invalid in circumstances where the whole-rock Hf budget is dominated by minerals that do not enter diffusional exchange with garnet, a common occurrence in metapelitic and felsic rocks that contain significant amounts of inherited zircon. Such problems are exacerbated by mineral separation and dissolution techniques that preferentially reduce zircon contamination in garnet relative to the untreated whole rock fraction, systematically skewing the Lu-Hf isochron to an apparent age older than the 'true' age. Furthermore, the moderate metamorphic grade of the Walter-Oatalpa samples (530 °C; 5 kbar) prevents an appeal to diffusion to explain the large Lu-Hf vs. Sm-Nd age discrepancy. As such, it is concluded that the problem of inherited Hf can produce spuriously old ages that falsely suggest a high closure temperature for the Lu-Hf isotopic system and/or an early onset of garnet nucleation. This should urge caution in the interpretation of Lu-Hf data without consideration of potential inheritance effects.

## Timing the Main Central Thrust (MCT) in the Larji-Kullu-Rampur tectonic window, NW India

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The Main Central Thrust (MCT) is a N-dipping crustal-scale shear zone marking the boundary between the Greater Himalaya series in the hanging-wall and the Lesser Himalaya series in the foot-wall. This major shear zone has traditionally been known as a key factor in the evolution of the recumbent folds of the Greater Himalaya. Three of the current widely accepted tectonic models use this shear zone for explaining the tectonic history of the Himalaya. The channel flow model and the wedge extrusion model claim that the Greater Himalaya has been extruded between the MCT and the South Tibetan Detachment system (STD). This implies that the MCT must be coeval with the STD. The Alpine fold-nappe model suggests that the recumbent structures of the Greater Himalaya are the result of overthrusting on the MCT and thus names these folds as fold-nappes. Although the MCT has a leading role in all these models, there is still significant debate as to its age. Therefore, timing the movement on the MCT has important implications in developing a better understanding of the formation of the Himalaya, and as to how the recumbent structures in the Greater Himalaya formed.

The boundary of the Larji-Kullu-Rampur tectonic window in NW India provides a well-preserved series of the rocks overprinted by the MCT. Microstructurally and microchemically focused  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology was applied in this research to investigate the deformational history and to constrain the age of the movement on this part of the MCT. The complex microstructure of the deformed rocks in the MCT zone preserves the main shearing event in the form of inter grain slip and recrystallisation within an older white mica fabric. This shear-related recrystallisation of white mica is more muscovitic and the newly recrystallised zone is sandwiched between selvages of the more phengitic older fabric.  $^{40}\text{Ar}/^{39}\text{Ar}$  geochronology on white mica yielded a relict age limit of >18 Ma (early-Miocene) and an age population at 14-15 Ma (mid-Miocene) that is reached by rising from ca. 8 Ma (late-Miocene). The decussate phengitic fabric maybe relict from earlier metamorphism, and associated with the older age whereas the main activity of the MCT can be constrained to between 15 and 8 Ma. An alternative scenario would be that the main activity occurred at 14-15 Ma followed by a later event at ca. 8 Ma.

Our research showed that the MCT operated much later than the STD (reported as 21-24 Ma). This contradicts the requirement of coeval movement of the MCT and STD that is required in the channel flow and wedge extrusion models. It also disproves the Alpine fold-nappe model in which the Greater Himalaya recumbent folds (represented by Oligocene Phojal fold) formed by thrusting on the MCT over the Lesser Himalaya rocks. This research suggests that the MCT is a Miocene shear zone that postdates the Greater Himalaya recumbent folds.

## U-Th-He Dating of goethite in a “Stalactite-like” iron-rich structure

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A “Stalactite-like”, iron-rich structure with a series of concentric rings from an iron ore mine in the Hamersley Province of Western Australia was petrologically, mineralogically and chemically characterised. The chemical composition of the sample is dominated by Fe, present as goethite. The sample also contains 10% silica occurring as scattered chalcedony and 0.5% alumina mainly concentrated in the outer layers of the sample. Ce, Nd, La and Y were also detected as well as U (3.5 ppm). The sample was sliced and sub-sampled at 5—10mm intervals from core to rim and 4—6 aliquots were analysed using the (U-Th)-/He method. The age of the goethites from the centre of the sample are around 2 Ma. The ages of the goethite in the outer layers varied from 6 to 10 Ma. Analyses from the same ‘ring’ either side of the core yielded the same age. The ages of the goethites measured in the sample are in good agreement with previous dating on channel iron deposit matrix and demonstrate a large, wetter “goethitic” period around 6 to 10 Ma in the Hamersley Province of Western Australia.

## The Great Artesian Basin– mapping the basin architecture and variations in water chemistry

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The Great Artesian Basin (GAB) is Australia's largest groundwater basin in both area and groundwater volume. Recent hydrogeological reviews have provided new insights into our understanding of the regional basin geometry, its hydrostratigraphy and physical characteristics of the rocks and groundwater within the GAB. The new hydrogeological atlas of the GAB presents a compilation of maps documenting key regional geological, hydrogeological and hydrochemical aspects of the basin.

The Atlas draws upon recent work undertaken by Geoscience Australia (GA) in Great Artesian Basin Water Resource Assessment project and the former Carbon Capture and Storage project as well as subsequent new information which has led to refinement of some new concepts and interpretations. Key highlights in the Atlas include a revised basin extent, thickness and outcrop extents of all hydrostratigraphic units of the GAB, geomorphology, a regional watertable map, transpiration evidence for regional leakage, and a basin-wide perspective of the variations of water chemistry in all major aquifers.

The Cadna-owie - Hooray Aquifer and equivalents is the most widespread and shallowest artesian aquifer within the GAB, present in all constituent sub-basins and characterised by extensive peripheral areas of outcrop/subcrop which delineate zones of groundwater recharge. This aquifer descends into the central parts of each sub-basin to depths of 1900 m in the Eromanga Sub-basin, >700 m within the Poolawana Trough and about 700 m in within the southern Mimosa Syncline of the Surat Sub-basin.

Mapping of the regional watertable has revealed subtle features that give an indication of interaction with underlying confined aquifers, as well as groundwater recharge and discharge processes. The watertable contours produced are not smooth like that of the Cadna-owie - Hooray Aquifer and equivalents, but form local recharge mounds extending far into the basin. Some of these recharge mounds are coincident with structures like the Innamincka Dome.

The hydrochemistry maps in the atlas provide insights into regional-scale chemical processes within each of the aquifers. The impact of different aquifer source material on groundwater evolution can be observed, with higher proportions of clay and interbedded siltstones and mudstones south east of the GAB resulting in brackish water in the recharge zones and potentially stagnant flow. One specific example is the effect of microbial methanogenesis via carbonate reduction. A region of highly enriched  $\Delta^{13}\text{C}$  in the dissolved inorganic carbon is found in the deeper, central part of the Surat Sub-basin. This enriched  $\Delta^{13}\text{C}$  signal in the groundwater is coincident with shifts in the water isotope ratio values, low sulphate concentrations, high pH, and the presence of methane gas with a carbonate reduction signature. The enrichment in  $\Delta^{13}\text{C}$  for the dissolved inorganic carbon for this region was previously attributed to marine carbonate dissolution but the new information suggests it is largely due to microbial-mediated carbonate reduction.

The Atlas of the GAB is [available now from the Geoscience Australia website](#) as well as in Hardcover format. It is hoped that the Atlas will contribute to better-informed water management decisions on the GAB

## **AuScope – planning the next decade's investment in Australian Earth and Geospatial Science research infrastructure.**

**Rawling, Tim**

AuScope Ltd

For the last 10 years AuScope Limited has been the primary provider of national scale research infrastructure to support the Australian Earth and Geospatial communities. In this time over \$80M of Federal Government investment has lead to the development of a number of significant pieces of research infrastructure around the country: from the Very Long Baseline Interferometry telescope network to the acquisition of thousands of kilometres of deep reflection seismic profiles, the development of web based data delivery tools in all of the state surveys to the placement of research quality seismometers in secondary school classrooms.

During this time AuScope's funding has primarily come from the federal governments NCRIS and EIF schemes. With the recent announcement of the renewal of the NCRIS scheme for another 10 years there exist exciting opportunities for future large-scale investment in research infrastructure to benefit our communities.

This session is designed to showcase some of the significant highlights of the last 10 years of AuScope activity in our community, but more critically, to outline our vision for future investment over the next ten years. Importantly the roadmap for future investment is still being shaped and during the session there will be opportunity for input and questions from the floor. We will be seeking to stimulate an ongoing community discussion that will impact future investment and impact of AuScope until 2017 and the session will close with a Town Hall style discussion.

Please come along and have your input.

## **Sea Level during Past Warm Periods – Rethinking the Bathtub Model**

**Maureen E. Raymo** and PLIOMAX Project Members.

*Lamont-Doherty Earth Observatory, Columbia University*

Changes in sea level, whether rapid or gradual, influence the style and preservation of shorelines and near-shore features including fossil reefs, paleo-sea cliffs and scarps, as well as intertidal and subtidal facies and biota. Using insight from modern shoreline systems, members of the PLIOMAX project have mapped mid-Pliocene, MIS11, and MIS5e shorelines at numerous localities around the world and modeled the effects of subsequent glacial isostatic adjustment on their current position. For MIS5e we find evidence for a rapid rise in sea level in the later phase of the interglacial, consistent with a collapse of the West Antarctic Ice Sheet. Estimates for maximum sea level during MIS5e, between 6 and 9 m, are in agreement with other studies and imply mass loss from ice sheets at both poles. For MIS11, which appears to have been slightly warmer than MIS5e, our best estimate of sea level rise is 6-13 m, a value subsequently narrowed to 8.512 m. For the Pliocene interval around 3 Ma, we cannot place useful bounds on sea level because shoreline features have been vertically displaced by tens of meters by mantle dynamic topographic changes of uncertain magnitude and, probably to a lesser degree, by flexure associated with sediment redistribution. However, these once horizontal shorelines, which are sometimes hundreds of kilometers long, provide useful targets against which to measure the performance of time-dependent mantle convection models. Ultimately, the paleo shoreline data is telling us that when global climate warming is more than 2°C (relative to pre-industrial, or >1°C relative to today), significant loss of ice occurs at high latitudes, equivalent to a minimum rise in sea level of 6m.

## **Microbial-mediated transformation of gold in temperate European environments**

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The biogeochemical cycling of gold (Au) i.e., solubilisation, mobilisation, and precipitation, which leads to (trans)formation of Au grains, has been demonstrated under a range of environmental conditions in Australia, New Zealand and South America (Reith *et al.* 2012; Reith *et al.* 2013; Shuster *et al.* 2015). These transformations are mediated by microbial biofilm consortia living on Au grain surfaces. In this study we investigate the transformation of Au grains from temperate European sites, where little research has been conducted to link surface morphologies and geomicrobial processes. Gold grains were collected from 33 sites in Germany, Switzerland and UK in a variety of geological/geochemical scenarios ranging from primary epigenetic and hydrothermal deposits as well as glacial, eluvial and alluvial placer deposits. Grain morphologies and compositions were analysed using (focused ion beam)-scanning electron microscopy (FIB-SEM) coupled with X-ray dispersive analysis (EDXA) and electron microprobe analyses (EPMA), respectively, as well as Next Generation Sequencing (NGS), used to assess the composition of biofilm communities. Gold grains from all environments displayed abundant secondary Au morphotypes indicative of Au/Ag dissolution and Au neoformation, e.g., nanoparticles, µ-size crystals and bacteriomorphic Au. Grains from Sulzburg (Germany) display distinct 'spongy' surface and subsurface textures highly indicative of silver (Ag) de-alloying. Secondary nano-particulate, spheroidal and bacteriomorphic Au were particularly abundant on grains from Huebli and Col-de-Plannes (Switzerland), as well as Ochill Hills and Whympton (United Kingdom). At these sites, Au nanoparticles were mostly associated with polymorphic layers composed of microbial cells associated with ferruginous, carbonaceous and siliceous materials. These biofilms consisted of a range of bacterial phyla capable of metal detoxification and metal biomimetic mineralisation. Overall, the further the grains were collected from a primary source, the more biogeochemical transformation had occurred. In conclusion, these results demonstrate that geomicrobial processes play a critical role in the transformation of Au grains in the temperate environments in Germany, Switzerland and UK.

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## Using microbial indicators in mineral exploration: New lessons from Australia

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The discovery of world-class gold (Au) and base metal deposits is becoming increasingly difficult in Australia, because many un(der)explored regions are covered by thick layers of *in situ* and/or transported regolith. An on-going revolution in molecular biology now offers the prospect of using the microbial signatures of these materials to explore for underlying deposits [1].

Weathered materials are highly bio-active zones of the environment hosting large microbial communities of commonly  $>10^9$  cells g<sup>-1</sup>. These communities are primary drivers of C-, N-, S- and P- cycling. They also drive metal cycles, because many metals are used as micro-nutrients and for energy generation. If contents of mobile heavy metals, e.g., Ag, Cu, Au, Ni, Pb, U and Zn, exceed certain thresholds, metals become cytotoxic. This changes the microbial community composition, while some species thrive others decline. Generally, thriving species display an increased capability of dealing with metal toxicity by expressing more genetic metal-resistance determinants. This allows them to detoxify their immediate cell environment, and is commonly also linked to the immobilisation of metals via the formation intra- and extra-cellular biominerals.

Modern molecular techniques (e.g., next generation sequencing and high throughput microarrays) have enabled the generation of highly detailed profiles of compositions and functions of microorganisms inhabiting these metal-anomalous zones, as well as understanding of the genetic pathways that enable organisms to survive in metal enriched environments. Using advanced statistical modelling allows us to link the genetic profiles to geochemical/geological parameters of underlying deposits. In a number of recent Australian studies of soils overlying VMS-, Au-, Pt-, Cu-Au-U- and base deposits microbial communities compositions and abundances of metal-resistance genes were closely linked to the underlying mineralisation, demonstrating that pinpointing underlying ore bodies is feasible using these techniques [2, 3, 4]. To provide a dataset against which these anomalies can be compared the Biomes of Australian Soil Environments (BASE) project is currently underway, with 1400 sites across the Australian continent currently in the database. As this database will keep growing and the price of sequencing will decrease further, these new geobiological tool using easy to obtain surface soils/sediments samples, will provide critical advantages for exploration in covered terrains.

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## **An interdisciplinary approach to constructing models of the lithosphere across the Australia-Antarctica conjugate margin.**

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Terrane boundaries that define orogens separating the West and South Australian Cratons are evident in a number of datasets, including geological, geochemical, geomagnetic anomalies, gravity anomalies and seismic tomography maps. Understanding this architecture is important in constraining the evolution of Proterozoic Australia. It also impacts on the lateral variations of rheology of the underlying lithosphere and asthenosphere of Australia's former neighbour in Gondwana, East Antarctica, and hence on geothermal heat flux, glacial isostatic adjustment and other global climate system observables. Better understanding such systems has the potential to improve national preparedness and international resilience to global changes such as sea-level rise.

This research brings together diverse and disparate datasets that all inform, in different ways, the boundaries and deep structure of ancient cratons and orogens of western and southern Australia. These are constructed in the context of their disposition during the time of the southern hemisphere continents being configured together in the Gondwana supercontinent, i.e. with the overprint of the Pan African orogeny. The datasets that provide the foundation for the new models are seismic tomography maps from Australia and Antarctica. As these are smoothed models, our methodology is to add terrane boundaries informed by the geology and geochemistry of surface observations. We also incorporate information from airborne geophysics and remote sensed data. The methodologies used include changepoint detection and other informatics-based approaches. We thus extract new knowledge from the patterns and changes that occur across the layers in this high-dimensional dataset. We also guide the reconstruction of these boundaries across continental conjugate margin using well-informed plate-reconstructions, including recognition of the diverse Continent-Ocean-Boundary transitional crust along the Australian-Antarctic margin.

We produce families of alternate models of the lithosphere, accessible through a visualisation framework. These provide focus for discussions on alternate tectonic hypotheses, and are also made available for continent scale rheological and seismological simulations. This approach allows a variety of information to be included in a single model, with differently constrained parts of the model being handled with quantitative rigor. Applications of the new candidate models include heat flux calculations, glacial isostatic adjustment studies and will also be of value in sensitivity testing prior to new instrument deployments focussed on continental deep structure. Model suites will be made available to the research communities in interoperable data formats.

## Data Driven Knowledge Discovery for Earth Sciences: Aims and Actions

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The combination of large datasets and contemporary compute power has opened the door for ‘Big Data’ approaches to inform and progress many undertakings in the applied Earth Sciences. Such techniques enable knowledge discovery from large amounts of data in ways that are not possible with small amounts. They afford a distinct new set of predictive and/or pattern detection tools that we should make full use of in the context of the Uncover initiative. Such techniques should, with current compute capabilities, be strongly represented in all 4 Theme areas of Uncover (Characterising the cover, Lithospheric Architecture, 4D Evolution and Metallogeny, Distal Mineral Footprints). Importantly preparatory data assembly tasks, demanding national cooperation across academic, government and commercial stake holders, have not been widely recognised as urgent first steps in the (generally excellent) Uncover Industry Roadmap published by AMIRA in 2015.

This presentation highlights capabilities of machine learning / data analytics providing a summary overview of exemplar machine learning strategies for getting the most from multiple, high-dimensional datasets. The overarching philosophy is ‘the geologist helps the computer helps the geologist’, i.e. domain expert (the geologist) and the compute power combining the complementary strengths of human and machine. To be absolutely explicit, there is never any sense of computers replacing field expertise. Computational results add immense value and can direct the key human input to the areas of greatest impact.

As an applied geoscience community associated with initiatives such as Uncover, we must play our part in defining clearly the aims of the desired knowledge discovery: 1) what *exactly* do we want to predict, or what kinds of patterns might be informative; 2) what data do we need, and how much data is sufficient to undertake the prediction or pattern detection goal; 3) what technologies (data collection and compute) do we have that can be reasonably utilized; 4) how do we manage the data; and 5) how do we communicate the results back to the domain expert such that their ongoing use is effective and a constructive human-computer-human dialogue continues.

Our machine learning approaches may be understood in three stages. Data collection and preparation, computation, and prediction evaluation. Of these, the first stage of data collection and preparation is by far the most challenging. Hence, outstanding actions to be integrated into the Uncover initiative are 1) data assimilation and base assembly; 2) some attempt at standardisation of ongoing inputs; 3) recognition that all data should be collected and archived even if the value of a particular parameter is not immediately evident. As a community, we need to recognise that these priorities can be opaque to those not familiar with ‘Big Data’ techniques. We need all our colleagues from the core-shed to the board room onside for this broad-thinking strategy to have the impact that should undoubtedly result.

## **Monitoring of coal seam gas depressurisation using magnetotellurics**

**Rees, Nigel**, Heinson, Graham, Krieger, Lars, Boren, Goren

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Depressurisation of coal seam gas (CSG) formations causes in-situ fluids to migrate through primary and secondary porosity. Removal of large volumes of water from coal measures reduces the in-situ fluid pressure allowing natural gas to be released from the coal matrix. In principle, changes in fluid distribution within the depressurised lithologies (which may be hundreds of metres thick) will alter the bulk electrical resistivity of such layers. Monitoring of the resistivity from surface magnetotelluric (MT) measurements indicates orientation of fluid flow resulting from depressurisation, which can be mapped in three dimensions and attributed to spatial and temporal variations in permeability. Thus, MT is introduced as a low-cost, low-impact technology that can be used for short- and long-term environmental monitoring. This approach is of significant interest not only for industry in order to optimise production and extraction well locations, but also to regulatory bodies, where a desire for a reliable method for monitoring changes in subsurface fluid distribution allows sound risk assessment of potential environmental hazards.

We report on an industrial field study conducted in Queensland, Australia, in which fifty MT sites along two transects were used to monitor depressurisation over a depth range of 300-700 m at a number of wells. We show a causal link between changes in resistivity and depressurisation of the target formations. The coal matrix shrinks due to the release sorptive gas during depressurisation, resulting in a small increase in bulk permeability. This increase in permeability enables conductive fluids held within the matrix to connect resulting in a small drop in bulk resistivity. Such changes in resistivity can thus be used as a proxy for fluid-flow allowing a determination of areas with greater permeability and hence production capacity.

## **A mobile app for geological/geochemical field data acquisition**

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We have developed a geochemical sampling application for use on Android tablets and phones. This app was developed together with the Field Acquired Information Management Systems (FAIMS) at Macquarie University and is based on the open source FAIMS mobile platform, which was originally designed for archaeological field data collection. The FAIMS mobile platform has proved valuable for hydrogeochemical, biogeochemical, soil and rock sample collection due to the ability to customise data collection methodologies for any field research.

The module we commissioned allows for using inbuilt or external GPS to locate sample points, it incorporates standard and incremental sampling names which can be easily fed into the International Geo-Sample Number (IGSN). Sampling can be documented not only in metadata, but also accompanied by photographic documentation and sketches. The module is augmented by dropdown menus for fields specific for each sample type and user defined tags. The module also provides users with an overview of all records from a field campaign in a records viewer. We also use basic mapping functionality, showing the current location, sampled points overlaid on preloaded rasters, and allows for drawing of points and simple polygons to be later exported as shape files.

A particular challenge is the remoteness of the sampling locations, hundreds of kilometres away from network access. The first trial raised the issue of backup without access to the internet, so in collaboration with the FAIMS team and Solutions First, we commissioned a vehicle mounted portable server. The server installed in our field vehicle allowed us to back up, completely automatically, any data we collected while in the field, it has an uninterruptible power supply that can run for up to 45 minutes when the vehicle is turned off, and a 1TB hard drive for storage of all data and photographs. The server can be logged into via any of the field tablets or laptop to download all the data collected to date or to just view it on the server.

## Real time fluid chemistry: applications for drilling optimisation and early detection

**Reid, Nathan<sup>1</sup>, Gray, David<sup>1</sup>, and Gazley, Michael<sup>1</sup>.**

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Drill fluid chemistry is complicated. It is an amalgamation of the fluid introduced to the hole, additives, input or loss to aquifers, and input or loss of elements to the solid material being drilled. However, the fluid is a critical part of the drilling process with large costs involved in maintaining its cleanliness to optimise drilling speed and core recovery. This project provides real-time analysis of drilling fluids to provide fast feedback about drilling muds, cover/rock geochemistry and opportunities for drill optimisation.

The requirements for this new technology were split into three focus areas: (1) early detection (aquifer interception and drill bit wear); (2) monitoring/managing the drilling fluids; and (3) exploration hydrogeochemistry. Each of the three focus areas had different requirements in terms of critical elements, and the detection limits required for those elements. There is also significant overlap in elements which provide information for several purposes, for example, a sulfide sensor can be useful in the detection of sulfide mineralisation, but it also provides information about the decay of sulfonated polymer additives that break-down to sulfide with time.

The development of a working sensor array prototype has required several critical steps before useful chemical data can be presented to drillers and/or geologists. These steps include sample collection and handling (how fluid is presented to the sensors without abrading or clogging the system), data acquisition and data capture, and finally data interpretation and presentation. Ion selective electrode sensors have been chosen for this prototype based on their robustness, ease of use, limited interferences, ease of interpretation and applicability to the three focus areas. Other sensors could be added to the prototype over time as improvements in filtration and data interpretation algorithms are developed.

The testing has highlighted the need for information about sources of contamination, such as from the wearing of tungsten carbide drill bits, which have the potential to be detected as mineralisation and can damage some sensors.

A prototype system has been deployed to the Mineral Systems Drilling Program in South Australia where 12 sensors collected data every 30 seconds for ~2500 m of diamond drilling. The data has shown when different additives are added to the system and when they have been consumed (which could lead to optimisation). It clearly shows the quality of the fluids over time, and there are indications that geological information can be extracted, which can be directly correlated with the drill core.

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## Can drilling fluids be used as a mineral exploration sampling medium?

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The northern Yilgarn hydrogeochemical mapping project showed evidence of large-scale (4-8 km spacing) signatures in groundwater chemistry related to lithology, as well as Au and U mineralisation. The aim of this project was to change the field sampling paradigm by testing whether information about the changes in lithology or fluid composition could be seen in drilling fluids.

Groundwater geochemistry can show broader signatures than other sample media (drill core), as the chemistry is influenced by immediate contact with rocks as well as other materials which have previously contacted the groundwater. Drilling fluids are a combination medium, comprised of: the fluids used to aid the drilling (usually mains or bore water) with various additives; they can also incorporate any aquifers that are passed through in the drilling; and, the material that is being drilled through if it is possible to dissolve some of that fine material in the time it takes to collect the sample.

As such, the deconvolution of these signatures is important to understanding whether this sample medium can provide useful information about the host rock or the groundwater chemistry. One of the major challenges that has been identified, is the contamination from the drilling additives and from the wearing down of the drill bit. This can introduce large concentrations of elements such as W, Ag, Cu, Zn, Mo, S and N into the fluid, and under the right conditions these elements remain in solution. For example, regional groundwaters in the northern Yilgarn Craton, Western Australia, display W anomalism around Au ore bodies, and the magnitude of this anomalism is in the 10's of ppb, in drilling fluids the background concentrations of W can be in the 100's of ppb and up to ppm levels when hard rock is drilled or when a new bit is broken in. This W is in solution as can be seen from Na<sub>2</sub>O<sub>4</sub>W crystals which form in the solution after filtration through a 0.45 µm filter paper. Knowledge of this contamination means that contaminated elements can be avoided and only those which are not affected can be used for geological information.

This research can lead to faster decision making during a drilling campaign by providing fast feedback on fluid parameters. This could ultimately reduce the cost of drilling and increase the speed of detection of deposit footprints under cover.

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## Mineral prospectivity and $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology of Proterozoic mobile belts: an example from the Gawler Craton

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Hematite breccia style iron oxide-copper-gold (IOCG) mineralisation is an upper crustal phenomena, as exemplified by the Olympic Dam deposit, eastern Gawler Craton. IOCG mineralisation occurs where meteoric waters mix with fertile magmatic waters associated with sub-volcanic intrusions, within zones of active deformation. Where changes in fluid chemistry (e.g. oxidation) occurs, this can lead to brecciation and sulphide mineralisation. In addition to widespread iron oxide alteration, key indicators of prospectivity for IOCG systems include syn-magmatic deformation to focus regional fluid systems and the preservation of shallow crustal levels from the time of the mineralisation event.

The presence of syn-mineralisation volcanic sequences in the central Gawler Craton suggests this region was at relatively shallow crustal levels at the critical time (c. 1590 Ma). Large swathes of the western and northern Gawler Craton, however, lack volcanic rocks and are instead dominated by Palaeoproterozoic gneisses. Previously published and new  $^{40}\text{Ar}/^{39}\text{Ar}$  ages from biotite and K-feldspar from these gneisses are c. 1640–1560 Ma, supporting the notion that some areas within this region cooled below ~300 °C before the c. 1590 Ma mineralisation event. Assuming a 30 °C.km<sup>-1</sup> geotherm, these gneisses were <10km deep at the time; possibly much less given the likely higher thermal gradient. A sericite  $^{40}\text{Ar}/^{39}\text{Ar}$  age of c. 1590 Ma from an altered granite in a drill hole southeast of Prominent Hill Mine, is evidence for fluid flow at the time of the mineralisation event, in a region otherwise lacking indicators of this event. In contrast, biotite from a sample of sheared granites west and southwest of Prominent Hill has  $^{40}\text{Ar}/^{39}\text{Ar}$  ages c. 1575–1560 Ma, suggesting post-1590 Ma cooling related to deformation. Adjacent gneisses preserve c. 1640 Ma biotite ages. Although thermochronology data is relatively sparse, the emerging pattern is that: (i) cooling was domainal within shear zone bound blocks, (ii) deformation within shear zones continued post-1570 Ma, and (iii) regions of altered c. 1590 Ma upper crust are preserved, enhancing prospectivity for IOCG and related styles of mineralisation in these areas.

In general, mobile belts adjacent Archaean cratons are prospective regions for a variety of mineralisation styles since they are sites of reworking of deep Archaean crust and, potentially, mantle lithosphere. Shear zones that connect to the mantle, such as in the deep crust below Olympic Dam, likely provide pathways that tap the mantle during magmatic and deformation events, which can lead to the formation of ore deposits.  $^{40}\text{Ar}/^{39}\text{Ar}$  thermochronology can be used to provide constraints on the timing of movement along crustal scale shear zones and is a proxy for crustal depth through time. Such thermochronological data can determine cooling history and style, and can be indicative of the preservation potential for mineral deposits formed at specific crustal levels within a given region.

## The evolution of submarine basaltic volcanoes

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Exceptional resolution three-dimensional seismic data from the Bass Basin, offshore southern Australia, reveals the evolution of ancient submarine volcanoes constructed in 90–140 m of water. Analysis of well log data and seismic facies indicate that they are monogenetic tuff cones composed of fragmental volcanic rock and range in volume from 0.1–1.1 km<sup>3</sup>. The cones are constructed atop features interpreted as pillow-lava volcanoes. These in turn are built on top of maar- and diatreme-like edifices. The data indicate that these tuff cones, which are commonly associated with Surtseyan activity, represent the late-stage features of eruptions that varied from explosive to effusive in nature. This challenges the assumption that the early stages of emergent tuff cone growth are associated with explosive eruptions above the seabed. We suggest that the initial stages of submarine eruptions may also be characterised by sub-seabed explosions. Our understanding of submarine volcanism has therefore previously been biased towards emergent, constructional landforms such as tuff cones.

## **Structure and dynamics of the Curnamona Province and Flinders Ranges from the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP)**

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A total of 74 long period magnetotelluric stations were used for 3D modelling of the electrical resistivity structure across the Neoproterozoic Flinders Ranges and adjacent Paleo-Mesoproterozoic Curnamona Province. This dataset is part of the greater Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP), which has an eventual outcome of covering Australia with MT sites at 0.5 degree site spacing (~55 km), to image the subsurface down to hundreds of kilometres.

We present the results of the first three-dimensional magnetotelluric inversion to image the Flinders Conductive Anomaly (FCA), previously identified from many geomagnetic depth sounding (GDS) surveys conducted within our survey region. The FCA runs north-south through the Curnamona Province, and then follows the axis of the Nackara Arc, snaking to the southwest toward Adelaide. The inversions were performed using the software ModEM, and reveal a relatively resistive lithosphere beneath the Flinders Ranges, with two parallel conductive bands of width ~50 km each, length ~300-400 km, located in, and following the axis of, the Nackara Arc. These conductors span depths of about 20-60 km, and run on either side of the previously interpreted Flinders Conductivity Anomaly. The Nackara Arc is mechanically weakened from the multiple rift episodes that have occurred in the last ~820 Ma, and is host to diamondiferous kimberlites that have erupted through the weakened crust in the Jurassic. The conductors are interpreted to be the result of an enriched crust from rifting, where magmatism never surpassed its early stages, thus retaining some fertile elements. The easternmost of the two conductors runs along the eastern edge of the Nackara Arc and appears to be a major lithospheric feature at the transition from Proterozoic Australia in the west to Phanerozoic Australia in the east.

The previous GDS surveys predict the northern extension of this anomaly to run in a north-south direction up into the Curnamona Province. We indeed observe a conductor here, however, it appears likely that this conductor is not actually attached to the conductor within the Nackara Arc. A large portion of the Curnamona Province exhibits very high conductivities (at depths of 5-30 kms) for a region thought to have a cratonic core with Delamerian Orogeny-related reworking only at its edges. We suggest that fluids, perhaps those associated with ancient subduction of the Olarian or Delamerian Orogeny, have pervasively modified the crust, resulting in an enrichment of carbon and sulphides, a signature that has been retained for at least half a billion years.

An additional topic of interest within the Flinders Ranges is the cause of the intraplate earthquakes. A recent interpretation suggested high pore fluid pressure in the ductile mid-lower crust causing brittle failure. From our model, we do not see any significant correlation of conductive regions and clusters of earthquakes, indicating that at a large scale (at least tens of kilometres), fluids do not seem to play a significant role in the seismicity. However, due to our large station spacing, we are unable to comment on a fluid-earthquake relation at any smaller scale.

## The electrical resistivity of the Delamerian and Lachlan Orogenes of Victoria using magnetotellurics

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The passive electromagnetic method of magnetotellurics (MT) was used to image the lithosphere beneath the Delamerian and Lachlan Orogenies in Victoria, Australia. Three adjoining east-west broadband (0.001-2 000 s) MT transects were collected over this region since 2012. Combined they are 450 km in length, following deep crustal seismic lines collected in 2006-2011. The transitional boundary between the orogenes runs along the Stawell Zone with geochemistry suggesting this region changed from being an extended continental passive margin during the Proterozoic into an Andean-style subduction margin in the Cambrian.

Mineralised copper porphyry prospects were discovered in the Grampians-Stavely Zone in the 1970's-late 1990's which is above this possible subduction zone. Lack of confidence about the geological setting at the time of the discoveries meant that the near surface distal propylitic alteration was never followed up with deeper drilling to test for potentially better mineralized potassiac alteration. The fact that Andean style subduction margins can host large deposits provides a good economic reason for better understanding the geological evolution of this region- and the porphyries.

A distinct change in resistivity structure is observed from phase tensor ellipses at crust to upper mantle depths across the transition from the Delamerian to Lachlan Orogen. The location of this change coincides with the Mortlake Discontinuity, a previously observed change in Sr and Pb isotopic chemistries of Pliocene to Recent intraplate basalts of the Newer Volcanics. The discontinuity was interpreted to reflect either differences in the geochemistry of the mantle source of the basalts, or the degree of crustal contamination. The resistivity variation across the discontinuity extends down into the upper mantle, so the MT supports the differing mantle source hypothesis. These mantle differences could exist because the Delamerian was a region of thinned Proterozoic continental lithosphere whilst the western Lachlan was floored by (now deformed) Cambrian oceanic lithosphere.

Resulting electrical resistivity models from 2D inversions of the MT profile reveal the mantle to be more conductive beneath the Stawell Zone, with conductive pathways emanating up from this mantle up into the crust, with the mid-crustal region being the most conductive. The mid crustal conductive region has been suggested as serpentised sea floor basalt and pyrrhotitic black shales that lie along the interface between the basaltic lower crust and the quartz turbidites of the upper crust, however the deeper conductivity needs other explanations. In modern day subduction zones, serpentinisation of mafic rocks by fluid flux enhances conductivity significantly through the creation of magnetite. The MT may be imaging the ancient analogue of this with the conductive pathways from the mantle possibly mapping fossil alteration zones and serpentinisation associated with dehydration and fluid and partial melt from the subducted Cambrian slab. To investigate the complex resistivity of the Stawell Zone in the third dimension, a parallel MT transect is planned for this year. These two detailed broadband lines can then provide detailed control to complement the long period data from AusLAMP (Australian Lithospheric Architecture Magnetotelluric Project) collected in a large array over this region with much coarser spacing.

## **Geotourism, Geotrails and Geoparks – Pathways for Future Development in Australia**

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The serious pursuit of ecotourism in Australia was ‘kick started’ nearly 25 years ago through the establishment of Ecotourism Australia Ltd which now represents some 500 operators in Australia. Whilst the potential for geotourism, a related field of ‘nature based’ tourism was first recognised in Australia in 1996 through presentations to the 1996 AESC, the concept was only conceptualised locally by the convening in Western Australia of a Global Geotourism Conference in 2008, with the subsequent establishment of geotourism constituency groupings firstly by the Geological Society of Australia in 2011, and then by Ecotourism Australia through the creation of the Geotourism Forum in November 2013.

As well as noting the rapid emergence and growth of geoparks overseas, in Australia however, the concept of ‘geotrails’ is thought to offer, as a first step, a universally acceptable mechanism for delivering deliver geotourism experiences through a journey linked by an area’s geology and landscape ‘as the basis for providing visitor engagement, learning and enjoyment’. Geotrails can offer the advantages of relating directly to the tourism experience of a journey linking destinations and should incorporate and package in the biodiversity and cultural components (including mining heritage) of the region through which the geotrail traverses.

For geotourism to reach its potential nationally, new pathways for development such as geotrails need to be implemented, having regard to government interest in nurturing regional development and new job creation through celebrating geotourism, geological and mining heritage. The Australian Government’s Australian National Landscapes Programme and the development of a range of existing and proposed geotrail projects which offer exciting new opportunities for geotourism growth, whilst not overlooking Australia’s extensive protected areas as venues for enhancing geological and landscape interpretation and education as part of the overall ‘nature-based’ tourism mix. Ultimately, it is envisaged that geopark proposals will emerge, but with the full backing and support of state/ territory governments.

A recent submission to the Chief Government Geologists Committee, prepared by the Geotourism Standing Committee of the Geological Society of Australia (GSA), has detailed recent geotourism developments in Australia, explaining both the geopark and geotrail concepts, as well as explaining what the potential of the geotourism industry offers for employing geoscientists, and for becoming an important customer for the goods and services of geological surveys of Australia and their equivalents. This submission has been supported by the Australian Geoscience Council.

Geotourism offers another benefit by raising public interest in geoscience, particularly as a means of encouraging young people to see that a career path based on a geoscience qualification can open up a wider range of future employment opportunities. Based on the anecdotal observations of travellers enjoying a quality geotourism experience ‘in the field’, it is now being recognised that the educative (and ‘excitement’) value greatly augments the more traditional experiences such as offered by special exhibitions and by natural history museums

## The Blue Mountains and Jenolan Caves Geotourism Revival

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The Greater Blue Mountains World Heritage Area and the Jenolan Caves Karst Conservation Reserve can arguably claim recognition as Australia's earliest global geotourism attraction since European settlement. In 1997, the Geological Survey of New South Wales (GSNSW) published 'The Layers of Time', a popular handbook which has celebrated this world-famous landscape now recognised as one of Australia's 16 iconic National Landscapes.

The Greater Blue Mountains World Heritage Area (dedicated in November 2000) is an accessible wilderness, covering more than one million hectares of rainforest, canyons, eucalypt forest and heath lands west of Sydney. The Blue Mountains is a sandstone plateau of Triassic Age which shelters a rich diversity of fauna and flora, including a number of ancient plant species, the most famous of which is the Wollemi Pine. The geology and geomorphology of this World Heritage Area, which includes 300 metre cliffs, slot canyons and waterfalls, provides the physical conditions and visual backdrop to support outstanding biological values. The property includes large areas of accessible wilderness surrounding now closely settled suburban areas managed by the Blue Mountains City Council. Its exceptional biodiversity values are complemented by numerous others, including Indigenous and post-European-settlement cultural values, geodiversity, water production, wilderness, recreation and natural beauty.

In recent years, geotourism development efforts in New South Wales have been inspired by two symposia organised by the Linnean Society of NSW at Port Macquarie in 2010 and at Jenolan Caves in 2013. Resulting from the latter event, this imperative has led to the construction of a geotour which links Jenolan Caves through visits to the World Heritage Exhibition Centre in the Blue Mountains Botanic Garden at Mt Tomah and the Blue Mountains Cultural Centre (managed by the Blue Mountains City Council). The geotour also includes visits to exemplary geosites including the iconic Triassic sandstone landscapes at Govetts Leap and Echo Point as well as the sandstone escarpment and underlying Permian coal measure exposures in Jamison Valley, accessed by the steepest passenger railway in the world.

The geotour has also highlighted links to the oil shale mining heritage exposed in the historic precinct of Hartley Vale, located beneath the western escarpment of the Blue Mountains and includes a visit to the Silurian karst landscapes encompassing Jenolan Caves. Staying overnight in heritage accommodation, the experience of the Jenolan Caves includes guided tours and encounters with wildlife including Platypus and other wildlife including Eastern Grey Kangaroos.

This geotour was first experienced in 2015 as a post conference tour organised for the American Association of Petroleum Geologists, and co-led by Dr Ian Percival of GSNSW). The ideas explored during this exercise have now led to a concept of developing a broader 'Sydney Basin Geotrail' (linking the botanical gardens at Mt Tomah with its sister facilities at Mt Annan and Sydney and Centennial parklands), a project now being scoped out by various land management government agencies including the GSNSW, a university earth sciences school in Sydney, with guidance being afforded by the GSA Geotourism Standing Committee.

## Harnessing nitrate-enriched groundwater for the regulation of 'low-acid' sulfide oxidation

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Acid drainage (AMD/ARD) is undoubtedly one of the largest environmental, legislative and economic challenges facing the mining industry. In Australia alone, at least \$60m is spent on AMD related issues annually, and the global cost is estimated to be in the order of tens of billions \$US. Furthermore, the challenge of safely and economically storing or treating sulfidic wastes will likely intensify because of the trend towards larger mines that process increasingly higher volumes of lower grade ores and the associated sulfidic wastes and lower profit margins.

While the challenge of managing potentially acid forming (PAF) wastes will likely intensify, the industrial approaches to preventing acid production or ameliorating the effects has stagnated for decades. Conventionally, PAF waste is segregated and encapsulated in non-PAF tips to limit access to atmospheric oxygen. Two key limitations of the 'cap and cover' approach are: 1) the hazard (PAF) is not actually removed; only the pollutant linkage is severed; and, 2) these engineered structures are susceptible to physical failure in short-to-medium term, potentially re-establishing that pollutant linkage.

In an effort to address these concerns, CSIRO is investigating a passive, 'low-acid' oxidation mechanism for sulfide treatment, which can potentially produce one quarter as much acidity compared with pyrite oxidation under atmospheric oxygen. This 'low-acid' mechanism relies on nitrate, rather than oxygen, as the primary electron acceptor and the activity of specifically cultured chemolithoautotrophic bacteria and archaea communities. This research was prompted by the observation that, in deeply weathered terrains of Australia, shallow (oxic to sub-oxic) groundwater contacting weathering sulfides are commonly inconsistent with the geochemical conditions produced by ARD. One key characteristic of these aquifers is the natural abundance of nitrate on a regional scale, which becomes depleted around the sulfide bodies, and where pH remains neutral.

The "low-acid" oxidation of sulfides with nitrate as an electron acceptor has been demonstrated at the laboratory scale. In 90-day microcosm respirometry experiments, we exposed a mixture of pulverized quartz and pyrite-rich ore to natural, high-nitrate groundwater and inoculated the microcosms with a culture of aerobic and anaerobic nitrate-dependent iron and sulfur-oxidising microorganisms, which were enriched from ore, groundwater and activated waste water. Incubations were performed under both oxic and anoxic conditions, in addition to abiotic controls. Initial results show that oxidation of the sulfides under nitrate-rich and microbially enhanced conditions does produce less acid than the same material under oxic conditions, and to some degree can match the models as long as oxygen ingress can be controlled. These results are the focus of further research into how this process can be enhanced and whether it can be applied in the field.

Nitrate-driven oxidation of sulfides could potentially be used as a new approach to reduce acid generation and leaching of contaminants from waste dumps, in a passive or actively managed process designed to deplete and/or ameliorate (i.e. through surface passivation) the mineralogical hazard. Developing our understanding of biological aspects of these processes may also allow testing of longer-term "bio-caps" for various tailings and dump materials.

## Sulfur-accumulating plants: fixing soluble sulfur as recalcitrant biominerals

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We present insights on sulfur-accumulating plants (thiophores) from the Australian Great Sandy Desert, which accumulate up to 40 times as much sulfur (2-5 %S) compared with other species sharing their habitat, and develop gypsum-like mineralisation throughout their foliage. This mineralisation could provide a mechanism by which sulfate can be removed from soils and sequestered as 'biominerals', pointing to these plants as potential revegetation or phytostabilisation tools for remediating reactive sulfur-enriched substrates (e.g. mine tailings, acid-sulfate soils). However, the usefulness of this mineralisation depends how these plants internally store and cycle the sulfur and calcium (i.e. do they treat the excess as a limiting nutrient or waste?) and how resilient these biominerals are to photo-biodegradation once shed to ground litter.

Field studies were designed to address these questions: We sampled healthy mature phyllodes, senescent phyllodes on the branch, recently shed and older, more degraded ground litter from ten individuals of the thiophore, *Acacia bivenosa*. Additionally, two thiophores (*A. bivenosa*, *A. roborum*) and a non-thiophore comparator (*A. ancistrocarpa*) were selected for detailed soil/regolith studies: We sampled soils from trenches bisected by each tree, collecting material at varying depth (20-500 mm) and distance from the stem (0.1-5 m). Dried foliage was cleaned, sectioned for SEM-EDXS examination and the elemental compositions of foliage and soils were determined using microwave-assisted acid digestion and ICP-OES/MS.

Each species generated a 'halo' of elevated S/Ca in the soil immediately beneath their crowns, anomalies which were confined to shallow soil (20-50 mm) that likely contained leaf litter fragments, suggesting limited S/Ca re-mobilisation from the litter down the soil profile. By assessing foliar elemental concentration ratios, which indicate relative variations in composition through the litter cycle (healthy > senescent > fresh litter > degraded litter), it was possible to observe that limiting nutrients were recovered from senescenting phyllodes: P (0.38 ± 0.13), Zn (0.59 ± 0.24), Mo (0.71 ± 0.28), Mg (0.86 ± 0.13) and that non-limiting or potentially toxic elements were hyper-deposited in senescent tissues: Ba (1.29 ± 0.22), Ca (1.17 ± 0.08), Co (1.33 ± 0.33), Fe (1.49 ± 0.59) and Mn (1.39 ± 0.49). Despite this evidence for both nutrient recovery and waste removal behaviour, sulfur remained effectively constant (1.08 ± 0.12), suggesting that these thiophores do not regulate sulfur as a limiting nutrient nor actively hyper-deposit the mineralisation to tissues that will be shed, which would constitute an active physiological response to avoiding S/Ca toxicosis, akin to how halophytes tolerate saline soils. Chemical and mineralogical data demonstrate that, whilst some elements (K, Mg, P) were leached from the litter through photo-biodegradation, sulfur (0.91 ± 0.12) and calcium (0.99 ± 0.09) were retained as extensive gypsum-like mineralisation, even in the oldest litter fractions.

These findings show that thiophores can bioconcentrate sulfur several hundred times from soils into their foliage and return that sulfur to the soil as a tissue-encapsulated, sparingly soluble mineral that is recalcitrant to photo-biodegradation under semi-arid climates. These traits show the potential of these plants for restoring or treating degraded soils and polluted substrata.

## **A palaeo-perspective on climate sensitivity**

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Estimates of climate sensitivity from palaeoclimate data have been clouded by issues of definition and terminology. I will present a scheme that minimises these issues and leads to values that are both comparable between observational palaeoclimate studies, and formally comparable with specific estimates from climate modelling studies. I will discuss examples for the Pleistocene, Pliocene, and the general Cenozoic, which all reveal remarkably similar values. I will then evaluate the challenges we face in trying to improve on these estimates – can we narrow the long tails of the probability distribution? Finally, I will use the palaeoclimate perspective to outline a longer-term context to the climate change targets agreed at the 2015 Paris Climate Conference (COP21). This longer-term context includes the climate change due to slow feedbacks that we are inevitably committed to already; even if we stopped all emissions today. It is not a pretty picture.

## Identification and characterisation of extremely low-concentration non-target components in copper ores and concentrates

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Mesoproterozoic copper ores in South Australia contain low to moderate concentrations of uranium, representing either a potential economic by-product - or an unwanted contaminant - depending on concentration. The daughter products of uranium decay, including the short half-life  $\beta$ -emitters,  $^{210}\text{Po}$  and  $^{210}\text{Pb}$  (hereafter  $^{210}\text{RN}$ ), are present within the parent orebody at extremely low concentrations. Over geologic time, substantially different physical behaviours of U and its daughters may result in spatial and chemical decoupling as a result of fluid- and pore-driven migration. Remarkably little reliable information is currently available regarding mineralogical hosts for  $^{210}\text{RN}$  in any solid media, thus making the search for  $^{210}\text{RN}$  in complex, fine-grained ores or concentrates a major challenge. Identification and characterisation of mineral hosts for  $^{210}\text{RN}$  are, however, essential to guide attempts to eliminate or reduce unwanted  $^{210}\text{RN}$  in industrial copper concentrates. These are the overarching goals of the Australian Copper-Uranium Transformation Research Hub.

Concentrations of  $^{210}\text{RN}$  are so low (< parts-per-trillion) that they cannot be measured directly by conventional microanalytical methods. Bulk measurements of mill feed and concentrates give quantitative abundances, but no information on specific mineral hosting (or lack of hosting, in the potential case of liberated nanoparticles) of  $^{210}\text{RN}$ . High-resolution scanning electron microscopy (SEM) provides detailed mineralogy of concentrates down to ~1 micron, but fails to discern if our target radionuclides are in solid solution in a mineral or exist as discrete nanoparticles within grain boundaries.

Our solution is to use a multi-faceted approach, starting with new techniques designed to accurately track the location of  $\beta$ -emitters in-situ within a polished thin section. Once areas likely to contain  $^{210}\text{RN}$  are located, ca. 10 x 30  $\mu\text{m}$ -sized slices are extracted in-situ from the section using focussed-ion-beam SEM and prepared as thin foils for transmission electron microscopy (TEM), permitting visualization of, and compositional data on the smallest particles of interest.

Thus far we have identified several potential  $^{210}\text{RN}$  hosts, including <5  $\mu\text{m}$  crystals of galena and its selenide and telluride analogues (clausthalite and altaite.) Subordinate hosts may include barite and other sulphates, iron oxides and hydroxides, and various rare earth element-bearing minerals known to contain uranium and lead.

## Geodynamics of the Tasmanides: accretion vs. bending

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The Tasmanides constitute the eastern third of the Australian continent and its origin has traditionally been attributed to Palaeozoic subduction and accretion processes along the active margins of eastern Gondwana. Nonetheless, there is only limited evidence supporting the idea that terrane accretion played a major role during Tasmanide orogenesis, thus raising questions on the fundamental processes that drove deformation and crustal growth. The recognition of oroclinal structures (curved orogenic segments) may provide a crucial insight into this problem.

In the New England Orogen, a series of tight oroclinal structures developed in the Early Permian (299-272 Ma), during a period that was dominated by crustal extension. Our structural, palaeomagnetic and geochronological results show that at the time of oroclinal bending, rocks were positioned in an extensional backarc region that was likely associated with a retreating subduction zone. The oroclines, therefore, likely represent the overriding-plate expression of plate boundary curvatures in response to trench retreat and subduction segmentation.

Similar types of tectonic processes, which involve a substantial mobility of plate boundaries and slab segmentation, have recently been proposed also for the Lachlan Orogen (Moersi et al., 2014, *Nature*, 508, 245-248). We further propose that ~E-W crustal-scale lineaments along the Thomson-Lachlan boundary may represent a segment of a larger oroclinal structure, possibly connected to the Delamerian Belt in the southwest and to the Anakie Inlier in the northeast. If so, orocline formation must have initiated relatively early in the development of the Tasmanides (i.e., in the Neoproterozoic or Cambrian), segmenting the northern and southern Tasmanides, and providing pre-existing geometrical heterogeneities that would eventually trigger and amplify the formation of second order oroclines.

## Lake variability in Lützow-Holm Bay, East Antarctica, inferred from fossil diatoms

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Decadal-centennial scale climate variability in coastal Antarctica remains poorly understood due to the limited number of highly resolved, well dated records. Here we present a 900 year, decadal scale reconstruction based on sedimentary diatom analyses from Lake Abi in the Skarvsnes Foreland of Lützow-Holm Bay, East Antarctica. Hydrological change is inferred based on the ecology of key diatom taxa, in conjunction with a previously published regional training set which implies that water depth, nitrogen availability and lake water specific conductivity are the key variables that drive changes in diatom community assemblage. Our data suggest that Lake Abi underwent a series of subtle environmental changes related to these environmental variables, possibly driven by changes in catchment snow melt and the duration of seasonal ice cover. Detrended correspondence analysis and canonical correspondence analysis are used to trace the major patterns of change in the diatom community, with notable shifts identified between 470-400 and at ~350 calibrated years before present (cal a BP; where present = CE 1950). These patterns corroborate a regionally calibrated diatom inferred conductivity reconstruction, although the magnitude of change within that reconstruction falls within the bounds of prediction uncertainty. The frequency of environmental variability at Lake Abi is broadly consistent with a record of the Interdecadal Pacific Oscillation during the last millennium, but contrasts with the apparent climate stability recorded at Law Dome and for the Antarctic continent as a whole. Further research is required to better understand the limnological and ecological responses of both diatoms and lakes in coastal Antarctic in order to obtain more rigorous palaeoclimate reconstructions from these sites of immense potential, and to understand how these compare to other Southern Hemisphere climate records.

## Electrokinetic monitoring of groundwater flow in fractured rock media

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Monitoring groundwater flow is typically determined through the use of observation boreholes in the area of interest. This methodology requires expensive drilling, disturbs the hydrogeological environment, and gives point measurements at typically large spacing from the pumped well. In laterally-uniform clastic sedimentary environments, singular point measurements are sufficient, as the media can be generalised in all directions with some confidence when extrapolating observations.

Fractured rock aquifers, by contrast, are heterogeneous, with high permeability through secondary porosity in fault, fractures and bedding planes. Here, flow is almost exclusively through such faults, fractures and bedding planes as they represent a path of hydraulic conductivity that maybe orders of magnitude higher than the matrix. Monitoring of flow in fractured rock is becoming increasing important to understand the dynamics and long-term sustainability of groundwater for both domestic and industrial uses.

A prospective means for monitoring groundwater flow is through measurement of surface voltages, known as the self-potentials (SP). Voltages occurring at the Earth surface are the direct result of the generation of electrical current associated with the advective transport of negatively charged ions in solution, while positive ions are absorbed onto grain boundaries. Such advective potentials are often known as electrokinetic, and can be measured by an array of electrodes that measure the surface voltages relative to a distant reference point. Electrokinetic methods are cheap to undertake, can cover a wide spatial area and can be used to monitor change in almost real time.

This paper presents two programs of electrokinetic monitoring of groundwater flow in a fractured rock aquifer system: at Watervale in the Clare Valley, SA; and at Balhannah, Adelaide Hills, SA. At each site, controlled and repeated pump tests were carried out, and groundwater was monitored by both an array of 48 electrodes and multiple observation wells. Additionally, at each site, we have acquired complementary geophysical data including cross-hole electrical resistivity tomography, borehole to surface electrical mapping, DC resistivity and time-domain EM, downhole geophysical logs, and salinity measurements.

We present initial results from the electrokinetic observations that show strong spatial patterns of voltage changes (of order of a few millivolts) that are aligned with the strike of the major fracture and bedding plains, and consistent with observed drawdown. However, the observed voltage changes are not always spatially coherent across the array and did not show consistent behaviour between repeated pump tests. We attribute some of the ambiguity to the complex heterogeneity of flow (and variable recharge rates) in these fractured rock environments, but further work is required to understand the background noise levels and electrochemical soil potentials. Finally, we will show a new 3D tomographic image method used to model the surface potentials in terms of a probability of source depth; such tomography is the first step towards quantifying the electrokinetic method.

## **Palaeobiogeographic test of hypotheses for the formation of coupled oroclines in the central New England Orogen, eastern Australia?**

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Palaeobiogeographic data have famously provided some of the earliest evidence for global scale tectonic processes such as continental drift (Wegener, 1912, 1915; Du Toit, 1937), the mosaic makeup of Asia (Waterhouse and Bonham-Carter, 1975), the exotic origins of circum pacific suspect terranes (Nur and Ben-Avraham, 1977; Yancey, 1979; Colpron et al., 2007), and the rate of true polar wander (Runnegar, 1979; Torsvik and Cocks, 2013). Perhaps biogeographic and biostratigraphic data may now be used to test explanations for orocline formation within the central New England Orogen (NEO)?

Although the number of oroclinal bends within the NEO is still a matter of debate, it is widely agreed that the coupled Z-shaped Texas and Coffs Harbour megastructures are both real and genetically related (Runnegar, 1974; Korsch and Harrington, 1987; Murray et al., 1987; Cawood et al., 2011; Rosenbaum et al., 2011). However, the hypotheses that have been advanced to explain the current configuration differ widely in their palaeogeographic implications. Both Korsch and Harrington (1987) and Murray et al. (1987) made the coupled orocline by moving crust from the Queensland side whereas Cawood, Pisarevsky and Leitch (2011) and Cawood et al. (2011) kept the Queensland sector stationary and doubled up the orogen from the South. In contrast, Runnegar (1974) and Rosenbaum (2014) have proposed that orocline formation was more or less an in situ process.

The recent suggestion of an autochthonous origin for the Gympie terrane (Li et al., 2015) may allow this outboard element of the NEO to serve as tracer of tectonic transport during orocline formation. Complex rugose corals and other warm-water elements of the Permian faunas (Runnegar and Ferguson, 1969), together with detrital zircon spectra from Gympie Group sediments (Korsch et al., 2009; Li et al., 2015), suggest significant southward transport of the Gympie terrane. Although the Gympie terrane may not have participated in orocinal flexure, its southwards transport may be indicative of a long lived tectonic regime at the eastern edge of Gondwana.

## Geophysical framework of the Lord Howe Rise: Characterisation of candidate International Ocean Discovery Program (IODP) deep drilling sites

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The Lord Howe Rise (LHR) is a ribbon of submerged and extended continental crust that separated from Australia during the Late Cretaceous. Current knowledge of the LHR is based on limited information, including regional-scale marine and satellite geophysical data, isolated dredge samples and shallow Deep Sea Drilling Program (DSDP) drilling into Cenozoic pelagic sediments and latest Cretaceous sediments.

Improving the knowledge of LHR geology and the evolution of the eastern Gondwana margin requires drilling into rocks that record the complete Cretaceous–Cenozoic tectonic and climatic history of the region. To this end, an IODP proposal (871-CPP) to drill a deep stratigraphic hole through a LHR rift basin using *D/V Chikyu* was submitted in October 2015 and is currently under review. This proposal, prepared by an international team of scientists from 20 different institutions, outlines plans to recover core samples from Cretaceous and older rocks up to 3.5 km below the seafloor.

Existing seismic reflection data image a number of rift basins containing sediments up to ~6 km thick. These existing data have been interpreted to show a compositionally-variable pre-rift basement (sedimentary, volcanic, intrusive and metamorphic), two Cretaceous syn-rift mega-sequences comprising presumed terrestrial to marine sediments and volcanics, and a Late Cretaceous–Recent post-rift sequence that can be tied to the DSDP 208 drill hole. The rift basins lie adjacent to fault-bounded horst blocks. Seismic data also provide some indication of sub-horizontal detachment faults in the mid-crust, but the crustal structure of the LHR is generally unknown. Two ship seismic refraction measurements from the 1960s and more recent regional gravity modelling suggest that the thickness of the crust at the axis of the LHR is ~25–30 km, reducing to ~15–20 km on the western flank. The proposed IODP deep drilling and two site surveys will help to address the uncertainties in crustal structure and rift-basin geology.

The first of two site surveys was undertaken from March to May 2016 in order to characterise the candidate IODP deep drilling sites at a higher resolution than is available from pre-existing datasets and to better constrain the crustal-scale geological and tectonic framework of the LHR. The survey obtained: 1) a deep-crustal multi-channel seismic reflection profile across the Tasman Sea oceanic crust and the LHR continental crust; 2) seismic refraction data recorded on ~100 ocean-bottom seismometers along the same profile; 3) a total of ~350 line km of 2D seismic reflection data along three east–west and three north–south profiles at each of the three candidate deep drill sites; and 4) multibeam bathymetry, gravity and magnetic data. This paper will present an overview and preliminary interpretation of these new datasets.

## Gold in silcrete as a new vector to volcanic-hosted massive sulphide mineralisation

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The decline in mineral resource discoveries in Australia is in part due to the difficulty of developing new geochemical methods for exploration through regolith profiles. The present contribution reports new data on the first occurrence of supergene Au deposits in a near-surface silcrete over the Scuddles VHMS deposits in the Golden Grove district, Western Australia. Supergene weathering profiles attain up to 90 m in thickness and are developed on dacite, rhyodacite and siltstone that host primary Cu, Zn, Pb sulphides with Au-Ag ores. From the base, an idealised weathering profile composed of: (1) a supergene sulphide enrichment zone; (2) supergene carbonate-/sulphate-/phosphate-rich zone; (3) Fe oxide-rich zone; (4) leached kaolinitic saprolite that is changed laterally into silcrete; and (5) mottled clays/ferruginous duricrust zone.

Silcrete at Scuddles consists of massive and silicified, collapsed breccia of vitreous ripples embedded in white, silica cement. Mineralogically, it consists of >90% quartz and <10% residual kaolinite, muscovite, rutile/anatase, cassiterite, native Ag, zircon, xenotime and monazite. Pyrite, galena, chalcopyrite, sphalerite and argentite occur as inclusions in rutile, cassiterite and quartz. Gold in silcrete occurs as cavity- and fracture-fillings in Ag halide cement. It consists of nanocrystalline (<10 nm) grains that clustered together forming microcrystalline, spongy and reniform aggregates. Gold grains are mainly pure, whereas few show inner, Ag-rich cores and outer, Ag-poor rims suggesting inheritance from the primary Au. Chemically, the silcrete is characterized by: (1) a multi-element anomaly of Au (35 ppm), Ag (1030 ppm), I, Br, Cl, Sb, Sn, Bi, Hg, Mo, W, Te and Ge; (2) leaching of Al, Fe, K, Na, Ca, Mg, Ba, Sr, Rb, Cs, Ti, P, F, Ni, Cu, Zn, Co, S, Se and V; and (3) residual concentration, with a local mobility, of Ti, Zr, Hf, Nb, Ta, Y, Th and U.

The formation of the supergene Au in silcrete involves a mobility of Au and Ag and their pathfinder elements by an oxidative solution under acidic and saline (halogen-rich) conditions resulted from the oxidation of sulphides at depth. This acidic solution reached the surface via fracture systems, escaping the alkaline and reducing conditions in the supergene Cu sulphide, carbonate, sulphate and phosphate-rich zones. The acidic solution dissolved clays causing collapse, reacted with rutile, cassiterite, zircon, quartz and precipitating Ag halides, Bi, P, Pb, Sb, Ag-rich aluminosilicates and QAZ (quartz-anatase-zircon) cements. Gold precipitation in the silcrete may have taken place in response to a rise in pH and/or dilution of the halide concentration.

Discovering supergene Au in the silcrete over VHMS deposits has significant implications for exploration, not only in Australia, but also in regolith-dominated terrains with similar weathering histories elsewhere in the world. These include: (1) the silcrete can substitute gossan as a target sampling medium, particularly if the VHMS mineralisation are hosted in silica-rich volcano-sedimentary sequence; and (2) the different dispersion patterns and sharp separation between the shallow Au-Ag halo in the silcrete from the underlying supergene Cu and Zn deposits do not necessarily mean detecting anomalous Au at surface will lead to buried Au deposits at depth.

## **AuScope Australian Seismometers in Schools, helping communities understand the Earth and our impact.**

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The Australian Seismometers in schools (AuSIS) program has provided communities around Australia with the tools and skills to monitor their own back yards. Community concerns about new ventures such as coal seam gas extraction, carbon sequestration and mining has created concern within the public as the question of induced seismicity pops up in the media. In many cases in Australia sites are monitored privately and data is not provided openly to all, fostering a lack of trust. The AuSIS program provides independent instrumentation that a community can monitor itself, along with an education program that helps them to gain an understanding of earthquake processes.

The AuSIS program consists of 43 research quality seismometers installed in schools around Australia and education modules to help to integrate the seismometer data into the classroom. The seismometer data can be viewed in real-time at the school and available to the public in near real-time. Three areas covered by this program are areas where there are concerns about induced seismicity.

1. In Kalgoorlie the school requested a seismometer in part because of mine activity. The school is less than 2 km from the mine and the blasts are often strongly felt in the area. In 2010 a magnitude 5.2 mb rocked Kalgoorlie-Boulder causing significant damage. The epicentre was less than 2 km from the mine leading to questions from the community about whether mining activities had caused the earthquake. In this case some were already alarmed about the mine activity, but the seismometer now helps them understand the difference between a blast and an earthquake.
2. The school in Harvey is close to the proposed southwest carbon sequestration hub. The seismometer was put into the school to help maintain a good relationship with the locals. It provides an independent measure of any earthquake activity that the community itself can monitor.
3. Lastly seismometers have been installed in schools surrounding the Hunter Valley that will help monitor any increase in seismicity due to coal seam gas extraction. These sites were sponsored by the NSW department of trade and investment to provide independent data that is freely available.

The AuSIS program provides an opportunity to engage positively with communities creating trust, while also educating our future Earth scientists. Finding ongoing support for the network is an ongoing challenge but feedback from teachers and students has provided significant encouragement for its future.

## The AuScope Inversion Lab: data science tools for the community

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The AuScope Inversion Lab is a consortium of scientists from the university, government and industry sectors with interests in the development and application of inversion methodologies for the Earth Sciences. iLab is intended as a platform for the exchange of ideas, a portal to inverse modeling resources and an opportunity to connect researchers and practitioners. The inversion lab forms part of the iEarth initiative, a synergy of geophysics, applied mathematics, computer sciences, physics, chemistry and geology. The aim is to link classically disparate disciplines and enable new science based on robust approaches to quantitative inference available to all. In this way iLab helps facilitate the move of the Geosciences from empiricism to quantitative inference allowing data driven predictive modelling and inversion.

The iLab software portal supported through AuScope 2011-2014 is a project to make advanced inference and data analysis software available to the geoscience community. Many of the packages have been developed specifically for iLab, with others contributed by the authors. All iLab scientific software is provided free of charge for research and education. For commercial use interested parties are advised to contact individual authors. At present there are 20 separate packages covering specific purpose inversion tools, data analysis algorithms as well as generic software libraries for integration into the users own programs. The current list of available software includes high-level tools for 3D inversion of geophysical data using the finite element method; parallelized parameter search for optimization and Monte Carlo sampling of non-linear inverse problems, trans-dimensional regression and inverse modelling, as well as specific packages for thermal history matching, noise reduction in finite-rotation datasets for plate kinematic reconstructions, as well as various tools for seismic modelling and inversion. The poster will provide further details of individual packages and their uses as well as highlighting some of this software in action.

The software portal may be accessed at <http://iEarth.edu.au>. A single registration allows download of any and all available packages. By February 2016 there have been in excess of 400 registrations on the iLab portal from more than 100 countries requesting more than 750 downloads of individual packages. Contributions to the software portal are possible by contacting [Malcolm.Sambridge@anu.edu.au](mailto:Malcolm.Sambridge@anu.edu.au).

## **Hyperspectral analysis of minerals in the Precipice Sandstone and overlying formations**

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Hyperspectral scanning of drill cores provides a method for contiguously profiling mineralogical changes in rock sequences and it complements other methods for investigating mineralogy such as X-ray diffraction (XRD). In this Study, we used the TSG-CoreTM software to analyse hyperspectral data acquired by HyLoggerTM to study the Short Wavelength Infrared (SWIR) and Thermal Infrared (TIR) hyperspectral characteristics of the Precipice Sandstone, Evergreen Formation, and Hutton Sandstone in core from the Wolleebee Creek GW4. The objective was to understand the distribution of reactive, non-reactive and potentially baffling minerals, in particular clays within potential reservoirs for CO<sub>2</sub> injection. Previous work by Farquhar et al (2013) had only SWIR available, and a secondary objective was to compare results.

The results show that the dominant mineral in the Precipice Sandstone is Quartz (>95%), with some Dickite and Kaolinite. The presence of Dickite would assist in determining hydrothermal fluid movement through the sequence, but its identification is contentious and previous XRD work not conclusive. Kaolinite and Quartz are the most dominant minerals in the Hutton Sandstone, which are associated with some intermittent montmorillonite. Montmorillonite, Quartz and Kaolinite are dominant in the Evergreen Formation. Therefore, the subdivision of the published Formations can be recognised based on interpretation of the HyLogging data. Different amounts of Sulphates, Chlorites, and Carbonates, which are secondary minerals that can react with CO<sub>2</sub> over the short-term, can be observed but in low quantities in the Precipice and Hutton Sandstones and Evergreen Formation. Sulphates like gypsum are dominant in the Hutton Sandstone and present in the Evergreen Formation but are less abundant in the Precipice Sandstone. In addition, a minor amount of Chlorite is present in the Hutton Sandstone and Evergreen Formation while carbonates are dominant in the Hutton Sandstone. The findings from this study are comparable to those previously, but also assist in understanding the spatial distribution and relative contribution of minerals within these targeted reservoirs.

## Micro-ablation and source rock analysis: A new technique for removing hydrocarbon contaminants and facilitating biomarker analyses of cuttings

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Biomarkers and other hydrocarbons from potential source rocks act as important geochemical proxies in petroleum exploration efforts. However, for biomarker-based petroleum studies to be accurate, acquisition of reliable data and proof of their syngeneity is essential. Unfortunately, contamination of geological samples with petroleum products during drilling, storage and sampling can be particularly problematic as these hydrocarbons can over-print an original indigenous biomarker profile (e.g. Brocks et al. 2008). In order to obtain an indigenous hydrocarbon signal, a number of methods have been developed to remove contaminants. One particular method, the “micro-ablation technique”, allows for the sub-millimetre removal of layers of contaminated surfaces from pieces of sedimentary rock that are too small or irregularly shaped to be trimmed using a saw. The process involves the use of a vibratory tumbler that removes exterior rock surfaces with the help of ceramic polishing media and silicon carbide as an abrasive. Previous work by Jarrett et al. (2013) has demonstrated the effectiveness of this technique in either removing surface hydrocarbon contaminants or help in quantitatively evaluating the migration of these allochthonous hydrocarbons into a rock sample. While the micro-ablation technique has been successfully applied to rock samples derived from whole cores, it has never been tested on smaller sidewall cores or disaggregated cuttings. This is unfortunate as these types of rock samples are more commonly derived from standard drilling techniques employed in the petroleum industry. They are commercially cheaper to obtain than whole cores yet provide significant insight into the subsurface geology of petroleum basins. However, cuttings are not usually recommended for biomarker analyses because they are most readily affected by flushing with oil- and water-based drilling muds and lubricants. We recently extended the micro-ablation technique to test the suitability in processing cuttings. Experiments were conducted on a variety of different shale and carbonate cuttings with a diameter of 1 cm. Micro-ablation was successfully able to remove the exterior surfaces of cuttings, leaving the residual surfaces polished. Gas chromatography-mass spectrometry results demonstrate the effectiveness of the technique in removing associated hydrocarbon contaminants from cutting surfaces. A quantitative evaluation can subsequently be conducted to measure hydrocarbon concentration differences between the removed rock exterior and the remaining interior. In the case of contaminants infiltrating pores and fissures, concentration gradients can be detected whereby lighter molecules will permeate deeper into rocks than heavier ones. Ultimately, this technique will reveal unprecedented insights into previously inaccessible biomarker/hydrocarbon maturity data for petroleum exploration efforts.

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Jarrett A.J.M., Schinteie R., Hope J.M., Brocks J.J. 2013. *Organic Geochemistry*, v. 61, p. 57-65.

## Geochemical constraints on the evolution and setting of the Cambrian Stavely Arc, western Victoria

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Several belts of poorly-exposed igneous rocks occur in the Grampians-Stavely Zone of western Victoria, close to the interpreted Cambrian east Gondwana continental margin. Previous studies on the exposed igneous rocks around Mount Stavely, Mount Dryden and the Black Range have recognised geochemical characteristics similar to those found in modern magmatic arcs. These rocks are collectively considered to form part of a single Middle to Late Cambrian arc system, referred to as the Stavely Arc. While outcropping examples of the Stavely Arc are well studied, the character of other rocks imaged by geophysical data beneath thin cover has remained enigmatic. Geochemical data from a recent stratigraphic drilling program, together with analysis of rocks from government and industry drill holes has allowed for a more complete understanding of the Stavely Arc package.

The oldest recorded age for Stavely Arc magmatism is provided by an isotopically juvenile, arc-related felsic intrusive with a U-Pb zircon age of ~510 Ma. This age is synchronous with tholeiitic dolerite, also dated at ~510 Ma, which is interpreted to have been emplaced in a back-arc extensional setting. Most ages for volcanic rocks of the Stavely Arc, including historic dates, show that arc magmatism was ongoing until at least ~505–500 Ma.

The majority of arc-related rocks comprise low- to medium-K calc-alkaline basalt, andesite, dacite, and quartz diorite, which share similar LILE- and LREE-enriched patterns and moderately evolved to juvenile Nd isotopic compositions ( $\text{Nd}_{500\text{ Ma}} = -3.95$  to  $+0.46$ ). High-Al basalts intersected during stratigraphic drilling also show a weakly-developed subduction signature. However, these are distinguished from the other calc-alkaline rocks by having higher  $\text{Al}_2\text{O}_3$ , N-MORB-like trace element patterns, relatively flat REE patterns and more juvenile Nd isotopic compositions ( $\text{Nd}_{500\text{ Ma}} = +4.73$  to  $+6.33$ ). High-Al basalts are spatially associated with boninites intersected by previous mineral exploration drilling and occur in a separate belt to the more evolved calc-alkaline rocks.

Overall, the geochemical data suggest that the majority of calc-alkaline rocks of the Stavely Arc have closest affinity with modern island arcs that have limited continental involvement. It is unlikely that interaction with any pre-existing Precambrian crust was great, given the Nd isotopic compositions and limited amounts of inherited Mesoproterozoic or older zircons. These data support existing interpretations of the Stavely Arc being emplaced through an attenuated continental ribbon outboard of the Gondwana continent, analogous to present-day Japan-type arcs. In comparison, the juvenile isotopic characteristics, weakly-developed subduction-related features, and spatial association of boninites with the high-Al basalts are consistent with a more primitive island arc setting, and may represent an early phase of Stavely Arc magmatism. Similar geochemical characteristics, ages, and inferred tectonic setting are consistent with the Stavely Arc forming part of a larger Cambrian arc system that includes the Mount Wright Arc in New South Wales and the Jamieson Volcanic Group (Selwyn Block) in central Victoria. These new data help to understand the nature of plate margin processes along the Cambrian east Gondwana margin, and provide a rare insight into a largely preserved ancient magmatic arc system.

## Titanite U-Pb geochronology: constraints on metamorphism and cooling in the east Albany-Fraser Orogen

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In the east Albany-Fraser Orogen, amphibolite to granulite-facies metamorphism at 1225 – 1140 Ma (Stage II of the Albany-Fraser Orogeny) is known from an extensive dataset consisting mainly of U-Pb zircon geochronology. Although the temperature of this zircon growth is unknown, it is commonly interpreted to date high temperature metamorphism. To enhance our understanding of the metamorphism and cooling of these rocks, we utilise U-Pb in titanite. Titanite has a closure temperature in the U-Pb system of 650 – 700°C and its crystallisation temperature can be estimated from its Zr content; these facets make it a useful tool in constraining not only the timing and duration of metamorphism, but also in dating the initiation of cooling. In this study, we analysed titanite crystals from eleven samples in the Biranup Zone, Nornalup Zone and Fraser Zone using in-situ laser-ablation inductively-coupled plasma mass spectrometry (LA-ICP-MS).

Three samples from the eastern Biranup Zone produced titanite ages of  $1201 \pm 9$  Ma,  $1185 \pm 28$  Ma and  $1168 \pm 9$  Ma, younging to the southeast over a distance of 50 km. These are interpreted as cooling ages after upper amphibolite facies metamorphism, previously dated at c. 1200 – 1190 Ma by U-Pb zircon geochronology. 300 km to the southwest, an additional Biranup Zone titanite cooling age of  $1159 \pm 14$  Ma post-dates nearby metamorphic zircon growth by c. 20 Ma. These titanite cooling ages also provide a constraint on the minimum duration of metamorphism.

Four titanite samples from the southeastern Nornalup Zone record cooling ages of  $1184 \pm 9$  Ma,  $1192 \pm 15$  Ma,  $1192 \pm 8$  Ma and  $1187 \pm 15$  Ma, across an 80 km transect from west to east. These ages are identical (within error) to U-Pb zircon ages from these sites, and are 25 – 30 Ma older than the titanite cooling age from the Biranup Zone.

Two samples from the Fraser Zone record titanite ages of  $1294 \pm 3$  Ma and  $1284 \pm 13$  Ma. These ages match c. 1290 Ma Stage I metamorphism in the Fraser Zone; no overprint associated with Stage II metamorphism was detected in these samples. However, the Newman Shear Zone, the southeastern boundary between the Fraser Zone and the Nornalup Zone, produced a titanite age of  $1132 \pm 26$  Ma. This suggests the shear zone was active late in Stage II, and may have played an important role in exhumation.

## **Geoheritage and consanguineous wetland suites of the Swan Coastal Plain, Western Australia**

**Semeniuk Christine**, Semeniuk, Vic

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A wide range of wetland types occurs on the Swan Coastal Plain, from basins, and flats, to slopes and channels. They vary in size, shape, water characteristics, sediments types, stratigraphy, vegetation, and maintenance processes. The wetlands range from large linear lakes to small round or irregular seasonally damp wetland basins to seasonally flooded flats, to seasonally flooded or permanently flowing channels; from fresh water to hypersaline to saline; and from surface-water perching to groundwater recharged, as determined by regional features such as geology, geomorphology, soils, climate and hydrology, and local physical/chemical processes. As repositories of Holocene to Pleistocene sedimentary sequences they are both significant reservoirs of information on wetland history, climate changes, and hydrochemical history, and templates on wetland maintenance and functioning diagnostic for their geologic/geomorphic setting. This variety of wetland types represents geodiversity that needs to be addressed in geoheritage assessments of the State of Western Australia.

The wetlands have been aggregated into natural groupings termed 'consanguineous suites'. There are some 30 different formally-named wetland suites related to geomorphic setting on the Swan Coastal Plain varying, for instance, from interdune depressions on a beach-ridge plain (the Becher Suite) to karst-formed linear lakes in limestone-ridge country (the Yanchep Suite) to irregular to round, semi-interconnected basins on a quartz sand subdued dune system (the Jandakot Suite) to linear and round basins formed along the hydrological contact between limestone and quartz sand (the Bibra Suite), amongst others.

From a global perspective, the diversity and array of consanguineous suites of the Swan Coastal Plain is unique. An understated aspect of the approach in identifying consanguineous suites of wetlands of the Swan Coastal Plain is that in their geological, geomorphological, and hydrological/hydrochemical setting they provide profound insights into gradual and uninterrupted wetland development, sedimentary filling, and ecological functioning because, for a given east-west transect, they are located in the same climate setting but in different geologic/geomorphic and hydrochemical settings. They appear to be unrepresented globally, and therefore internationally significant.

## **A protocol using the Geoheritage Tool-kit to identify, assess and prioritise sites of geoheritage significance in New South Wales, Australia**

**Semeniuk, Trudi**

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New South Wales has an abundance of sites of geoheritage significance, some of which have been described and registered on various databases, and with government agencies from Federal to local level. However, there are innumerable sites that have been documented as part of the Regional Forests Agreement studies, in local government reports, and in the scientific literature that are not, as yet, listed on any databases; nor have they been secured in conservation reserves. Given the extent and number of sites and regions of geological significance, there needs to be a systematic investigation and review to ensure that as much as possible of the State's geoheritage and geodiversity is conserved. Focusing on the region of the Sydney Basin, using the Brocx & Semeniuk Geoheritage Tool-kit, this presentation provides a case study for a protocol for systematically dealing with the range of geology and sites of geoheritage significance in NSW.

## **Geoheritage significance of limestones recording changing climates and sea levels preserved in the three-phase evolution of a Pleistocene coastal plain in south-western Australia**

**Semeniuk Trudi<sup>1</sup>, Semeniuk, Vic<sup>2</sup>**

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The Yalgorup Plain of south-western Australia preserving is underlain by two Pleistocene limestones and a linear quartz-sand formation that record carbonate deposition in a prograding beach-ridge system of small cuspate forelands, and quartz sand accumulation in a shore-parallel coastal dune barrier. The cuspate forelands are linked to protective offshore limestone reefs, within a given Pleistocene wind-and-wave field, while the quartz-rich coastal dune barrier formed under increased swell conditions. These formations record three different Pleistocene interglacial depositional events, separated by unconformities, and each linked to a distinct climate and mean sea level. As such, this stratigraphic sequence is an excellent record of the climate and sea level history of south-western Australia. It represents the best-preserved system of Pleistocene coastal sedimentary history and Pleistocene climate and sea level history in limestones within Western Australia, and probably Australia. In particular, the foraminiferal assemblages within the limestones and in the carbonate lenses in the quartz sand formation faithfully record changes in minimum seawater temperature - using modern analogues, they show a warm-water accumulation with high production of carbonate, followed by cool-water accumulation with low production of carbonate, and then a return to warm-water accumulation. This outstanding record of Quaternary coastal geomorphic development, and its record of coastal carbonate and siliciclastic sedimentation linked to changes in climate and sea level in south-western Australia is relatively well preserved within the bounds of a National Park. Given the array of lithofacies, with their record of environmental, sea level and climate changes, as well as a biostratigraphy linked to such changes, these formations form a sedimentary package that is of international geoheritage significance.

## Geoheritage at the small scale: bubble sand in tidal deposits as diagnostic palaeoenvironmental indicators and features of geoheritage significance

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In identifying sites of geoheritage significance, commonly there has been an emphasis on the larger scale features. There are any number of examples, from those that are scenic to those purely of scientific significance, e.g., Uluru in central Australia, the Cotton Palace in Turkey, or the Grand Canyon in Arizona, and cliff sections showing an unconformity, or biostratigraphy, or large carbonate nodules embedded in mudstone, amongst others. However, often the story of geology and the significant features that are critical to unravel geological processes and geological history are small scale. These include, for instance, zircons crystals of Jack Hills, snowball garnets, mud cracks on a Precambrian mudstone, and *Skolithos* and eurypterid ichnofossils in a Silurian estuarine sequence. This contribution focuses on bubble sand (also known as 'keystone vughs') as features that are small-scale but nonetheless critically important to geology, and hence are of geoheritage significance.

Bubble sand is ubiquitous on modern beaches and tidal flats. It occurs in the uppermost tidal zone of sandy beaches, where it forms a distinct layer in the stratigraphy of a shoaling beach-to-dune system. It is a diagnostic indicator of upper tidal conditions and formed where a rising tide and a concomitantly rising watertable interact with the upper swash-zone wave processes. As such, it is a reliable indicator of tidal conditions, and a reliable sea level indicator for Holocene and ancient beach sequences. Bubble sand also may occur in the mid to upper tidal parts of sandy tidal flats; here it is a diagnostic indicator of tidal conditions, and forms where a rising tide and a rising watertable forces air upwards to be trapped in moist sand.

If found in ancient sequences bubble sand is a powerful environmental indicator of tidal conditions and, for beach sequences, an indicator of the high-tide level. Bubble sand has been found in a number of ancient sequences: within beach-to-dune shoaling stratigraphy in the Pleistocene limestones of the Perth Basin, and in tidal flat sands of the Mesozoic Broome Sandstone of the Canning Basin.

The bubble sand lithology is a significant geological tool for use in palaeoenvironmental reconstructions, palaeo-oceanographic reconstructions, and determination of the position of a palaeo-watertable. Given the rarity of their preservation, these bubble sand occurrences are of geoheritage significance in their own right and, depending on age of sequence and how common they are in the region, they may be Nationally significant or Globally significant.

## **The “8Gs” - a blueprint for Geoheritage, Geoconservation, Geo-education and Geotourism**

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Within the growing field of Geoheritage, Geo-education and Geotourism there is need to manage important sites of geoheritage significance. The objective of this presentation is to introduce concepts to land managers, policy-makers, educators, and tour-managers, and define terms in this arena. There is a logical progression from Geology the Science, through to Geoheritage and the identification of sites of geoheritage significance, to the establishment of Geosites/Geoparks, Geoconservation, leading to Geo-management, Geo-education and Geotourism. This presentation strongly emphasises the need to identify sites and their values, and design management before utilisation for Education and Tourism.

*Geology* is the discipline of study of the Earth, and the word *geology* is also used to denote all abiotic materials of the Earth (*viz.*, rocks, sediments, soils, groundwater, landforms, amongst innumerable others, and processes of the Earth). *Geoheritage* is the endeavour seeking to evaluate and recognise the features of the Earth, through a process of identification-categorisation-and-evaluation, ultimately for their preservation for heritage, research, education, and tourism. Once Earth features have been evaluated as to their significance they can be classed as Geosites or Geoparks, and secured through *Geoconservation* to protect significant sites through various land-use instrumentalities and Laws.

Once the value of a geological feature has been assessed as significant, *prior* to its use as a site for Education, Reference, Research or Tourism, its physical/chemical vulnerability and its ability to sustain frequent visitors and/or collecting, or its risk as a hazard to people needs to be ascertained, and management plans designed. This is the matter of *Geo-management* and has to be pursued *prior* to any use of the site(s) of geoheritage significance for Geo-education and Geotourism to ensure that the latter endeavours do not degrade or diminish the site through indiscriminate trampling, collecting, or anthropogenically-induced changes to the environment (*e.g.*, caves), otherwise sites of International or National significance can/will become degraded. *Geo-education* is the use of sites by Secondary and Tertiary institutions for the purposes for imparting geological information. *Geotourism* is the supervised, unsupervised, or billboard or otherwise-directed activities for imparting geological information to local, National, and International visitors.

*Geodiversity*, the diversity of geological features in a given area, is outside this sequence gradient of 7Gs. Geodiversity is linked to and underpins Biodiversity. In Geo-education and Geotourism, where they seek to link ecosystems to geology (*i.e.*, they seek to show that ‘Geodiversity underpins Biodiversity’), Geodiversity can be brought in as a separate endeavour.

## Crustal evolution and its consequences on Heat-Producing Element enrichment/depletion, insights from NE Queensland

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The role of crustal evolution/differentiation and tectonic processes in generating incompatible heat-producing element (HPE; U, Th and K) enrichment in granitic rocks remain poorly understood. To investigate this, we studied igneous rocks of the Bowen-Mackay region in northeast Queensland. Here, multiple episodes of silicic magmatism over the last 350 Myr can be studied within a 100 x 200 km area, helping to minimise major lateral changes in crustal thickness and composition as variables. We used petrography, whole-rock geochemistry including HPE enrichment/depletion trends, and zircon isotopic compositions from silicic igneous rocks to investigate long-term compositional trends to monitor for crustal evolution.

Two mineralogical and compositional groupings are observed. Group 1 comprise Early and Late Carboniferous, Permian and Early Cretaceous igneous rocks and are associated with large emplacement volumes. Group 2 include Triassic, Middle Cretaceous, and Tertiary A-type igneous rocks, and are associated with smaller-scale magmatic systems. Heat production values of high-silica igneous rocks exhibit a 'zig-zag' temporal pattern, with Early Carboniferous, Middle Cretaceous and Tertiary silicic igneous rocks having higher heat production values than Late Carboniferous-Permian, Triassic and Early Cretaceous granitic rocks.

Mineralogical and compositional characteristics are not clearly related to tectonic setting or fractional crystallisation, thus inferring that crustal source composition has a dominant control on heat production and bulk-rock geochemical compositions. The heat production pattern over time (0.7 to 4  $\mu\text{Wm}^{-3}$ ) mirrors the zircon Hf isotopic signature ( $\text{Hf} = -8$  to +11), except for Triassic igneous rocks. The highest heat-producing igneous rocks from Group 1 are also the most radiogenic indicating a larger proportion of Precambrian high heat-producing crustal materials in their petrogenesis. In contrast, the Group 2 higher heat-producing igneous rocks are interpreted to derive from the reworking of products from previous partial melting events.

A broad temporal trend towards more uniform (16.1 Hf units at 340 Ma to 2.5 Hf units at 130 Ma) and juvenile (average  $\text{Hf} = +1.4 \pm 4.8$  at 340 Ma to  $+9.4 \pm 0.6$  at 130 Ma) Hf isotopic composition exists in the study area and the trends are consistent with the overall juvenile trend previously reported for the Tasmanides. However, an exception then occurs with a return to more radiogenic compositions in the Tertiary ( $\text{Hf} = 0-5$ ). We interpret the overall trends to be intrinsically related to long-lived and repeated episodes of igneous activity, and to the intensity and magnitude of magmatic events, in particular: 1) melt extraction producing more refractory crustal materials, 2) "crustal jacking" whereby underplating drives pre-existing and melt depleted crust to higher structural levels, and 3) 'basification' by invasion of mantle-derived magmas forming dyke-sill networks through the crust. These processes can collectively produce a lower crust with more isotopically uniform and juvenile compositions. Deviations from this trend can arise during small-scale igneous events (ie, Group 2) where localised partial melting occurs, including of products of previous partial melting events and the long-term trends to more positive Hf isotopic signatures can be reversed.

## Modelling the Georgina and Eromanga Basins from magnetotelluric data, Boulia, Queensland

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In 2014-2015 the Geological Survey of Queensland, together with Geoscience Australia, undertook the collection of a large magnetotelluric (MT) survey, called the Isa Extension survey, in the Boulia region. One of the major aims for this survey was to better resolve the basin structure for the area, assisting explorers by de-risking future mineral exploration. Broadband magnetotelluric (BBMT) stations were collected at 809 sites in a 2 x 5 km grid in an effort to maximise coverage while maintaining lateral continuity between lines. This survey was complemented by 855 audio magnetotelluric (AMT) stations collected at 500 m intervals along 9 lines co-located with the BBMT data where possible.

Geoelectric dimensionality and strike for all stations and periods were determined using the phase tensor method. Where data are two dimensional, a strike of 160° east of north was determined. Inversions were conducted using the OCCAM 2D MT inversion code. Approximately thirty BBMT stations in the west of the survey area have significant 3D effects between ~0.4 – 20 Hz. Such data were removed before inversion to prevent misleading results as the inversion code selected assumes 2D MT responses. The full frequency of AMT data was inverted, while the BBMT data was truncated to frequencies higher than 0.4 Hz.

Initial inversions were conducted on the higher-resolution AMT data to gain a detailed understanding of basin architecture. Based on geological mapping, a contrast in resistivity between the Eromanga and Georgina Basins was expected. Interpretation of the inversion profiles was conducted in concert with available drill-hole and seismic data. Incorporating independent data as constraint on the interpretation produces a more robust model than interpreting the MT data in isolation. Inversions display a distinct difference in resistivity between the conductive Eromanga Basin and the more resistive Georgina Basin. In the southern AMT data set the Georgina Basin has a distinct two layer structure, with the lower basin sequences displaying lower resistivity. This is overlain by the more conductive Eromanga Basin sequences. The northern AMT lines show shallowing of the Georgina and Eromanga basins to the north.

The truncated BBMT data was inverted after the AMT data. Although resolution was significantly reduced (2 km station spacing rather than 500 m), the inversions still produced profiles from which the Eromanga and Georgina Basins could be interpreted. A priori knowledge from the AMT inversions was very useful in interpreting the lower resolution data. The BBMT inversions allowed the two-layer Georgina Basin signature evident in the south of the project area to be traced further north. They also delineated more complicated basin morphology in the west of the project area.

## Crustal and uppermost mantle structure of the Albany-Fraser Orogen from passive seismic data

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The Yilgarn Craton in Western Australia is one of the largest units of Archean lithosphere on earth. Along its southern and southeastern margin, it is bounded by the Albany-Fraser Orogen (AFO), a Paleo- to Mesoproterozoic extensional-accretionary orogen. In this contribution, we investigate the crustal and upper mantle structure of the AFO and adjacent regions using passive seismic data collected during the recent ALFREX experiment, a temporary passive seismic network consisting of 70 stations deployed in the eastern Albany-Fraser Orogen from November 2013 to January 2016. The array had an average station spacing of about 40 km and was designed to fill the gap between recently acquired active seismic profiles AF1/AF2 and AF3.

We present results from the analysis of P receiver functions and ambient noise tomography using the ALFREX data. Receiver functions were used to derive a Moho depth map via H-K stacking, for direct imaging (common conversion point stacking) as well as joint inversion with surface wave dispersion data to derive 1D S-velocity profiles beneath the stations. The obtained receiver functions show a marked change of character from west to east across the array. Whereas they feature clear and sharp Moho phases for stations on the Yilgarn Craton, significantly more crustal complexity and fainter Moho phases are seen throughout the AFO. Crustal thickness increases from 36-39 km for the Yilgarn Craton to values between 42 and 48 km across the AFO, then decrease to around 40 km in the east.

Ambient noise cross-correlations were used to derive maps of phase and group velocities of Rayleigh waves at periods between 1 and 30 seconds. A three-dimensional model of S wavespeeds throughout the area was then computed by pixelwise inversion of dispersion curves. Obtained S wavespeeds are generally very fast even in the shallowest crust (around or even above 3.5 km/s), with the AFO featuring even higher velocities than the Yilgarn Craton. The most notable feature in the S-velocity map are clearly elevated velocities in the Fraser Zone, a 450 km long elongated region of exhumed lower crustal metagabbros within the AFO. The footprint of the array limits the resolvable depth to about 40 km, hence we image mantle S velocities only in regions with relatively thin crust, i.e. for the Yilgarn Craton and the eastern and southernmost parts of the AFO. Due to the use of Bayesian inversion methods, the obtained results come with robust uncertainty estimates, which is an advantage in interpretation. We combine our results with evidence from active seismic experiments and potential field data to derive a three-dimensional model of the present structure of the region. This is ongoing work and most likely still in a preliminary stage at the time of the presentation. This model will be used to inform existing evolution models of the AFO and processes of modification of Archean crust.

## **Detrital zircons as palaeodrainage indicators: Insights into southeastern Gondwana from Permian basins in eastern Australia**

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Radioisotope geochronology of detrital grains coupled with quantitative classification of grain morphology can provide valuable insight into the history of sediment transportation and recycling. We present ~750 new concordant U-Pb ages from detrital zircon grains from a relatively understudied Permian sedimentary succession in the New England Orogen (eastern Australia), coupled with values of abrasion that provides a proxy for the relative source-to-sink distance. We show that cumulative proportion curves for age groups that correspond to plausible source regions provide insights into the palaeodrainage, even if the basin stratigraphy is relatively poorly constrained. This approach is particularly suitable for investigating complex depositional systems that received inflow from different provenance, such as back-arc and intra-cratonic basins.

Using the example from eastern Australia, our results show that during the Early Permian, a large regional fluvial system transported detritus from continental Gondwana across the landscape of the former active continental margin (New England Orogen) and the simultaneously developing East Australian Rift System. In addition, a local drainage system mobilised detritus within the New England Orogen and possibly from an oceanward positioned magmatic arc. Our new constraints for the Early Permian palaeogeography support the idea that the Lower Permian successions of the southern New England Orogen were deposited in a back-arc region that was likely linked to a retreating subduction zone.

## **Structural Facies analysis and facies distribution of Cryogenian glacial rocks and regional structures in the Willouran Ranges, SA**

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The Willouran Ranges lie at the far NW extremity of the Flinders Ranges, on a NW-SE fault-bound trend with the Peake and Denison Ranges along strike to the NW, and the Olympic Domain of the Gawler Craton on the footwall to the west. The range is formed from a near-continuous sequence of Adelaidean Neoproterozoic sedimentary and volcanic rocks and is cut by two major fault systems. The lower part of the Adelaidean succession is particularly well exposed in the region, including the Sturtian tillite, which is a glacial deposit thought to be deposited from the oldest Cryogenian global glaciation.

New maps of Termination Hill and the Nor'west Fault near Mount Nor'west will be presented along with sedimentary logs through the base of the Sturtian tillite to better understand the palaeo-environmental evolution of the region at the beginning of the Cryogenian. Meso-scale structural analysis will be presented combining fracture analysis along the Nor-west Fault with strain interpretations to better understand the deformational stress evolution of the region. These will be put into context of the low-temperature thermochronological evolution of this margin of the Gawler Craton to more comprehensively understand exhumation and landscape evolution of the Willouran Ranges.

## Reconstructing Environmental Histories of the Coorong Lagoon Using Sr and Ca Isotope Proxies in Water Samples and Otoliths

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To reconstruct the past environmental conditions in the Coorong Lagoon, which is the terminal estuary of the Murray River in South Australia, one can rely on selected elements and their respective isotopic system (e.g.,  $^{87}\text{Sr}/^{86}\text{Sr}$ ,  $^{44}\text{Ca}$ ,  $^{13}\text{C}$ ,  $^{18}\text{O}$  data) in suitable marine archives. Here we present available elemental and isotope data measured in different waters from the Coorong area, including (i) the lagoonal waters, (ii) Southern Ocean seawater, (iii) Murray River water, and (iv) a local groundwater source. We collected and analysed lagoonal waters from North and South Lagoons, as well as samples from the Murray River, Lake Alexandrina, Narrung, Lake Albert, Lower Boundary Creek, and an open ocean seawater.

Our results confirmed that *freshwater* and *seawater* end-member sources have different and characteristic  $^{87}\text{Sr}/^{86}\text{Sr}$  signatures, and thus their relative contributions and mixing within the lagoon system can be quantified. Our result also indicates that the groundwater discharge effect in some parts of the Coorong lagoon can be significant, where up to ~40% of Sr in the North lagoon waters originates from non-marine sources such as a local groundwater and/or atmospheric deposition. The salinity of the water samples was also quantified based on *conductivity* and Na concentration data, and overall these result shown an increasing salinity gradient within the Lagoon from north to south.

Fish otoliths, which are useful natural archives of elemental and isotope compositions of waters, will be used to reconstruct (i) past changes in the chemistry of marine environments throughout a fish's lifespan, and also (ii) migratory pathways and histories of fish movement within the ocean and coastal systems. The species to be investigated include a small-mouthed hardyhead (*Atherinosoma microstoma*) caught from different parts of the research area. This study aims to provide additional water and otolith data from the North and South Lagoon, and it will also explore various mixing elemental/isotope trends and scenarios based on different water masses. Specifically, we will analyse waters from Lake Alexandrina, along with otoliths samples to generate a more detailed  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{44}\text{Ca}$  database of the Coorong water masses (sampled along the salinity gradient). By comparing the  $^{87}\text{Sr}/^{86}\text{Sr}$  and  $^{44}\text{Ca}$  ratios (along with other  $^{18}\text{O}$  and  $\delta^{13}\text{C}$  proxies) in water samples and fish otoliths, we will be able to (i) calibrate these novel isotope proxies with respect to salinity variations in this unique hypersaline marine environment, and also to (ii) constrain possible migratory pathways and histories of *Atherinosoma microstoma* within the Coorong lagoon.

## **Uncover Cloncurry: an integrated approach to understanding the mineralisation systems of the Cloncurry District; case studies on Cameron River, Little Eva, and Trekelano.**

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The broad aim of the Uncover Cloncurry project is to provide petrophysical, geochemical and geophysical information on approximately 20 deposits/prospects in order to better understand the controls, mechanisms, and petrophysics of known systems in the Cloncurry region, and assist future exploration in undercover areas of the district. Discussed here are the results of three specific deposits / prospects, Cameron River, Little Eva, and Trekelano, and focuses on the interpretation of basic petrophysical data (i.e., density, magnetic susceptibility, NRM) and anisotropy of magnetic susceptibility (AMS) data and their utility for constraining 3D geophysical models of these deposits.

Density ( $\rho$ ), magnetic susceptibility (K) and remanent magnetisation (J) were measured using a Metler Toledo MS204TS analytical scale, an Agico MFK1 kappabridge and a CSIRO custom-made 2-axis flux gate spinner magnetometer respectively. Magnetite was the only magnetic mineral identified in all deposits as indicated by the linear relationships between K and  $\rho$ , and high proportion of viscous NRMs (~70% in these deposits). High viscous NRMs indicate that remanent magnetisation is not stable, as evidenced by the fact that it was overprinted by drilling at these three sites.

AMS is the measure of anisotropy of the magnetic grains within a rock. This data is presented as three vectors: K1 (long axis), K2, and K3 (short axis), which all define an ellipsoid that represents the average grain shape and orientation of the magnetic minerals within a rock. Additionally, depending on the ratio between these axes, it can be determined if a rock has a strong anisotropy (as defined by P, K1/K3). If a rock does have a high P value, it can be lineation dominant (as defined by L, K1/K2), or foliation dominant (as defined by F, K2/K3). The interpreted shortening direction that has led to the anisotropy in these rock packages is inferred to be parallel with K3.

The anisotropy of magnetic susceptibility (AMS) results were consistent, well clustered and definitive trends were identified within the data. Results were very similar, with all three deposits displaying a sub-horizontal east-west K3 cluster, and K1 and K2 distributed within a north-south girdle through the stereonet. This result is interpreted to represent an east-west shortening direction, with predominantly vertical extension localised within steep, north-south striking foliation (as given by a high F value). These results suggest that magnetite mineral growth occurred during or prior to the ca 1590 Ma D<sub>2</sub> event of the Isan Orogeny.

Petrophysical analyses found that significant remanent magnetisation was not present, and this allowed for simple petrophysical and structural constraints to be adopted. The geophysical models for Cameron River and Little Eva were constrained by petrophysics and mapped to the local structural framework, which is cut by numerous NE-striking faults. Trekelano modelling was not feasible due to the lack of petrophysical contrast between the host and ore. This study highlights that much of the magnetite in the Cloncurry district is pre-syn D<sub>2</sub>, but also that there is a strong affinity between NE-oriented faults and Cu-Au mineralisation.

## Garnet composition variations identified using HyLogger from Jervois, Arunta Region, Northern Territory, Australia.

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Analysis of garnet mineralogy is an established technique used to assess metamorphic conditions in geological terrains. Additionally, the spatial distribution, chemistry, and textures of metamorphic minerals such as garnet and apatite are considered genetically related to the formation of metamorphosed massive sulfide deposits (e.g., Broken Hill, Australia; Gamsberg, South Africa; and, Sullivan, Canada). These examples demonstrate that assessment of garnet mineralogy can be a useful guide to finding such mineralisation.

Established methods used to identify and distinguish garnets such as petrography, X-Ray Diffraction (XRD), and electron probe microanalysis (EPMA) require sample destruction and may introduce sample bias. Insufficient sample spacing over a drillhole interval may miss changes in mineralogy or mineral composition patterns. In contrast, HyLogger™ technology is a rapid, objective, non-destructive method of identifying mineralogy from drill core using high-density spectral reflectance measurements. This technique is capable of identifying changes in mineralogy which may map spatial patterns.

To characterise garnet mineralogy and distribution and related mineral assemblage changes, two drillholes from the Reward Cu-Ag-Pb-Zn deposit in the Jervois mineral field in the Arunta Region were scanned by the HyLogger. The Jervois mineral field comprises several stratabound, polydeformed, and metamorphosed iron-rich syngenetic massive sulphide deposits. Mineralisation at the Reward deposit is hosted in the Bonya Metamorphics, which at this location comprises a sequence of predominantly garnet and magnetite-bearing schists, calc-silicate rocks with subordinate marble, and metasandstones. Some of the schists have been interpreted as an interlayered clastic and hydrothermal sedimentary package. The sequence was intruded by bimodal magmas between ca. 1790 and 1780 Ma.

HyLogger garnet results were validated by petrography, XRD, and EPMA analyses. Garnet composition variations were also mapped using diagnostic reflectance features between 11,435 nm (andradite) and 10,685 nm (almandine). The HyLogged drillholes have intervals of andradite-rich massive garnet associated with quartz and magnetite, within or proximal to mineralisation. The spatial distribution of massive garnet differs in both drillholes. Drillhole KJD010W1 contains an andradite-rich massive garnet interval comprising several 2 m wide layers of andradite mixed with variable amounts of grossular. Spatially discrete zones of 10 m thick massive spessartine-rich garnet are found above and below the andradite-rich zones. Drillhole J13 has an 8 m thick andradite-rich massive garnet zone that is spatially associated with mineralisation. This andradite-rich massive garnet zone transitions at depth to a mix of andradite and grossular-spessartine that is spatially associated with epidote and apatite. In both holes, almandine occurs sporadically along layers within mica schists, spatially separate from the andradite-rich massive garnet zone.

The mineral assemblages and textures detected by the HyLogger are consistent with the interpretation of a local stratigraphic package comprising Al-rich clastic sedimentary rocks interlayered with Fe- and Mn-rich hydrothermal sedimentary rocks. The massive andradite-rich garnet zone is spatially associated with hydrothermal sedimentary rocks containing quartz, magnetite, epidote, ±apatite, ±hedenbergite. Conversely, interpreted Al-rich clastic sedimentary rocks host almandine garnet along schistose bands. The garnet compositions and textures vary spatially and support the genetic interpretation that discrete bands of hydrothermal sedimentary rocks are related to syngenetic mineralisation processes.

## Changing granite sources in the Mesoproterozoic evolution of the region separating the West, South and North Australian Cratons (the WAC, SAC and NAC)

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Granite geochemistry reveals the Proterozoic history of the region separating the WAC, SAC and NAC. Isotopic and geochemical signatures show that pre-1600 Ma granite sources in the Albany-Fraser Orogen (AFO) include progressively reworked Archean (Yilgarn) crust mixed with depleted-mantle contributions and reflect an evolving ocean-continent transition environment. In the Forrest Zone (Coompana Province), c. 1610 Ma magmatism (Toolgana Supersuite) is medium- to high-K, calc-alkalic and magnesian and possibly equivalent to the St Peter Suite, Gawler Craton. It recycled c. 1950 to 1700 Ma oceanic crust, including earlier arcs, along with fragments of older (Gawler?) material, in an arc setting that possibly fringed the craton. Extension in the Forrest Zone between c.1505 and 1487 Ma produced within-plate style magmatism (Undawidgi Supersuite) recycling arc (Toolgana) crust, with new asthenospheric inputs.

In the Madura Province, c. 1400 Ma plagiogranite and adakite formed in an oceanic arc as c. 1950 to 1700 Ma oceanic crust, including remnant hyper-extended AFO crust, was consumed, and eventually thrust over the AFO. From c.1330 to 1290 Ma ferroan granites in the AFO reflect hybrids of asthenospheric and AFO-lithosphere melts formed as the overthrusted passive margin underwent collapse and lithospheric delamination. Contemporaneous, but geochemically contrasting, calc-alkalic and magnesian granites in the west Musgrave Province (Mount West Supersuite) are subduction-related and record the last stage in the incomplete consumption of c. 1950 to 1700 Ma oceanic crust separating the WAC–NAC and SAC.

Magmatism between c.1220 and 1120 Ma affected all regions. High K-**Fe** series rocks dominate the crust of the Musgrave Province (Pitjantjatjara Supersuite) and regions of the Madura Province (Moodini Supersuite) and eastern Nornalup Zone of the AFO. These A-type magmas are ferroan, high-K, alkali-calcic to alkalic, distinctly Ti- and P-rich, relatively anhydrous and formed at up to 1000°C from a homogenised mix of asthenospheric melts and melts of anhydrous lower crust. In the west Musgrave and Madura Provinces, the lower crustal source component was dominantly reworked primitive c. 1950 to 1700 Ma crust. In the eastern Nornalup Zone and on the eastern margin of the Musgrave Province, an additional source component was isotopically evolved Archean crust. The Pitjantjatjara Supersuite also shows a regional variation in trace element, but not isotopic, compositions. This reflects a change, in the SE, to a higher LILE/HFSE basement source component – possibly the subduction reworked c. 1950 to 1700 Ma crust of the Forrest Zone. High K-**Fe** magmatism formed as asthenosphere was channelled into the zones of thin lithosphere marking the incomplete convergence of the WAC and SAC. High K-**Mg** series rocks occur only in the Forrest Zone and include voluminous shoshonites and shoshonite-series granites derived from relatively thick, previously subduction-modified lithosphere. Although the evolution of both regions can be traced to a common c. 1950 to 1700 Ma oceanic substrate, the inferred contrast in lithospheric thickness between the Madura Province and the more extensively subduction-reworked Forrest Zone might indicate that the Forrest Zone was the main, preserved, focus of plate consumption during convergence of the WAC-NAC and SAC.

## Lateral and Temporal Detrital Zircon Age Provenance Changes in the Roper Group, Greater McArthur Basin, Northern Territory.

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The 'greater' McArthur Basin of northern Australia stretches from Queensland through to WA and includes Palaeoproterozoic to latest Mesoproterozoic (and possibly Neoproterozoic) sedimentary and volcanic rocks (and their metamorphosed equivalents). Rocks commonly included as part of the 'basin' form a number of distinct sedimentary supersequences that really represent discrete depositional basins in their own right and have been termed 'packages' by the Northern Territory Geological Survey. The youngest of these is the Mesoproterozoic Wilton Package that is dominated by the siliciclastic Roper Group, which has seen a recent flurry of hydrocarbon exploration activity due to the high amounts of organic carbon preserved in a number of its argillaceous formations.

The vast extent of the Roper Group, and considerable stratigraphic thickness, provide challenges for intra-basin correlation. In addition, the tectonic geography of northern Australia through the Mesoproterozoic is controversial with suggestions of the margin being connected to Canadian Laurentia through much of this time disputed by other models suggesting an open margin, or with other continents being connected at the time. Here we present detrital zircon U-Pb data from sandstones from the buried Roper Group, and the correlative Birrindudu Basin, to compare with existing outcrop samples from the 'type' localities within the McArthur Basin to examine the maximum depositional ages of the formations, to address intra-basin correlation, and to examine both temporal and spatial provenance variations.

## New drilling technologies for mineral exploration productivity

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The vast majority of the developed mining world's economically-viable mineral deposits with a surface expression have been discovered. Improving the productivity of mining, indeed ensuring its long-term future, in the low sovereign risk countries of the developed mining world requires that new Tier 1 discoveries be made beneath barren cover with greater success and at lower cost than has been achieved to-date. Drilling is the only method by which discoveries can be made beneath cover, but is expensive, often permitting only single hole tests of geophysical targets. Cheaper, safer and more environmentally-friendly drilling techniques are the key to improving exploration success beneath barren cover.

Coiled Tubing (CT) drilling can provide the step reduction in drilling costs required to increase the success of mineral exploration beneath barren cover. The key positives of CT drilling are;

- ) it is faster and cheaper than conventional drilling because pipe connections are not required;
- ) it has rapid mobilisation and de-mobilisation using less labour than conventional drilling;
- ) hole stability is maintained because drilling is quicker and fluid circulation not turned on and off for connections;
- ) safety benefits through eliminating manual handling of drill pipe;
- ) environmental benefits through less intrusive set up of drilling pad, including drilling fluid recycling (no sumps), and;
- ) the drill tube is a conduit for downhole communications required for complementary real-time sensing.

Deep Exploration Technologies Cooperative Research Centre (DET CRC) has made significant progress toward the manufacture of a new CT drilling rig specifically designed for mineral exploration. This talk will provide a brief update of that progress and propose some potential applications of the new drilling platform and its associated sensing technologies.

## Still oceans apart – probing the Eucla basement shows what separates the Albany–Fraser Orogen and the Gawler Craton.

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The Eucla basement of southern central Australia represents a vast area of Precambrian crust covered by basin rocks, forming one of the world's largest karst plains — the Nullarbor Plain. Stratigraphic drilling of this basement by GSWA has revealed a distinct geological evolution of the region between the Albany–Fraser Orogen and the Gawler Craton, placing critical constraints on geodynamic models regarding the amalgamation of the West (WAC) and South (SAC) Australian Cratons. Drill sites were chosen to investigate geophysical domains in the region, and in combination with sparse exploration drill cores, provide a means of mapping the upper crust below the cover.

Two basement provinces are recognized from geophysical and drill core data — the Madura and Coompana Provinces. The Madura Province is dominated by metamorphosed basalt, gabbro and plagiogranite intruded by ferrogabbroic to Fe- and K-rich granitic rocks of the 1192–1125 Ma Moodini Supersuite. The older successions are part of a tract of oceanic and oceanic-arc crust — the Arubiddy Ophiolite. Geochemical, isotopic, and petrological constraints define a continental margin ophiolite of E-MORB character, overlying sedimentary rocks and fore-arc oceanic crust from a subduction-modified N-MORB source, and 1411–1389 Ma supra-subduction zone rocks including adakite (Haig Cave Supersuite). The Arubiddy Ophiolite is interpreted to record a history of c. 1900–1500 Ma rift–drift of the WAC margin and formation of an ocean-continent transition, followed by intra-oceanic subduction from c. 1411 Ma. Continent-trench collision led to emplacement of this ophiolite complex onto the passive margin of the Albany–Fraser Orogen (WAC), triggering Stage I of the Albany–Fraser Orogeny by c. 1330 Ma.

East of the Madura Province, the geological evolution of the western part of the Coompana Province — the Forrest Zone — is distinctly different, although their evolution can be traced to a common, c. 1.9–1.7 Ga oceanic substrate. The western margin of the Forrest Zone is truncated by the subvertical Mundrabilla Shear Zone, which underwent sinistral strike-slip motion with significant displacement either during or following emplacement of c. 1135 Ma Moodini Supersuite granite. In the southeastern Forrest Zone, c. 1610 Ma granitic to dioritic gneisses of the Toolgana Supersuite are interpreted as derived mainly from a subduction-enriched mantle source, compatible with an arc setting. The northwestern part of the Forrest Zone is characterized by rift-related, c. 1505 to 1487 Ma felsic to intermediate metagranites, mafic schist and metarhyolite of the Undawidgi Supersuite, produced by partial melting of lower mafic crust during lithospheric extension of the oceanic basement. Structural and spatial relationships indicate a major shear zone between the two supersuites. The c. 1500 Ma rift setting and remnants of c. 1610 Ma Toolgana Supersuite within the rift-related rocks suggest this is an inverted, extensional structure. As in the Madura Province, the Forrest Zone was extensively intruded by the 1200–1120 Ma Moodini Supersuite.

Both the Madura and Coompana Provinces preserve a geodynamic history dominated by oceanic and oceanic-arc crust formation. We find no evidence to suggest the WAC and SAC ever met during continental collision in this region.

## Insights on crustal architecture and evolution of the Madura Province, Western Australia, from deep crustal seismic reflection data.

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Recently acquired geophysical data and stratigraphic drill cores from the buried Precambrian basement of the Nullarbor region of Western and South Australia have provided critical information about the crustal architecture of this region and advanced our understanding of the crustal growth and amalgamation of the Archean and Proterozoic components of continental Australia. In this contribution we examine the Madura Province, an area of at least 65 000 km<sup>2</sup> that lies between the Albany–Fraser Orogen (AFO) to the west, and the Coompana Province to the east. The Madura Province is dominated by Proterozoic oceanic crustal rocks intruded by ferrogabbroic and granitic rocks of the 1200–1120 Ma Moodini Supersuite. We also examine differences in the expression of major structures and crustal features in the various types of geophysical data available — seismic reflection, MT, potential fields — and the implications for interpretation methodology. The western boundary of the Madura Province is defined by the Rodona Shear Zone, which in both the new seismic reflection line (13GA-EG1) and previously acquired seismic data (12GA-AF3) is imaged as a broad zone of moderately east-dipping reflectors of variable intensity. Utilizing the various geophysical datasets, the Rodona Shear Zone is interpreted to have a complex structural history that includes craton-vergent thrusting followed by sinistral strike-slip movement. Predominantly west-dipping, folded Madura Province oceanic crustal rocks with moderate to strong reflectivity occur in the hanging wall. In contrast, reworked Archean crust of the AFO, in the footwall of the Rodona Shear Zone, has weak reflectivity. In the lower crust, the Rodona Shear Zone appears to sole onto the Gunnadorrah Seismic Province, a region of subhorizontal reflectivity that extends down to the Moho and underlies most of the AFO and at least the western part of the Madura Province. The Moho has a depth of ~42 km beneath the Rodona Shear Zone, and undulates gently across the Madura Province.

To the east, the Madura Province is truncated by the Mundrabilla Shear Zone, which provides an excellent example of the expression of a subvertical, crustal-scale structure in seismic reflection data. In potential field data, the Mundrabilla Shear Zone is straight over at least 400 km, with clear sinistral drag. In the seismic reflection data it is imaged as a broad, predominantly non-reflective zone that is about 10 km wide in the lower crust, and tapers upwards to the surface. The structure appears to be offset locally by subhorizontal shear zones. This geometry, the non-reflective character, and the presence of Moodini Supersuite granite within the shear zone suggest structurally-controlled magmatism and fluid transport.

Internally, the Madura Province shows patches of undulating, or folded, moderate to strong reflectivity, truncated by non-reflective zones interpreted to represent voluminous Moodini Supersuite intrusions. In the potential field data, intrusions of Moodini Supersuite truncate folds in Madura Province oceanic crustal rocks. Both west- and east-dipping shear zones are visible, but unlike the bounding shear zones, appear to be confined to the upper crust.

## **Forecasting of tectonic and induced earthquakes**

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The science of ‘operational earthquake forecasting’ – the development of authoritative statements of time dependent seismic hazard – has improved markedly in the past few years. Such forecasts are now issued routinely in New Zealand, Italy is developing a national system, and independent testing centers have been developed in multiple countries.

There are two end member approaches to earthquake forecasting, statistical and physical. Examples of the former include the ETAS (epidemic type aftershock sequence) and STEP (short term earthquake probability) models, both use empirical relations and the initial statistics of a developing earthquake sequence to forecast the probability of future events of a given size. From a physical perspective, maps of Coulomb stress changes following large events have been shown to indicate areas likely and unlikely to experience near future earthquakes; these maps can be combined with rate-state frictional equations or with statistical methods to forecast earthquake likelihoods.

To date, forecasting models of these types have primarily been applied to tectonic earthquakes. However, induced seismicity is a rapidly growing problem in many parts of the world. For example, the US Geological Survey has assessed the likelihood of damage from earthquakes as 10-12% in intraplate Oklahoma, approximately the same as California. Oklahoma is now one of the most seismically active states in the US with events being induced by the injection of wastewater produced by gas and oil extraction. Hence, it may be appropriate to extend operational earthquake forecasting from tectonic to induced seismicity regimes.

## The geochemistry of marine pyrite in the 3.2 Ga Cleaverville Group black shales, Island, Western Australia: Insights into the chemistry of the Mesoarchean ocean and atmosphere.

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Quantitative laser ablation-inductively coupled plasma mass spectrometric (LA-ICPMS) trace element analyses of sedimentary pyrite from two separate Mesoarchean volcano-sedimentary sequences in the Cleaverville Basin, Pilbara Craton, Western Australia, has revealed that the global ocean was apparently Au-poor but Mo-rich at 3200 Ma (compared to the average values of Au and Mo in the global pyrite database). These findings stand in contrast to existing data from 2900 Ma, a period of high background Au in seawater which ultimately played a significant role in the creation of the largest-known accumulation of Au on Earth – the Witwatersrand Au reefs of South Africa. The low Au concentrations of the 3200 Ma Cleaverville pyrite reported here are in agreement with the fact that no major Au deposit of this age is known to exist.

Samples from the Dixon Island Formation also contain abundant carbonaceous spherules which are intimately intergrown with fine-grained quartz and pyrite. Raman laser imaging of the carbonaceous spherules shows that the carbon comprising the spherules is now graphite, owing to the low-grade metamorphism and deformation experienced by this group of rocks subsequent to their formation – not to mention the carbon maturation processes that have surely taken place over the last 3.2 billion years. Previous microanalytical research on these spherules has indicated that they are microfossils (i.e., fossil bacteria), though unequivocal evidence remains elusive.

This study is also in agreement with the interpretations of past workers that the Mesoarchean Cleaverville Basin was generally euxinic, but in local areas atmospheric oxygen levels may have been high enough to permit photosynthetic life, as happened on a larger scale later in the geologic record (e.g., at ~2700 Ma). Our work also further strengthens the validity of LA-ICPMS analyses of pyrite as a viable technique for reconstructing past ocean chemistry by mineral proxy.

## Deep systems and old groundwater: new noble gas tools and a shift in paradigms for interpreting established tracers

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In recent years we have seen a shift in paradigms in the interpretation of environmental tracers. This shift results from studies with initially contradicting tracer results, successfully reinterpreted using alternative conceptual models, improved understanding of transport processes in aquifer/aquitard systems, and technical and computational advances in numerical modelling. Tracer data have previously been interpreted as single scalar “groundwater ages”. Now it is appreciated that any groundwater sample represents a distribution of ages. This understanding is a reflection of the interplay between both chemical and hydrodynamic processes, including radioactive decay, advection, dispersion and diffusion. In deep hydrogeological systems, groundwater processes occur over long time scales. Here the age distribution becomes wider than at shallow depth and the influence of diffusion as transport mechanism is more important. Throughout Australia, where arid conditions, low hydraulic gradients and deep confined groundwater systems exist, such as in the Great Artesian Basin (estimated flow times of up to 2My), diffusion may be as important as advection, or be the dominant process.

A new generation of noble gas tracers become readily available through new or expanded capacity of analytical facilities. Thus complex transport processes can be better identified, leading to an improved understanding of deep hydrogeological systems. Helium has been used for decades as age indicator to characterise old groundwater systems. Recent applications have demonstrated the use of helium in pore water to assess very small velocities (<1 mm/y) in aquitards. Currently, this application requires fresh intact cores to be preserved at the drilling site under high vacuum immediately after coring. An alternative method uses helium accumulated in quartz grains from archived cores and cuttings as proxy to deduce pore water helium concentrations. Recent trials demonstrated the enormous potential of this novel method for future applications. Helium has also proved a useful tracer to detect the influx of very small amounts of very old water in shallow groundwater and surface water, where other tracers (<sup>14</sup>C or <sup>36</sup>Cl) are too insensitive.

All age-indicating tracers become unreliable in double porosity systems, where advective groundwater flow takes place in a small fraction of the pore space, while diffusive transport occurs in the remainder of the pore space. When neglecting double porosity effects, apparent ages inferred straight-forward from <sup>14</sup>C or <sup>36</sup>Cl concentrations can be out by a factor 4-40 and contradict each other. Only the application of multiple tracers can then allow deriving a unique quantification of advective flow and diffusive mass transfer into stagnant pore spaces and aquitards. Therefore, there is a need for new tracers operating at the same or intermediate time scales to those currently available. Several such new radioactive noble gas isotopes have been successfully applied in hydrogeological systems overseas, and are now available for application in Australia. These are the most robust and reliable tracers in their respective time ranges and cover decades (<sup>85</sup>Kr), centuries (<sup>39</sup>Ar) and up to a million years (<sup>81</sup>Kr). New interfaces between numerical modelling of groundwater systems and tracer applications will need to be developed, to assess the age distribution and occurrence of diffusion processes.

## A multi-tracer study reveals the Hutton Sandstone aquifer as a double porosity system

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Depressurization of the coal seam gas fields in the Walloon Coal Measures in Queensland may influence aquifers both over- and underlying the formation. We conducted a multi-environmental tracer study for the Hutton Sandstone aquifer at the Mimosa Syncline, complemented by a few samples from the Precipice Sandstone aquifer. The Gubberamunda Sandstone aquifer, which overlies the Walloon Coal Measures, is the starting point of the flow system of the Great Artesian Basin and has been the focus of numerous studies. In comparison, the Hutton Sandstone aquifer which underlies the Walloon Coal Measures has received much less attention. This aquifer, however, is the main supply of stock water for the beef industry in the area.

A pilot study used helium-4 ( $^4\text{He}$ ) in quartz grains as proxy to establish a profile of  $^4\text{He}$  in pore water across aquitards between the Walloon Coal Measures and over- and underlying aquifers. Because of the high diffusivity of  $^4\text{He}$  the transport mode across the aquitards can be derived from such tracer profiles, i.e. diffusion dominated or advection dominated. By applying a solute transport model, the pore water velocity was determined to be less than 1 mm/y on the vertical scale of formation thickness. By applying Darcy's law and using a known hydraulic gradient and effective porosity, the calculated hydraulic conductivity was found to be in a similar range as the centrifuge and triaxial test values based on the core scale ( $10^{-12}$  m/s to  $10^{-10}$  m/s).

Our multi-tracer study ( $^{18}\text{O}$ ,  $^2\text{H}$ ,  $^3\text{H}$ , CFCs,  $\text{SF}_6$ ,  $^{14}\text{C}$ ,  $^{36}\text{Cl}$ ,  $^4\text{He}$ ) demonstrated that the Hutton Sandstone aquifer behaves as a double porosity system. At the regional scale, such a system has a relatively small fraction of conductive rock surrounded by a fairly large fraction of low-permeable rock; tracer migration is by advection in the conductive part and mainly by diffusion in the low-permeable fraction. Apparent tracer ages, taken at face value from  $^{14}\text{C}$  and  $^{36}\text{Cl}$  concentrations, do not represent the real groundwater flow velocity. Instead, they differ from it by a factor of 4-40, leading to "apparent ages" for  $^{14}\text{C}$  and  $^{36}\text{Cl}$  differing by a factor of ten. The double porosity interpretation of the tracer data, in contrast, leads to a single groundwater flow velocity that agrees with all data considered. As a consequence of this interpretation, the deeper groundwater flow system of the Hutton Sandstone aquifer receives only about 3% of the recharge calculated from the Chloride Mass Balance approach at the intake beds. The other 97% is rejected recharge feeding some of the spring complexes in the Surat Basin and contributing to the baseflow of the Dawson River. This also suggests that the Hutton Sandstone aquifer is potentially more vulnerable to impacts from groundwater abstraction, including from stock water supply and CSG production, than previously anticipated.

## **Structural and Geochemical Controls on the Formation of the ‘Ernie Junior’ Ore Body at the Ernest Henry Mine, Queensland**

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The ~1530Ma Ernest Henry Iron Oxide Copper Gold (IOCG) deposit is located 35km north-east of the township of Cloncurry in North West Queensland and is the most significant Cu-Au deposit in the Cloncurry Mineral System. The pipe-like Ernest Henry ore body is hosted in brecciated and K-feldspar altered Mount Fort Constantine (intermediate) volcanics (~1740Ma) and dips ~40° towards the SSE. The ore body is structurally controlled by a series of sub-parallel shear zones and is ~250m thick, ~300m wide with a down-plunge length of over 1km and is open at depth. The ore assemblage is dominated by magnetite, chalcopyrite, pyrite, carbonate, quartz and apatite. The deposit is enriched in Fe, Cu, Au, K, Ba, S, Co, As, U, LREE, Mo, W, F and Ca and has geochemical similarities to other IOCG deposits in the Cloncurry area including E1 and Monakoff.

A smaller ore body known as ‘Ernie Junior’ exists in the foot-wall of the deposit. This area of mineralisation has never been directly studied and may hold the key to future brown-fields exploration at the Ernest Henry deposit. This project has utilised underground mapping and detailed core logging to establish structural and lithological controls on the distribution of the ‘Ernie Junior’ mineralisation.

The project incorporates petrography, SEM and MLA techniques to define the distribution of trace metals and the geochemical signature of ‘Ernie Junior’ and how these relate to its structural setting. Geochemical analysis of mineral phases (pyrite) will also be completed to establish whether Ernie Junior was formed from the same hydrothermal fluids that formed the main Ernest Henry ore zone and has implications for other distal exploration targets.

## Dynamic Vectors framing East Australian Plate volcanism since 100 Ma

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This long swathe of 100–0 Ma intraplate volcanic rocks includes over 20 post-3 Ma fields with eruptive potential. Alkaline and tholeiitic basalts and evolved lineages were generated within continental and seafloor settings, under multiple geodynamic forces. Long- and shorter-term vectorial forces, in combination, produced changes in stress fields and melting events.

Vertical vectors include asthenosphere upwells and attendant lithospheric uplift and thermal rifting, initiated at 105–95 Ma with cessation of Pacific margin spreading. Triple-point rifts, e.g. Gippsland Basin, East Tasman Rise, developed spreading ridges. Early volcanism from 100–60 Ma hugged rift floors and margins and formed some ‘central’ volcanoes, onshore and offshore (Rockhampton; Tasmanian seamounts). Later triple-point, thermal rifts, e.g. 65–60 Ma Coral Sea-Louisiane-Cato system, similarly expanded areas of hot asthenosphere. These fuelled later volcanism as moving lithosphere progressively overlapped its precincts.

Horizontal vectors from plate motion across asthenosphere, were mostly northerly under Southern Ocean opening. This vector was small between 80–70 and 50–40 Ma, both times of limited central volcano development (Rockhampton, Qld; Wallabadah, NSW). Faster Southern Ocean opening after 45 Ma created a regime of opposing central volcano migratory vectors, that initiated western (Hillsborough–West Bass Strait), central (Bunya–East Bass Strait), coastal (Fraser Island –Comboyne) and offshore Tasman Sea submarine (Tasmantid; Lord Howe) lines. These vectors include breaks and bends, variously attributed to underlying lithospheric thickness, plate margin collision events and asthenospheric flow effects. Accessory mantle upwells caused by lithospheric edge effects may account for extended lava fields that travel with the lithosphere. Primitive magmas in these lithospheric fields would have lower temperatures than those from deep mantle upwells. A minor NE–SW volcanic vector in SE Qld (1–0.4 Ma; Bundaberg – Boyne) exceeds the plate motion rate, possibly marking activity along a progressive lithospheric tear.

/ \ Examples of inclined vectors include slabs that descend from subduction events on the East Australian plate margins. Pacific slabs from pre-105 Ma westerly subduction may have affected early thermal rifting processes, but now are well removed as deeply buried residuals below the Australia-Antarctica spreading ridge. Slab descent from a stalled 50 Ma New Guinea subduction was tracked south under the Queensland margin. A calculated frontal uplift crossed near Townsville between 45–40 Ma, which coincides with known basaltic activity (Mingela Province). At 35 Ma, the uplift front was positioned near the zone of initial central volcano migration. At 25 Ma, the trailing slab lay below NE Queensland where basaltic activity was minimal. A later buried slab 300 km deep under North Queensland was related to a New Guinea subduction at ~30 Ma. This slab lies south of the young NE Queensland basalt fields (< 9 Ma) and at 10 Ma would underlie the NE region prior to its young activity. Farther south, a slab detached at 15 Ma from shallow easterly Loyalty subduction sank into asthenosphere below the Tasman Sea. Early stages of a cold slab descent under moving lithosphere would alter mantle thermal regimes and may explain later subdued Tasman volcanism.

## The structural evolution and kinematics of the southern Tamworth Belt of the New England Orogen at Gundy, Rouchel Block, New South Wales

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The Tamworth Belt constitutes the western subdivision of the southern New England Orogen (NEO) in New South Wales. Bound to the west by the Hunter-Mooki Thrust, and to the east by the Peel Fault, the Tamworth Belt has been interpreted to represent a forearc basin that formed in response to prolonged (Devonian to Triassic) west-dipping subduction along eastern Gondwana. During the Late Permian to Late Triassic, the NEO underwent an extended period of contraction (the Hunter-Bowen Orogeny) [2].

Gundy is located on the north side of Lake Glenbawn and lies within the north end of the Rouchel Block, a tectonic subdivision of the southern Tamworth Belt, interpreted by some to represent one of many allochthonous blocks. The regional stratigraphy is dominated by three unconformity-bound sedimentary groups: (1) Late Devonian to Early Carboniferous shallow marine mudstone, lithic sandstone, limestone and andesite; (2) Early Carboniferous terrestrial sandstone, conglomerate, shale, and volcanics; and (3) Middle to Late Carboniferous terrestrial lithic sandstone, conglomerate, and volcanics. The area is dominated by brittle faults and gentle, upright folds, except for the NNW-plunging Brushy Hill anticline on the western shore of Lake Glenbawn, in the oldest sedimentary group, which exhibits steep dips of bedding(50-70°) [1][3]. The dominant structures are developed only in the oldest two groups, suggesting a multi-phase deformational history.

This presentation will report on the structures and kinematics of the southern Tamworth Belt in and around the town of Gundy, an area that until now has not been studied in depth. Both the relative history of structural development and a series of cross-sections will be used to show how the Tamworth Belt developed through time, in an attempt to broaden our understanding of the southern Tamworth Belt and whether the deformational history can be treated as one ongoing deformational event, or as distinct deformational events separated by hiatuses.

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## Cambro-Ordovician eclogite in the southern New England Fold Belt

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Lawsonite-bearing metamorphic assemblages develop during high-pressure, low geothermal gradient metamorphism, and are most commonly interpreted to record subduction processes. Lawsonite-eclogite and blueschist rocks, encased within serpentinite-bearing fault systems, occur in the southern New England Fold Belt in New South Wales. Recent geochronological studies in this area provide differing perspectives on the timing of palaeo-subduction and accretion along the eastern margin of Gondwana. Phillips et al. (2015) interpreted a zircon U–Pb age of  $514 \pm 6$  Ma obtained from eclogite at Attunga as the timing of eclogite-facies metamorphism.  $^{40}\text{Ar}/^{39}\text{Ar}$  and K–Ar geochronology from white mica in blueschist from Pigna Barney, Glenrock Station and Port Macquarie gives ages of ca. 482, ca. 470 and  $\sim 420$ –471 Ma respectively, and constrains the timing of recrystallisation of high-pressure rocks at amphibolite–blueschist facies conditions in response to exhumation<sup>1,2,3</sup>. In contrast, Nutman et al. (2013) present U–Pb zircon grain ages between ca. 2900 Ma and  $251 \pm 6$  Ma from eclogite at Port Macquarie. These zircons are interpreted as pre-metamorphic detritus and therefore the eclogite-facie metamorphism at Port Macquarie would have a maximum possible age of  $251 \pm 6$  Ma<sup>4</sup>. The implication of this is interpretation is that subduction products continued to be accreted to the oroclinally deformed architecture of the southern New England Fold Belt during the early Mesozoic.

Lawsonite-eclogite from Rocky Beach at Port Macquarie formed at around 20kbar and  $550^\circ\text{C}$ <sup>5</sup>. SEM imaging revealed the presence of small euhedral zircons (5–15  $\mu\text{m}$ ), that occur in the rims of prograde zoned garnets as well as grains in the matrix. In-situ LA-ICP-MS U–Pb dating of these zircons yields an age of  $\sim 500$  Ma, in agreement with the U–Pb zircon age from eclogite at Attunga. The obtained age is significantly older than the  $251 \pm 6$  Ma maximum metamorphic age reported by Nutman et al (2013).

However, the age spectra of Nutman et al (2013) is similar to the age spectra we obtain from U–Pb detrital zircon analyses of the beach sand surrounding the eclogite. Therefore, we suggest our analysis of zircon in-situ within the texturally peak mineral assemblage represents the timing of eclogite-facies metamorphism. This further constrains the timing of subduction and exhumation during accretionary orogenesis, along the eastern margin of Australia during the early Paleozoic.

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## **Analysis of geological samples using laser-induced breakdown spectroscopy (LIBS)**

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Laser-induced breakdown spectroscopy (LIBS) is a powerful and versatile analytical technique for the elemental analysis of samples in the solid, liquid or gaseous state. LIBS uses short, powerful laser pulses to ionise a very small spot on a sample and measures the observed emission spectrum. Analysis of the emission spectrum yields information on the elemental composition of the sample. LIBS analysis of geological samples requires minimal sample preparation, can analyse a sample within minutes and can provide compositional information on light elements.

Samples of geological certified reference materials (CRMs) were analysed as loose powders with minimal sample preparation and results provided within minutes. Calibrations were developed for a variety of elements of interest using a small subset of the CRMs, against which the remainder of the CRMs were compared in order to determine the accuracy of the technique. The results show that even with a small subset of 10 calibration standards and next to no sample preparation, most elements were adequately characterised by the technique.

LIBS elemental mapping of lithium-bearing minerals is also described, showing the variation in lithium distribution across a sample of spodumene. LIBS is a very effective mapping tool that can be used to complement other mineral mapping techniques such as EDS X-ray mapping.

The use of LIBS for the analysis of gold in geological samples is also described. The method involves digestion of a gold-bearing CRM in aqua regia, followed by solvent extraction of the gold into methyl iso-butyl ketone (MIBK). The gold-bearing MIBK is then evaporated off a solid substrate, leaving behind a gold-bearing solute which is analysed by LIBS. Sub-ppt concentrations of gold in solution can be measured in this way.

### **Acknowledgements**

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## Thawing Earth: was there a pulse in silicate weathering at the end of the Marinoan glaciation?

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The Neoproterozoic marks an important stage of Earth's history, with several large-scale glaciations and the emergence of the first animals. Cap carbonates deposited at the end of the Marinoan glaciation are critical archives for understanding Neoproterozoic environmental changes, however their origin has been vigorously debated. One scenario suggests that they result from a massive flux of alkalinity to the oceans, as a result of intense chemical weathering on continents in the wake of deglaciation. If this was the case, large fluxes of nutrients and metals would have also been delivered to the oceans. This could have 'boosted' the evolution of life, leading to the emergence of Ediacaran animals.

The objective of this study is to test whether intense chemical weathering took place at the end of the Marinoan glaciation. To achieve this, we have measured lithium (Li) isotopes in Cryogenian cap dolostones of the Nuccaleena Formation, South Australia. Lithium isotopes in marine carbonates can be used as a proxy for riverine fluxes to the oceans, reflecting conditions of continental weathering. If chemical weathering intensified at the onset of deglaciation, this should be illustrated by heavy Li isotopic compositions at the base of the Nuccaleena dolostone. If not, this could support alternative hypotheses for the origin for cap carbonates, including (i) organo-diagenetic scenario, (ii) a condensation origin (iii) and/or the recently suggested 'shallow-ridge' hypothesis. Thus, while these results will have an important bearing on the environmental changes associated with the emergence of Ediacaran organisms, they will also provide a test for the different models of cap carbonate formation.

## **Geochemical and Sm-Nd isotope constraints on the origin of the ca 1800 Ma Boothby orthogneiss, Aileron Province, central Australia**

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Compared to global norms, parts of the North Australia Craton are characterised by voluminous granitic rocks that typically contain between 3 and 5 times global averages in U-Th concentration. The origin of these granite complexes has not been explored. The conventional paradigm is that high U-Th granites arise from crustal recycling. However the existing data from the North Australian Craton suggest this paradigm is not correct. Instead increasing concentrations of U-Th appear correlated with increasing amount of mantle input, pointing to the systematic involvement of compositionally modified mantle.

The Paleoproterozoic ca 1800 – 1780 Ma intrusive complex at Mt Boothby in central Australia represents one of the earliest suites of high heat producing granitoids and associated mafic rocks. It was intruded across the Reynolds and Anmatjira ranges during the ca 1815-1795 Ma Stafford event. The oldest intrusive phase is an intermediate gneiss that is composed of felsic and mafic components that are intimately interlayered. A younger felsic augen gneiss post-dates the development of one structural fabric within the intermediate gneiss but U-Pb geochronology from the two igneous phases are overlap within uncertainty suggesting an actively deforming system during igneous intrusion.

The augen gneiss is mostly peraluminous, high-K, with minor to large negative europium anomalies. By comparison the intermediate gneiss is medium-K, calc-alkaline with only small to no Eu anomalies. Spider plots yield large negative anomalies in HFSE for the high-K granitoids, but smaller ones for the medium K granites. A negative correlation of Zr/Hf ratios with increasing SiO<sub>2</sub> and the presence of mafic igneous rocks within the Boothby area suggests either source heterogeneity or magma mixing

Initial epsilon Nd values for the mafic phases of the Mt Boothby gneiss are -1.0 to +1.3, and even the values for the felsic portions are less negative than the surrounding metasedimentary source rocks. Mantle input into the source region of these earliest high heat producing granites of central Australia was clearly part of their generation, and may be responsible for the enrichment of these HHP elements in the suite.

## Linking Western and South Australia – insights from magnetotelluric profiling

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The Proterozoic basement under the Nullarbor Region of Western and South Australia links the Archean Yilgarn Craton with the Archean-Proterozoic Gawler Craton, and is one of the largest under-explored regions of the Australian continent. Its tectonic history and mineral endowment is currently being investigated and the recent 13GA-EG1 seismic and magnetotelluric (MT) transect across this region is designed to complement this work by imaging the crustal architecture, augmented by dense gravity profiling and numerical modelling.

We report on the continuous magnetotelluric (MT) profile, from west to east, imaging the edge of the Yilgarn Craton, the Albany-Fraser Orogen, (~300 km 12GA-AF3 MT profile), the Madura and Coompana Provinces, to the northern part of the Fowler Domain and western margin of the Gawler Craton (~830 km 13GA-EG1 broadband MT profile). Electrical resistivity profiles derived from rigorous 2D inversions of the MT impedance tensor have the ability to highlight areas of low resistivity which are typically a proxy for shear zones, and fossil fluid pathways.

The MT data shows varying complexity along the >1100 km profile, with pronounced three-dimensionality across the western end in the Albany–Fraser Orogen and in the Gawler Craton to the east. The Madura and Coompana Provinces between these regions generally show a 1D resistivity distribution (layered structure) in the near surface sedimentary cover, and predominantly 2D resistivity distribution (one predominant lateral strike) in the basement.

There exists a good correlation between narrow (~10 km wide) crustal zones of low resistivity and the location of shear zones from surface mapping and potential field data across the Fowler Domain and the Albany–Fraser Orogen. The Gawler Craton bounding Karari Shear Zone is imaged as a ~10 km wide deformation zone in the upper and lower crust, supporting its significance as a crustal-scale shear zone. The Colona and Coorabie Shear Zones bounding the Proterozoic Fowler Belt to the east show similar crustal-scale fossil fluid pathways and deformation zones, as does the Rodona Shear Zone separating the Albany–Fraser Orogen from the Madura Province. Separating the Madura and Coompana Provinces, the Mundrabilla Shear Zone is visible in the data to periods of close to 1000 s, indicative of a near-vertical crustal-scale shear zone.

The preferred current flow and associated geoelectric strike of the lower crust and upper mantle along the entire profile follows the main subregions of the Gawler Craton (NNE orientation) changing to due north for the Nullarbor Region. This suggests that the lower crust and mantle lithosphere records different tectonic domains with a contrasting history.

## Mantle fertility and mineral systems: insights from AusLAMP across the Gawler Craton

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The sub-continental lithospheric mantle (SCLM) plays a fundamental role in the location of deformation, magmatism, and fluid flux. Geodynamic and thermodynamic forces acting upon the rigid SCLM can lead to fluid-related refertilisation of depleted Archean lithosphere and large-scale melting events. The spatial distribution of these tectonic events plays a fundamental role in the location of ore deposits, and there is a primary correlation between the margins of thick lithospheric blocks and zones of mineralisation. Mapping the SCLM and overlying crust is a key undertaking in understanding the architecture of the lithosphere as well as to identify regions of enhanced prospectivity, which have undergone deformation and fluid flux.

The Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) uses long-period (5-20,000 s) magnetotelluric (MT) data spaced every half degree latitude and longitude to map the electrical resistivity of the crust and mantle lithosphere. We report on a 3D resistivity model of the lithosphere beneath the Gawler Craton, South Australia, derived from over 150 AusLAMP MT stations.

Areas of low mantle resistivity (<10 m) at depths greater than 100 km beneath the Gawler Range Volcanics suggest widespread fertilisation of the inferred Archean-Proterozoic lithospheric core of the Gawler Craton. The lithosphere-asthenosphere boundary (LAB) beneath the Gawler Craton, derived from p- and S-wave arrivals, is on the order of ~200 km. A reduction in resistivity due to asthenosphere melts is not expected and temperatures are not high enough for partial melts to occur. Instead a minor conductive phase in nominally anhydrous mantle rocks is the likely cause for a reduction in resistivity. A connection of the low resistivity region to the surface occurs around the eastern margin of the Gawler Craton, a region with extensive magmatism and Cu-Au mineralisation, particularly at Olympic Dam. Indeed, the conductivity anomaly suggests a causal link between mantle fertilisation and mineral enrichment in the crust.

In contrast, beneath the south-western region of the craton the electrical resistivity is high (>1000 m) to depths exceeding 200 km. If the inferred mantle fertility beneath the central-eastern Gawler Craton is due to metasomatic input from an Archean or Proterozoic subduction setting, it did not have a pervasive effect on the SCLM of the western part of the craton.

The broad-scale pattern of the SCLM electrical resistivity seen in the AusLAMP data is matched by the more evolved  $\text{Nd}$  isotopic values of syn-mineralisation (c. 1.59 Ga) magmatism around the margins of the craton. Taken together, these data support a hypothesis that links (i) magmatism derived from a metasomatically enriched, and therefore more evolved mantle, (ii) large-scale crustal contamination of syn-mineralisation mantle melt, and (iii) large-scale regional fluid pathways revealed in the 3D MT data to the Cu-Au mineralisation prevalent along the eastern margin of the craton.

## **Lithospheric architecture: a first order control on tectonics and mineralisation and cornerstone of UNCOVER**

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The sub-continental lithospheric mantle (SCLM) plays a fundamental role in the location of deformation, magmatism, and fluid flux. Geodynamic and thermodynamic forces acting upon the rigid SCLM can lead to fluid-related refertilisation of depleted Archean lithosphere and large-scale melting events. The spatial distribution of these tectonic events plays a fundamental role in the location of ore deposits. Mapping the SCLM and overlying crust is a key undertaking in understanding the architecture of the lithosphere as well as to identify regions of enhanced prospectivity, which have undergone deformation and fluid flux. One of the major hypotheses to be tested is whether there is a primary correlation between the margins of thick lithospheric blocks and zones of mineralisation.

Understanding Australia's lithospheric architecture is one of the four key areas of the UNCOVER initiative. National programs, such as the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) are underway in South Australia, Victoria, and Tasmania to map the electrical resistivity structure of the continent. The mechanical properties have been imaged extensively in the south-eastern part of the continent using the Wombat array based on seismic wave speed tomography.

This submission seeks to contribute to a wider framework of mapping and understanding lithospheric architecture. An example is the broad-scale pattern of the SCLM electrical resistivity seen in the AusLAMP data being matched by the more evolved  $\text{Nd}$  isotopic values of syn-mineralisation (c. 1.59 Ga) magmatism around the margins of the Gawler Craton. While future endeavours for the lithospheric architecture are based on numerical modelling of physical properties, the link between isotope mapping, magnetotellurics, seismic tomography and seismic reflection data will be pivotal.

## Regional metamorphism and alteration in the Nymagee area of New South Wales – a HyLogger study

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The Nymagee mineral system study in central NSW is the recently completed Geological Survey of New South Wales project to update the geological, geochronological, geochemical and mineral system framework for the Nymagee 1:250 000 map sheet and adjacent areas.

As part of the project, core from 41 diamond drill holes from 14 mineralised zones was scanned using the HyLogger based at the W.B. Clarke Geoscience Centre, Londonderry, NSW. This instrument measures spectra in three different wavelength ranges: the visible-near infrared (VNIR) between 380 and 1000 nm; the short-wave infrared (SWIR) between 1000 and 2500 nm; and the thermal infrared (TIR) from 6000 and 14500 nm. The spectral signatures distal-to and proximal-to mineralisation were systematically described for each of the mineralised zones, using VNIR-SWIR data and TIR where available. In particular, it was found that HyLogger data could be used for revealing changes in chlorite and white mica composition in response to mineralisation, within reactive rock types. In addition, other available datasets, such as assays, petrology and visual logs were used for supporting these interpretations.

The study recognised that sub- to lowest greenschist facies regional metamorphism occurred away from mineralised zones across the majority of the study area. In addition, the development of Mg-chlorite and talc in many mineralised zones points to ore-forming fluids being under-saturated with respect to iron. Although present in many of the mineralised systems, it was found that carbonate alteration is not a dominant alteration type in the area.

The high-density sampling afforded by the HyLogger, together with geochemical correlations and strong spatial associations with more than one mineralisation style, demonstrates its application to mineral exploration and to regional metamorphic studies. Systematic changes in background host rock response and alteration mineralogy can provide vectors for locating additional mineralised zones and can assist in mapping metamorphic grade in areas of deep weathering and/or shallow cover.

## Regolith of the Capricorn Orogen of Western Australia; geomorphic provinces and mineral exploration

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The Capricorn Orogen is a ~1000 km long, 500 km wide variably deformed region of Western Australia located between the Pilbara and Yilgarn Cratons. The Orogen represents a relatively underexplored area, little work has been undertaken to determine regolith-landform evolution and its application to mineral exploration. Large scale (N= 155 samples) transects across the Orogen combined with detailed case studies have resulted in the recognition of four major regolith-geomorphic provinces, each with different challenges and opportunities for exploration. The west is comprised of exposed crystalline basement, thin lithosols dominate and granitic tors are common in a dissected landscape. Soil composition reflects the underlying substrate suggesting soil sampling will provide the best sample medium, though size fractions will vary depending on the commodity of interest. In contrast, the south west is deeply weathered with thick saprolite developed over both sediments and volcanics. Ferruginous nodules and pisoliths are present at surface and weathering profiles capped by duricrust are common. Thick (up to 100 m) paleochannel sequences are found throughout the area, these are represented by mottled clays and sands. Multiple sample media have proven successful in this terrain including ferruginous pisoliths, soils and ferricrete. The lithologies in the north are dominated by mezoproterozoic basin sediments and can be split into two geomorphic provinces. The upland basin regions are highly dissected and possess several generations of ferruginous pisoliths and nodules, ferricrete, silcrete and calcrete developed in colluvium and alluvium and palaeochannel sediments, commonly located on the flanks of hill and as low mounds and hills which suggests topographic inversion. The lowland basin regions are dominated by hardpan, calcrete and colluvial/alluvial plains below low hills on which basin sediments are exposed. A range of sample media must be considered in this environment, including soils, ferruginous material, vegetation, termite mounds and calcrete, these media must be used in conjunction with an understanding of the landscape evolution.

Soil sampling has been undertaken across the four geomorphic provinces in order to establish the relationship between soils and the underlying substrate. Chromium and V concentration differentiates different provinces though this is due in part to the association of these elements with iron oxides which are more abundant in the deeply weathered terrains. The soil samples were split into four different size fractions, different elements are concentrated in the different size fractions. Concentrations of V, As and Cr and Fe are higher in the coarser (>2000 µm) size fraction, this is due to iron oxides being found within pisoliths and nodules which adsorb these elements. The fine fraction (< 75 µm) possess higher concentrations of elements such as Zn, W, Ni and Bi. This study of the regolith-landform evolution of the Capricorn Orogen has resulted in the recognition of four major geomorphic provinces, combined with variations in soil geochemistry a template for regolith mapping and mineral exploration in the Orogen has been developed.

## Regional hydrogeochemistry of the Capricorn Orogen, Western Australia

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The Capricorn Orogen is a ~1000 km long, 500 km wide variably deformed region of Western Australia located between the Pilbara and Yilgarn Cratons. The region represents a relatively underexplored area with thick sedimentary and regolith cover. Hydrogeochemistry provides a low impact and environmentally sensitive method for quickly gaining chemical information about lithology at depth. Groundwater geochemistry can show broader signatures (e.g. alteration haloes) than other sample media (drill core), as the chemistry is influenced by immediate contact with rocks as well as other materials which have previously influenced the groundwater. As part of the Capricorn Distal Footprints project, samples have been taken from 700 wells and bores used to water livestock from across the Capricorn Orogen, with an additional 400 samples planned for this year. Field measurements for temperature, conductivity, Eh and pH are taken at the sample site, as well as photographs and site descriptors critical for determining site contamination. Samples are analysed by ICP-MS, ICP-OES and ion chromatography for 60+ elements and assessed for contamination and links to known mineralisation and lithology.

The results are used to develop indices for mineral exploration linked to known deposits and highlight new areas of potential interest. We demonstrate the utility of previously developed indices (such as NiS and AuMin), as well as providing new pathfinder element suites to improve exploration of the hydrologically complex Capricorn Orogen. Geological terranes are identified within the hydrogeochemistry; for example, the Sylvania inlier in the north of the Capricorn region possesses a distinctly different hydrogeochemical signature with increased salinities and higher concentrations of sulphate than the surrounding Mesoproterozoic basin sediments. This shows that background chemical signatures vary significantly with lithology across the Orogen. Anomalous concentrations of W, As, Cu and Zn are used to distinguish areas of possible Zn and Cu mineralisation whilst elevated Au and As concentrations delineate zones where detailed follow up work should be considered. Deposits such as the Abra base metal deposit are identifiable through elevated concentrations of Pb within bore holes close (<500 m) to the deposit.

The results from this study have additional value for exploration targeting by seamlessly merging with the north Yilgarn hydrogeochemical dataset allowing for comparison with this well studied region. Future work will also be carried out in constraining the aerial electro-magnetic data based on the conductivity of the groundwater determined as part of this research.

## A geochronology and environmental record through Marine Isotope Stage 3 from North Stradbroke Island, south-east Queensland

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Marine Oxygen Isotope Stage 3 is a critical period in Australia's recent geological history. During MIS3, humans arrived on the continent and the last megafaunal extinctions occurred. The extent to which climate change and variability played a part in Australian megafaunal extinctions is a source of ongoing debate. A recent study has suggested that substantial aridification of central Australia coincided with the extinctions (Cohen et al. 2015; *Geology* **43**), while research from ocean sediment cores shows no such link (De Deckker et al. 2012; *Nature Geoscience* **5**). Further consideration of this issue is hampered by an absence of well dated records of sufficient resolution from the Australian mainland.

Here we present a new record of environmental change derived from  $\mu$ XRF scanning of a sediment core covering the past ~100,000 years from Welsby Lagoon, North Stradbroke Island, a large sand island off the coast of Brisbane. As there is little or no overland flow into the lagoon, it is thought that geochemistry of the sediments reflects changes in windblown dust from the Australian continent (Petherick et al. 2008; *J. Quaternary Science* **23**). The record is dated using numerous optically stimulated luminescence ages (focussed on MIS3) in combination with more traditional radiocarbon techniques. We find no evidence to indicate that there was a substantial hydrological change that occurred at the time of megafaunal extinction. In this presentation we will discuss the challenges of OSL dating in this environment.

## **Reconstructing the tectonic history and palaeodrainage evolution of Mesozoic NE Australia.**

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The geologic framework of eastern Australia during the Jurassic to Early Cretaceous, including the precise tectonic and palaeogeographic configuration of the continental margin, and the source of voluminous sediments that filled the basin during this time, remains a topic of considerable debate and interest. The answers to many of these questions can be found by investigating the Great Artesian Basin (GAB), a vast sedimentary system and archive of geologic events recorded during the late Mesozoic. Two events of particular interest are the provenance of Jurassic and Cretaceous sandstones of the GAB, and the timing of emplacement of the Great Dividing Range (GDR) in central northern Queensland, which are still not fully resolved. Two competing hypotheses for these sediments postulate (1) a volcanic arc along the eastern margin of the Australian continent, and (2) a rift related continental silicic-large igneous province (S-LIP). In addition, the GDR has a suggested antiquity coinciding with the rifting away of the Cretaceous volcanic arc from approximately 80 Ma; however, other workers have suggested that in Far North Queensland the divide has been stable since the Middle Jurassic. Here we employ palaeocurrent measurements, detrital zircon geochronology, sandstone petrography and stratigraphic analysis from multiple study areas across the GAB to determine the sources of these volcanics and better constrain the maximum age of uplift of the GDR throughout Queensland. Over seven-hundred detrital zircons were analysed from seven Jurassic-Cretaceous units from the Laura, Eromanga and Surat basins. Results reveal significant zircon age populations at ~125-145 Ma and ~160-180 Ma. Palaeocurrent measurements exhibit flow originating from the current continental divide (GDR) in each study area. As no known magmatic source areas presently exist to account for most of these ages, we suggest a significant palaeogeographic shift occurred post-Jurassic deposition, possibly coincident with the uplift of the GDR, and significant erosion of these Jurassic to earliest Cretaceous volcanic sources, which contributed significant sediment to the basin during this time. This data provides critical information and can be used as a platform for further work that is being completed in the GAB, particularly in terms of the formation processes, and how it relates to the tectonic configuration of eastern Gondwana during the Jurassic and Early Cretaceous.

## Thermochronological constraints on the Karoo Basin: evidence for regional reheating during emplacement of a Large Igneous Province from $^{40}\text{Ar}/^{39}\text{Ar}$ , U-Th-He and paleomagnetic analysis

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The sedimentary history of the Karoo Basin and equivalent basins in South America records a common history of deposition along the active, western margin of southern Gondwana. The intrusion of the early Jurassic Karoo Large Igneous Province (LIP) is a noted precursor to the break-up of Gondwana and the opening of the Indian and Southern Oceans. The thermal effects of the emplacement of LIPs have been posited as a source of greenhouse gas, principally through the release of carbon from heating of organic-rich country rocks. For example, the Karoo LIP has been linked to a Toarcian carbon isotope excursion. In order to test the effects of the Karoo L.I.P. on the Karoo Basin sediments, we have carried out a joint paleomagnetic and geothermochronologic study of basaltic sills and Karoo Basin sedimentary rocks (Ecca Group and Beaufort Gp.) of the Western Cape Province in South Africa. This study was carried out in parallel with magnetostratigraphic studies of the and U-Pb SHRIMP analysis of interbedded volcanic ashbeds, which together established depositional ages of ~275 – 262 Ma for several different sections. Paleomagnetic analysis of several basaltic sills (10 sites, ~100 samples) of the Karoo L.I.P. demonstrates the preservation of a single magnetic component hosted by Ti-magnetite. The paleomagnetic direction is compatible with known Jurassic directions from Gondwana, and we interpret this direction as a primary thermoremanent magnetization. An equivalent direction is observed as a magnetic overprint during paleomagnetic analysis of the sedimentary rocks, typically removed by heating to 350–450°C, depending on site and lithology. We report new 40Ar/39Ar age data from single grain, step-heating analyses of hornblende, biotite, and plagioclase from Karoo basalt. Plateau spectra from biotite and plagioclase yield ages of 182–184 Ma, compatible with known geochronologic constraints from the Karoo LIP farther east and north. The U-Th-He analysis of zircon from volcanic ashes interbedded with Permian sediments yields a tightly-grouped cluster of ca. 180 Ma ages, indicating regional heating above 180°C, the closure temperature for helium diffusion in zircon. An additional constraint on the maximum temperature of Jurassic reheating is imposed by the preservation of Permian cooling ages from muscovite cooling ages. We explore a rock magnetic technique for constraining the duration and temperature of reheating.

## Regional Brines in the Mt Isa Inlier: Unavoidable Phase Separation and Consequences for Fluid Chemistry and Crustal Structure

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The Eastern Succession of the Mt Isa Inlier is one of the most extensively metasomatised metamorphic belts on Earth, and this alteration is associated with thousands of small, and occasionally large, Cu-Au occurrences of considerably variable character. The regional metamorphic grade varies from lower greenschist facies in the north to upper amphibolite facies in the south, and is typical of other regions in the world that have numerous so-called orogenic gold deposits, and yet there are no typical orogenic gold deposits in this region despite the extremely metal-rich nature of the crust. We, and others before us, have found that the fluids responsible for the metasomatism across a broad expanse of the Eastern Succession were unusually highly saline compared to the fluids that typify other metamorphic belts. Various sources have been suggested for these fluids, from metamorphic, to granite-derived, to reworked basinal brines, and the long duration of the Isan Orogeny and punctuated nature of the metasomatism and mineralisation implies that each of these contributed at different times. Given that thick sequences of the regional metamorphic rocks are metaevaporites containing abundant scapolite and carbonates, and that scapolite progressively loses Cl during metamorphism, it is likely that the regional metamorphic fluids were highly saline and carbonate saturated. Since higher salinity enhances carbonate dissolution, these fluids would have been CO<sub>2</sub>-rich at the source. Decompression of such a highly saline, CO<sub>2</sub>-rich fluid in response to the fault valve activity that typifies the brittle-ductile transition in metamorphic belts like this unavoidably leads to phase separation into immiscible CO<sub>2</sub>-dominated fluid and saline brine. This phase separation has several important consequences: (1) the solubility of quartz in the brine increases, causing dissolution of this mineral above the level of phase separation, (2) this quartz dissolution is expected to create a zone of increased porosity in the crust connected to the fault-controlled fluid plumbing system, (3) these zones of increased porosity would focus subsequent fluid flow, which may either increase the porosity further or create porosity infill textures, depending on the chemistry of the fluid, and (4) the fluid phase separation enhances the salinity of the brine phase and causes metals to partition into the brine, creating a more metal-concentrated fluid primed for ore precipitation at higher levels in the system. Intrusion of large volumes of felsic magma after the main stage of metamorphism may have reinvigorated the hydrothermal system, by adding magma-derived fluid with similar chemistry, creating thermal gradients in the crust, modifying the fluid flow pathways and possibly adding metals to the system. In such a system one would expect that mineral deposits formed across a broad period of time, and that these would contain elements easily mobilised by hot brines, such as Fe, Cu and Au, as well as U and REE, which have enhanced mobility due to the increased solubility of F facilitated by the high salinity. These fluid characteristics explain the lack of orogenic gold deposits, which are characterised by low abundances of base metals because they have low salinity.

## Improving the Durham Downs Gas Field three dimensional earth model by integrating regional data, image log data and seismic waveform classification

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Three successive field development plans have been improved through integration of regional data, image log data and seismic waveform classification, each in turn refining and improving the definition of the current three dimensional (3D) geological conceptual model in the Durham Downs Gas Field, South West Queensland.

One of the critical steps in developing a 3D earth model of a gas field revolves around the distribution of reservoir within the model. Using modern day analogues with conventional regional studies, sand body connectivity and fluvial channel dimensions can prove difficult to represent accurately. Integrating seismic waveform attribute classification, core and image log data can assist in determining gross sand depositional trends. Dimensions of the fluvial bodies and palaeocurrent direction can also be resolved using stratigraphic cross sections and well log data subsequently supporting further development of the field.

Improvements in 3D fluvial modelling have been gained by using directional trends from palaeo-topographic trends overlain with palaeocurrent direction of corresponding sands from image log data. Inverting seismic waveform attribute classification into sand probability maps has assisted with 3D fluvial modelling of the main reservoir units. A positive correlation between seismic waveform class and gross sand has been recognised for the main reservoir units increasing confidence in the depositional trends of the sand dominated facies. Lastly fluvial channel dimensions have been interpreted and used as an input to the 3D fluvial model using the Fielding and Crane methodology (*Fielding and Crane 1987*), where channel height was calculated pre-compaction and width inferred from the Fielding and Crane database.

Evidence has been presented to support a NNW–SSE palaeocurrent direction found over the Durham Downs field at the Toolachee (upper Permian) level from regional maps, correlations, image log rose diagrams and seismic waveform classification maps spanning the corresponding interval. Regional paleo-topographic maps and corresponding regional stratigraphic cross sections from Tinchoo-1 in the north to Durham Downs in the south also indicate a thickening Toolachee section in the southern part of the Durham Downs Gas Field. The thickening Toolachee formation coincides with the move from a proximal tributary system to more distal fluvial geological setting also displayed in the seismic waveform attribute maps. Using the Fielding and Crane methodology (*Fielding and Crane 1987*) the upper Toolachee (PC40) channel belt width was calculated to be between 80 m and 1500 m and the lower Toolachee (PC60) estimated channel belt width as between 200 m and 2500 m.

The resultant integrated fluvial models have been used in conjunction with structural interpretation, well production data, pressure communication and seismic data to predict sand fairways and depositional trends to reduce the uncertainty of further development drilling opportunities.

Fielding C.R. & Crane R.C 1987. An application of statistical modelling to the prediction of hydrocarbon recovery factors in fluvial reservoir sequences. *Society of Economic Paleontologists and Mineralogists Special Publication 39*, 321-327.

## Regional mapping in the Ordovician Girilambone Group of New South Wales: implications for exploration targeting volcanic-associated massive sulfide mineralisation

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The Girilambone Group, in northwestern NSW, is a fining-up sequence of deep-marine turbiditic rocks with minor chert and both OIB and MORB basalts. The unit is poorly exposed, complexly folded and variably metamorphosed (to lower greenschist facies). It hosts volcanic-associated massive sulphide (VAMS) mineralisation (see Jones 2012, Gilmore 2015) that forms a number of economic deposits (e.g. Tritton).

Characteristics of these deposits include:

- ]/ Mineralisation is hosted within metasedimentary rocks.
- ]/ Mafic rocks (MORB) occur in the footwall.
- ]/ Variably mineralised silica–iron horizons immediately overlie the ore.
- ]/ Mineralisation comprises pyrite-rich banded and massive sulfide zones, with sub-economic stringer and discontinuous veins in the footwall.

Mapping in the Girilambone Group by the Geological Survey of NSW has allowed:

- ]/ Subdivision of the group into three formations based on micropalaeontology (conodont) and lithology.
- ]/ Placement of the metasedimentary sequences hosting mineralisation in the Early Ordovician Narrama Formation.
- ]/ Formal definition of the Budgery Sandstone Member. This unit, the only marker horizon in the Narrama Formation, is interpreted to be stratigraphically above the mineralisation horizon.
- ]/ The mapping of extensive, strongly magnetic silica–iron horizons, the Birrimba Member, and their correlation with the silica–iron horizons associated with mineralisation.

Results of a study by Gilmore (2015) of mineralisation and the silica–iron horizons include:

- ]/ The silica–iron rocks associated with economic mineralisation can be distinguished geochemically from those associated with barren systems by having increased Eu, enrichment in REE, and elevated Cu and Ag.
- ]/ Sulfur isotopes from these silica–iron rocks and from the ore suggest that the source of contained sulfur was reduced seawater sulfate.
- ]/ Interpretation of pyrite geochemistry (using LA-ICPMS) of the sulfide zone and overlying silica–iron horizons indicates that the hottest part of the mineralising systems was the basal zone and, based on variations in Ni/Co ratios, the magmatic to sedimentary input into the hydrothermal fluid decreased up the system.

Using this and other data, Gilmore (2015) proposed a model for mineralisation formation: Temperature- and redox-controlled cupriferous sulphide precipitation in hydrothermal cells in unconsolidated turbiditic sediments. These cells were driven by MORB emplacement during incipient Early Ordovician rifting. The overlying equivalent exhalative silica–iron horizons and their lateral equivalents formed by precipitation from cooler spent-fluids.

In conclusion, geological mapping combined with mineralisation studies may assist targeting of similar mineralisation in the Girilambone Group as:

- ) Known mineralisation is hosted by the Narrama Formation.
  - ) Structural models may help locate prospective horizons.
  - ) Mineralisation is associated with MORB (not OIB) in the footwall.
- 
- ) The Budgery Sandstone Member overlies the known ore horizon.
  - ) Magnetic silica-iron horizons lie at a similar stratigraphic level as mineralisation. Those overlying mineralisation can be distinguished geochemically from more distal horizons.

### **References**

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## Reworking of Archean (Yilgarn) basement during the Proterozoic in the Bunger Hills, east Antarctica

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The isotope-time profile of igneous rocks can be used as a geochemical tracer for the crustal evolution of geologic terranes. This is particularly important in reconstructing the tectono-magmatic history of continental margins which may involve both *in situ* crustal recycling and crustal refertilisation by the addition of new, juvenile material and accretion of exotic fragments.

The Musgrave-Albany-Fraser Orogen (MAFO) lies at the junction of the North, West and South Australian cratons and extends into east Antarctica, and is interpreted to represent the site of Proterozoic crustal growth and reorganisation along these Archean craton margins. However, little is known about the age and isotopic character of the Bunger Hills which occupies a pivotal location as the westernmost exposure of this system and one of few outcrops within east Antarctica that can be directly correlated with the Australian constituent terranes of the MAFO.

Combined U-Pb and Lu-Hf data from the Bunger Hills reveal a previously unrecognised Archean basement (ca. 2800–2700 Ma) of Yilgarn Craton affinity. These basement rocks are overlain by a Paleo-Mesoproterozoic (ca. 1700–1500 Ma) cover sequence and late Mesoproterozoic magmatic intrusives (ca. 1260 Ma and 1200 Ma) that were coeval with high grade metamorphism. Isotopic data reflect the progressive influence of an Archean crustal component during Proterozoic magmatism. Paleoproterozoic magmatism was characterised by voluminous juvenile input and minor recycling of Archean crust. In contrast, Mesoproterozoic magmatism is isotopically evolved, and is interpreted to have been derived largely from reworking of the Paleoproterozoic crust and Archean basement. Strong parallels between the age and isotopic composition of igneous rocks over time from the Bunger Hills and Albany-Fraser belt in southwest Australia suggest that the Paleo-Mesoproterozoic tectonic evolution of these two regions of the MAFO is analogous. Specifically, the Bunger Hills are interpreted to represent the Paleo-Mesoproterozoic (para)autochthonous modification of a rifted, reworked fragment of the Archean Yilgarn Craton that was extended during the late Paleoproterozoic.

## Use of the Elementary Effects approach to undertake global prediction sensitivity analyses using a regional scale numerical groundwater flow model

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Models are commonly used to provide predictions of future states of natural systems. Such predictions are typically uncertain due to various factors, including (1) the suitability of governing equations; (2) the inability to accurately characterise initial conditions, boundary conditions, or model parameters; or (3) the inherent uncertainties associated with the observed data to which model outputs are compared. The degree to which model predictions are affected by various sources of uncertainty may be assessed through the performance of sensitivity analysis (SA). When SA is undertaken as part of model calibration, it is the sensitivity of observations (not predictions) that is typically evaluated. In the present research SA was instead applied to rank the sensitivity of predictions to various parameters, and to thereby identify those parameters of greatest influence.

Sensitivity analysis methods are classified into local or global approaches. Local methods explore the uncertainty of model predictions when parameter values in the vicinity of an initial preferred value are tested. The most commonly used local SA method is the One-At-a-Time (OAT) approach, which is used in both manual and automated model calibration procedures. In comparison, global methods do not assume the existence of an initial preferred value. Instead, these approaches explore the uncertainty of model predictions when parameter values are selected from a defined interval (i.e. from a prior distribution). As such, global SA approaches are considered to provide more robust estimates of prediction uncertainty (strictly relating to parameter uncertainty, and excluding structural and measurement noise), as they involve a more comprehensive sampling of the parameter space. Examples of global SA approaches range from the highly efficient, derivative-based approach of Morris (1991) to more comprehensive approaches such as the variance-based approach of Sobol (2001) and the density-based approach of Plischke et al. (2013).

In the present research the Morris (1991) approach to global SA, also known as the Elementary Effects (EE) method, was used to estimate the sensitivity of drawdown and flux predictions produced by a numerical groundwater flow model to changes in parameter values. An existing MODFLOW-SURFACT model of the regional scale groundwater flow system of the Gunnedah Basin was used to generate predictions. This model was previously developed to estimate the hydraulic impacts of coal seam gas production. Predictions of interest included drawdown and vertical fluxes in the key confined aquifer in the basin, the Pilliga Sandstone aquifer. Model parameters tested included the horizontal and vertical hydraulic conductivity and storage properties of the ten hydrostratigraphic units represented in the model. Parameter sensitivities were then ranked in order to identify those of greatest influence .

The EE method was compared to other global approaches as well as to the local OAT approach in terms of both efficacy and efficiency. More generally, the use of SA to estimate the sensitivities of well-defined predictions to key model parameters was demonstrated. Performance of this SA provided insights into the dynamics of the regional groundwater flow system of the Gunnedah Basin.

## **Impact of pore pressure versus fluid saturation on elastic properties in Murteree Shale of the Cooper Basin**

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Understanding the effect of overpressure and fluid saturation on elastic properties is quite helpful to determine well locations and ensure safe well design. Overpressure and gas saturation may cause a similar decrease in P-wave velocity. Some authors suggest other elastic properties such as Poisson's ratio, MuRho and LambdaRho can resolve this ambiguity. The objective of this study is to compare the impact of pore pressure to fluid saturation on various elastic properties. This study focusses on the Permian Murteree shale gas play in the Cooper Basin where recent drillings results have confirmed the presence of gas accumulation and variable overpressure. To address the above-mentioned ambiguity issue, pore pressure data from DST and mud weights are compared with analyses of well logs and several rock physic models. Results show the effect of pore pressure is minor compared to fluid saturation. Poisson's ratio and MuRho show a significant increase with increasing pore pressure while P-wave velocity change is negligible.

## **The nature and causes of ‘megadroughts’ in south-eastern Australia: evidence from Holocene lake sediments, Victoria**

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Documenting and understanding centennial scale hydroclimatic variability in Australia is significant both to global climate science and to regional efforts to predict and manage water resources. In particular, multidecadal to centennial periods of low rainfall – ‘megadroughts’ – have been observed in semi-arid climates worldwide, however they are poorly constrained in Australia. Lake sediment records offer long and sensitive archives of hydrological variability over millennial timescales at up to annual resolution. Past climate variability is recorded in the mineralogy, microfossil composition, elemental and isotope geochemistry of lake sediments. Furthermore, coupled isotope-hydrological modelling facilitates a deeper understanding of the hydrological and geochemical response of lakes to climatic variability. Here, we will summarise recent efforts to document Holocene hydroclimatic variability from numerous lake sediment archives in western Victoria, Australia. Our data record the intensification of modern day ENSO driven climate variability from the mid-Holocene onwards. Furthermore, they illustrate the pervasive nature of multi-decadal and centennial scale periods of both wetter and dryer conditions. These data will be discussed in the context of the causes of hydroclimate variability in south-eastern Australia, the implications for future management of water resources and considerations for future research in the region.

## **Complex life-stage-related and environmentally diagnostic soldier crab ichnology and its preservation in beach rock along the Pilbara Coast, Western Australia – its geoheritage significance**

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Ichnology as part of geology axiomatically is subsumed under geoheritage and, as such, interesting and unique ichnofossils can be of geoheritage significance albeit at the small scale, e.g., well-developed *Skolithos* burrows and the eurypterid tracks on Silurian sandstone in Western Australia that function as environmental and palaeoecological indicators. The Western Australian soldier crab presents an unusual and unique association between crab and ichnology because as the crab progresses through life, its behaviour becomes more complex and its neichnofossils become commensurably more varied: from small, sandy clots and pustules, progressing to shallow, pellet-roofed feeding tunnels and then, when emergent and swarming, exit holes, discard feeding pellets, and re-entry rosettes. The size of tunnels, exit holes, pellets, and re-entry rosettes correspond to the age and size of the crabs. The link between crab ichnology, life stage, and behaviour is so direct that if its traces are preserved as ichnofossils, they can be used to interpret fossil crab sizes, population structures, behaviour and palaeoenvironment. In this context they comprise very important palaeoenvironmental and palaeoecological indicators.

Middle Holocene soldier crab ichnofossils occur in 5000-year old beach rock at Port Hedland, Western Australia. The ichnofossils include rosettes, pustules, pellet-roofed tunnels, and air cavities. These ichnofossils provide information on fossil crab sizes, population structures, and behaviour, and the nature of the environmental condition along the middle Holocene tidal shore. The ichnofossils are of geoheritage significance in their own right for the palaeontologic and palaeoenvironmental information they present. However, given the rarity of preservation of soldier crab ichnology, and the location of well-developed beach rock in coastal Western Australia largely restricted the arid Pilbara Coast, as compared to the paucity of beach rock in soldier crab habitats in eastern Australia and elsewhere in the Asian region, these ichnofossils are a rare and a significant geological tool for use in palaeoenvironmental and palaeoecological reconstructions, and hence are globally significant.

## Non-traditional isotopes applied to mineral exploration and grade estimation

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Isotope tracing has emerged as a new technique applied to the petrogenesis and evolution of ore deposits from their formation to later alteration. Recently, non-traditional isotopic systems, e.g. Li, Fe, U, Ti, Mo, have been proposed for use as an exploration tool. Here we present two case studies: (1) Zn isotopic signatures of ferro-manganese (FM) crusts as a robust capacity to vector to hydrothermal Zn mineralization, and (2) U isotopic signatures of U minerals and rocks for exploration for uranium deposits.

Coatings of manganese and iron oxide minerals, FM crusts, occur in various forms on a range of surface materials in the subaerial environment. Manganese oxide minerals in particular, have high adsorption capacities for transition metals, thus there is potential for such crusts to adsorb anomalous concentrations of target and pathfinder elements, thereby offering potential for geochemical exploration. A case study of FM crusts from a known Zn deposit from the Capricorn Orogen, in semi-arid Western Australia, shows that Zn liberated from an ore deposit by meteoric fluids can be preferentially adsorbed onto Mn oxide minerals within FM crusts. Concentrations of Zn in FM crusts are high in close proximity to primary ore but decrease distal to mineralization. To test a possible genetic link between the Zn in FM crusts to primary ore, non-traditional Zn isotopic analysis was performed. Low  $^{66}\text{Zn}$  values were observed for ore-zone primary sphalerite, typical for hydrothermal Zn mineralization, and similarly low  $^{66}\text{Zn}$  values were observed for FM crusts in close proximity to mineralization. However,  $^{66}\text{Zn}$  values for FM crusts became progressively higher with increasing distance from mineralization, more typical of slow Zn precipitation in low-temperature surface environments. Thus analysis of Mn oxide minerals in FM crusts can be a useful tool for geochemical exploration, but combined with Zn isotopic analyses, FM crusts offer a robust capacity to vector to hydrothermal Zn mineralization.

In another case study, we investigated the uranium isotopic compositions of uranium ores from various uranium deposit types to better understand (1) the primary mechanisms for fractionation of  $^{234}\text{U}$  and  $^{235}\text{U}$  isotopes with respect to  $^{238}\text{U}$ ; and (2) the relations between the observed variations in isotope ratios and source of uranium, processes of uranium mobilisation and transport, the mechanism of uranium capture and post-depositional fluid alteration of both ore and source rocks for all of the major types of uranium deposits. The

$^{238}\text{U}$  values of uranium ore minerals from a variety of deposits are controlled by the isotopic signature of the uranium source, the efficiency of uranium reduction in the case of  $\text{UO}_2$  systems, and the degree to which uranium was previously removed from the fluid, with less influence from temperature of ore formation and later alteration of the ore. The isotopic composition of uranium minerals changes gradually with proximity to mineralisation and this potentially can be used in exploration for uranium deposits. As there is a gradient of  $^{238}\text{U}/^{235}\text{U}$  ratios with the highest ratios distal from the redox centre, uranium isotopes may be used as exploration vectors and even for estimation of the deposit size.

## Regional 3D Mineral Maps from Hylogger Data – examples from eastern Gawler Craton

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The Geological Survey of South Australia (GSSA) has scanned over 700 drill holes across the state including over 300 drill holes in the eastern Gawler Craton. Summary information and The Spectral Geologist (TSG) files for individual drill holes can be downloaded from SARIG (<https://sarig.pir.sa.gov.au/Map>). The existing HyLogger products provide an excellent summary of mineralogy for individual drill holes but are difficult to map the spatial distribution of minerals in three dimensions. To this end the GSSA in conjunction with Deep Exploration Technologies Cooperative Research Centre (DET CRC) have developed a method to integrate multiple scanned drill holes into 3D mineral maps. The method involves down sampling the original TSG files to one metre intervals, extracting TSG mineralogy and spectral scalars, importing data into gOcad where it was then gridded in three dimensions.

The eastern Gawler Craton is a world class mineral province that contains several significant IOCG deposits including the giant Olympic Dam deposit. IOCG mineral systems have a characteristic alteration mineral assemblage that can extend kilometres from the deposit. K-feldspar-sericite forms the distal alteration assemblage and becomes progressively more intense towards the centre of the system. The deepest parts of the system have magnetite-calc silicate +/-biotite alteration assemblage. Higher in the system magnetite-chlorite alteration assemblage becomes dominate followed by hematite-sericite-chlorite alteration that forms at the highest levels of the system. The regional 3D mineral maps derived from HyLogger data were able to map IOCG alteration minerals (excluding iron oxides) across the eastern Gawler Craton.

Subtle variations in sericite and chlorite mineralogy can be identified from changes in the wavelength of the absorption minimum. Sericite alteration is made up of fine-grain white mica, usually muscovite ( $K_2Al_4(Si_6Al_2)O_{20}(OH)_4$ ) or phengite ( $K_2(Al,Mg,Fe)_4(Si_{6+x},Al_{2-x})O_{20}(OH)_4$ ). Muscovite has an AlOH absorption minimum at wavelength ~2,206 nm whereas phengite has an AlOH absorption minimum at longer wavelengths ~2,218 nm. Chlorite composition ( $(Mg,Fe_{2+},Fe_{3+},Mn,Al)_{12}[(Si,Al)_8O_{20}](OH)_{16}$ ) can vary widely. With an increase in iron content in chlorite the wavelength of the FeOH absorption minimum to shift from ~2,245 nm (Mg-Chlorite) to ~2,260 nm (Fe-Chlorite) and the wavelength of the MgOH absorption minimum to shift from ~2,325 nm (Mg-Chlorite) to ~2,340 nm (Fe-Chlorite). By plotting and gridding the absorption minimum in three dimensions subtle variations in sericite and chlorite composition can be identified. The changes in composition of alteration minerals may reflect potential sites of metal deposition.

## Tectonic Evolution of the North Qinling Terrane, Qinling Orogen, central China

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The North Qingling Belt lies within the Qinling Orogen that bisects central China to form the suture between the North China and South China Cratons. The geology of the North Qingling Belt consists of Proterozoic basement rocks of unknown tectonic affinity that include rocks interpreted to be ophiolites and Neoproterozoic accretionary complexes. The 'Qinling Group' forms the major unit of the North Qingling Belt and consists of gneisses and other metamorphic rocks intruded by Neoproterozoic and Palaeozoic magmatic rocks that are interpreted as subduction-related. In this contribution we will present new field, metamorphic, geochronological and geochemical data to constrain the tectonic evolution of this key component of this long-lived orogenic belt to better understand the tectonic geography of the southern margin of North China in the Palaeozoic. Specifically, metamorphic  $P-T$  analysis (pseudosections), petrography, age determination (U-Pb geochronology) and field work (sampling) within the belt will be presented. These will constrain the metamorphic  $P-T$  conditions which reflect the development of the North Qingling Belt. These will be complemented by the presentation of a north-south transect across the Qinling group that forms the framework for new geochemistry, and U-Pb geochronology to constrain the timing of formation and subduction of the Qinling group.

Together these data will give us a better understanding of the tectonic geography along the margin of North China through a time when the craton split from the remains of Rodinia, possibly adjacent to Siberia, and eventually collided with South China.

## Understanding the 3d Structure of the Gilmore Fault Zone through Geophysical Modelling: implications for Lachlan Tectonic Reconstructions

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The aim of the study is to shed light on the tectonic evolution of the Lachlan orogen by modelling the subsurface character of the Gilmore fault zone (GFZ). The Lachlan Orogen records a complex history with the GFZ presenting a particularly interesting puzzle piece. It marks a very distinct geophysical contrast between high-grade metamorphic rocks found in the Wagga Metamorphic Belt (WMB) to the West, and the low-grade volcanic rocks found in the Macquarie Arc and Silurian rift basins to the East. Understanding the structure of this fault zone at depth will provide important constraints on the existing models for the tectonic evolution of the Lachlan (i.e. terrane accretion, accretionary orogen or orocinal bending).

The deep crustal extent of the fault is conceptualized using 3D forward potential-field modelling and joint inversion of gravity and magnetics, constrained by existing reflection seismic profiles, and by physical properties data collected on local lithologies. Saturated density, magnetic susceptibility and Koenigsberger ratios were the physical properties collected and analysed. Since outcrop is limited, samples were taken from drill core of representative lithologies. These additional parameters allowed the refinement of both the long and short wavelength features in the model.

Parametric inversions (using simple geometric shapes) were used instead of voxel inversions to create a 3D model based on 2.5D cross section slices. Cross sections were modelled across three separate areas of interest along the fault zone. Direct inversion methods were not used as the GFZ is a geologically complex area. Data from the seismic reflection surveys conducted by the Australian Geodynamics Cooperative Research Centre (AGCRC) and the NSW Department of Mineral Resources in 1999 aided in deep crustal interpretation.

A distinction is made between the Gilmore fault (GF) and the Gilmore fault zone (GFZ): preliminary modelling has revealed that the mappable GF (between the localities of Temora and Barmedman) is a shallow, east-dipping thrust fault, but it is only a secondary antithetic structure off the main west-dipping, crustal penetrating fault that separates the Macquarie arc and the WMB. Another, steeper west-dipping fault cuts these structures and separates the WMB from the Tumut Trough, a Silurian rift basin. However, this later fault was also truncated by later west-dipping structures associated with major basin inversion and fault reactivation, probably in the Early Devonian.

At present, it is not clear what structures the GFZ should be applied to. If it is the NNW-trending structure extending toward Cobar and previously dated at 410-405 Ma, then it is the last major structure recognised in the modelling and was probably associated with basin inversion. In this interpretation, the earlier structures record extension and contraction events more closely related to construction of the Lachlan orogen, but further modelling along-strike is required to determine their true geodynamic significance.

## Cryogenian interglacial stratigraphy of the Amadeus Basin, central Australia

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Carbonate-rich strata of the Amadeus Basin in central Australia preserve evidence of changes in both the physical environment and C isotope composition of shallow seawater during the Cryogenian interglacial period. These sediments, which comprise the Aralka Formation, therefore provide an opportunity to expand the Cryogenian  $^{13}\text{C}_{\text{carb}}$  record and evaluate correlations with other Neoproterozoic basins. The upper Ringwood Mbr. of the Aralka Fm. records a negative C isotope excursion with a nadir of -4‰ that seems to correlate with excursions in the Taishir Fm. of Mongolia and the Gruis Fm. of northern Namibia. The onset of this excursion within the Ringwood Mbr. coincides with a transition from stromatolitic to laminated silty carbonate, and the nadir occurs at a contact (which we interpret as a maximum flooding surface) between laminated dolostone and overlying shallowing-upward parasequences of a highstand systems tract. Recovery to values of 3‰ begins in these parasequences and continues in overlying stromatolitic carbonate of the uppermost Ringwood Mbr. These microbialites are separated by a sequence boundary from trough cross-stratified sandy carbonate of the overlying Limbla Mbr. that have  $^{13}\text{C}_{\text{carb}}$  as high as 10‰ and which correlate with the Keele Fm. of NW Canada. This set of chemo-, litho-, and sequence- stratigraphic relationships in central Australia seems to be mirrored in mid-Cryogenian sediments of Mongolia and Namibia, suggesting that  $^{13}\text{C}_{\text{carb}}$  fluctuations of approximately 14‰ comprising the Taishir and subsequent Keele Peak anomalies occurred during a period of significant eustatic fluctuation that was apparently unrelated to global glaciation.

## Mid-Devonian basaltic magmatism and associated sedimentation of central-eastern South Australia of the Ooloo Hill Formation: a far field response to Tabberabberan orogenesis?

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Ooloo Hill Formation is a recently defined rock package occurring subsurface, adjacent to the NW Flinders Ranges (Sheard 2012; White *et al.* 2012). Two significant members are recognised: the major member is a marine sedimentary sequence (D-o<sub>1</sub>), and a more localised basaltic volcanic member with minor clastic and epiclastic sediment (D-o<sub>2</sub>).

This formation is dominated by laminated and massive greyish to tan shale and thick tan to dark brownish grey siltstone. These contain well-preserved small- and large-scale slump structures, slump breccias, crossbedding, ripple marks, small scour-and-fill structures, and fine lamellae. There are intercalated pale-hued sandstone beds.

Four main lava flows are recognised in the volcanic member (D-o<sub>2</sub>), separated by clastic sediments. Dark grey to black and dark greenish grey vesicular to massive basalt lavas display auto-breccia basal zones and some remnant auto-breccia tops. Thin laminar dark-hued fine-grained sediment intervals and tuff beds are interbedded with some of the basalts in this member. Two very thin bands of phosphatic to calcareous marine bivalves and hash also occur within one flow. The presence of these fossils indicates submarine eruptions below a water column of <300 m.

SHRIMP U-Pb detrital zircon geochronology for sediment beds of the Ooloo Hill Formation yield populations of varying age, with the youngest zircons being Early Cambrian (~510 Ma; Jagodzinski 2011 in appendix 5 of Sheard 2012). The zircon data show that the sedimentary succession and basalt flows post-date the Cambro-Ordovician Delamerian Orogeny. This is consistent with whole-rock K-Ar dates for four basalt samples that lie within uncertainty and yield an average Mid-Devonian age (~390 Ma). We infer this to be the minimum age of eruption of these basalts.

The basalts have geochemical features typical of continental, within-plate basalts which include high Ti, Zr and Y and low MgO, Cr and Ni. Trace element and REE signatures of Ooloo Hill Fm basalts closely resemble continental arc and back arc basin basalts, suggesting they were generated during high degrees of lithospheric thinning in an extensional continental arc/back arc-type setting prior to or potentially during the Tabberabberan Orogeny. The Ooloo Hill Formation demonstrates that the processes of extension that led to formation of volcano-sedimentary basins in the eastern Lachlan Fold Belt also affected regions that had been previously incorporated within the Delamerian fold belt.

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## Palaeoproterozoic syn-tectonic magmatism on Eyre Peninsula: insights from new geochemistry and geochronology of the Peter Pan Supersuite

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The Palaeoproterozoic represented a period of major crustal reworking across Australia. In South Australia, the Kimban Orogeny was a craton wide event characterised by crustal-scale shear zone development and high heat flow metamorphism, and was associated with extensive felsic and mafic intrusive magmatism. Although the structural and metamorphic architecture of the Kimban Orogeny has been investigated in some detail, little work has focused on the magmatic systems that formed during this time. Here we report new data that constrains the timing and geochemical affinities of magmatism that spans the time interval of the Kimban Orogeny, which is now subsumed within the newly defined Peter Pan Supersuite.

The Peter Pan Supersuite comprises widespread felsic and lesser mafic intrusions accompanying deformation of the Kimban Orogeny and have been characterised into three suites based on age, petrology and geochemistry.

The Moola Suite (1750–1735 Ma) comprises undeformed to weakly foliated granites to amphibolites on NE Eyre Peninsula. Granites of the Moola Suite are predominantly metaluminous, alkali- and LREE rich and preserve evolved  $\text{Nd}_{(1740 \text{ Ma})}$  values (-17.1 to -7.8). Mafic intrusions of the Moola Suite suggest a heterogenous mantle source region; enriched amphibolites are characterised by high  $(\text{La/Yb})_N$  ratios and evolved  $\text{Nd}_{(1740 \text{ Ma})}$  values (-8.8); depleted amphibolites have low  $(\text{La/Yb})_N$  ratios and higher  $\text{Nd}_{(1740 \text{ Ma})}$  values (-4.3 to 0.4).

The Pinbong Suite (1735–1700 Ma) comprises weakly foliated to migmatitic granites and gabbros and represent the most widespread suite, predominantly occurring on northern Eyre Peninsula; gabbros are found in the western and northern Gawler Craton. Granites are mostly peraluminous and LREE enriched, while gabbros are metaluminous, have slight LREE enrichment and positive Eu anomalies. Pinbong Suite granites with juvenile crustal signatures ( $\text{Nd}_{(1720 \text{ Ma})}$  values -3.5 to -0.8) are found on the NW and SE extent of the suite on Eyre Peninsula, while granites in the central region are all evolved ( $\text{Nd}_{(1720 \text{ Ma})}$  values (-11.3 to -6.4).

The Moody Suite (1710–1700 Ma) comprises undeformed to weakly foliated granites, contain abundant metasedimentary xenoliths and have restricted distribution on southern Eyre Peninsula. Moody Suite granites are LREE enriched and have crustal REE and trace element signatures.

Taken together, c. 1750–1700 Ma magmatism reveals a pattern of increasing crustal melting through time. Early mantle melting synchronous with regional extension facilitated localised lower crustal melting. Syn-Kimban Orogeny melting was extremely widespread and included both crustal and mantle source regions. Later phase melts are predominantly crustal in origin, possibly reflecting peak metamorphic conditions and intra-crustal melting during compressional orogenesis.

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## **Climate or Subsidence? Geologic Controls on the Stratigraphic Distribution of Coal Beds in the Jurassic Walloon Coal Measures, Surat Basin, Australia**

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The interplay of climate and subsidence at the time when the original peat accumulated determine the eventual lateral and vertical dimensions of coal beds. The fluvio-lacustrine Walloon Coal Measures of the Surat Basin, Australia's largest and most productive coal seam gas play, contain numerous thin (<0.4m) and discontinuous (<5km) beds which are an important consideration in exploration and understanding patterns of gas drainage around wells. The abundance of zircon yielding volcanic ash fall tuffs provides the opportunity to 1) calculate intraformational subsidence rate on timescales of <1myr and 2) accurately link the timing of deposition to global climatic events, elucidating geologic controls on coal accumulation. New results reveal tectonic subsidence rates (on average 11m/Myr through the Walloon Coal Measures) in a warm temperate climate with abundant rainfall at high latitudes (>75°S). If conditions were stable, thick, meter-scale coal beds should have formed, however, rapid climate fluctuations through the Oxfordian (<1Myr), 100kyr eccentricity cycles and three months of winter darkness may have limited the windows of opportunity for peat accumulation in the basin. Despite increasing subsidence rates providing the trigger for coal accumulation, increased seasonality, fluctuating temperatures and subsequent impacts on the overwintering of peat-forming plants could have contributed towards the thin, discontinuous nature of coal beds in the basin. Controls on the distribution of facies in other basins would benefit with similar, high resolutions studies.

## **The Correlation of Fluvio-Lacustrine Strata with Dated Volcanic Tuffs: An Example from the Jurassic Walloon Coal Measures, Australia**

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The Jurassic Walloon Coal Measures of the Surat and Clarence-Moreton Basins hosts Australia's largest and most productive coal seam gas play, containing over 33,000PJ of probable and proven (2P) gas reserves as of 2014. Coals were deposited within a 500m succession of fluvio-lacustrine strata at high latitude (>75°S) during a greenhouse epoch. Numerous thin (<0.4m) and discontinuous (<5km) coal beds within the Walloon Coal Measures pose a series of challenges for both stratigraphic correlation and gas production. The abundance of zircon-yielding volcanic ash fall tuffs interbedded within the coals provides a unique opportunity to examine chronostratigraphic relationships on a regional scale and to determine allocyclic controls on the distribution of facies. CA-TIMS techniques were used to determine precise (within an error margin of <100kyr) dates from a series of volcanic tuff beds across the Surat and Clarence-Moreton Basins. Five datums, determined by correlating volcanic tuffs of similar age were then constructed between the basins, providing for the first time a reliable stratigraphic framework for the Walloon Coal Measures on a regional scale. These dates reveal the diachronous nature of the Walloon Coal Measures from the Clarence-Moreton Basin (168Ma) into the Surat Basin (164Ma). New paleogeographic reconstructions show the location of coal-forming mires (many of which are <20km<sup>2</sup> in extent) is random with consistent SW-SSW fluvial drainage over a time span of 3.6Ma which may be related to syntectonism. These new results substantially modify existing lithostratigraphic schemes, which are not tied to any chronostratigraphic datums. Using the CA-TIMS technique may provide a useful tool in elucidating continental strata elsewhere in the world; from assisting in the construction of reliable stratigraphic frameworks and understanding the controls on facies distributions in space and time.

## Exploring the nature of the Thomson–Lachlan boundary through zircon Lu-Hf and O isotopes

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The southern Thomson Orogen of northernmost NSW is one of the least exposed provinces in Australia and the nature and location of its boundary with the northern Lachlan Orogen remains poorly understood. One candidate is the poorly characterised Olepoloko Fault: some workers interpret this crustal-scale geophysical feature as a suture juxtaposing disparate provinces; others contend that it is within the Lachlan Orogen. To test these competing hypotheses, we investigate the character of the lower crust on both sides of the Olepoloko Fault, as imaged by Lu-Hf and O-isotopes of zircons in granites with magmatic ages between 430 and 410 Ma.

Two hundred kilometres south of the Olepoloko Fault, granites from the central Lachlan Orogen (Nymagee area) indicate derivation from one or more evolved sources ( $Hf_{(t)} = -8$  to  $-3$ ,  $^{18}O_{VSMOW} = 7$  to  $10\text{‰}$ ). A similar distance to the north, granites from the inboard Thomson Orogen (Hungerford area) are isotopically similar ( $Hf_{(t)} = -8$  to  $-1$ ,  $^{18}O = 8$  to  $10\text{‰}$ ). Granites in the Cuttaburra area (proximal to the central section of the Olepoloko Fault) are similar to both groups of granites ( $Hf_{(t)} = -9$  to  $-7$ ,  $^{18}O \sim 7\text{‰}$ ). This contrasts with Thomson Orogen granites at the western end of the Olepoloko Fault close to the Koonenberry Belt (Tibooburra area) and Lachlan Orogen granites further to the east (Byrock area): both are characterised by more juvenile  $Hf_{(t)}$  (-2 to 0; 0 to +5 respectively), and  $^{18}O$  (6 to  $7\text{‰}$ ; 5 to  $8\text{‰}$  respectively) values indicating less supracrustal input.

Data coverage remains sparse in this reconnaissance study; however, we have not yet identified any contrast in Lu-Hf or O-isotopic character between the interiors of the two orogens. Granites immediately to the north of the north-dipping Olepoloko Fault in the Cuttaburra area may have been sourced from either orogen, as ‘Lachlan’ crust appears to underlie ‘Thomson’ crust here. In the southwest Thomson Orogen, the relatively juvenile Tibooburra granites lie within a NW-trending zone of distinctive magnetic character 60–120 km wide, bounded by the Olepoloko Fault and Tongo Fault. These granites may be related to the Koonenberry Belt. The lower crust of the northeastern Lachlan Orogen is also relatively juvenile, perhaps because of proximity to the Macquarie Arc. Future analyses will interrogate regional trends in this area, by analysing granites on the northern (Thomson) side of the easternmost extent of the Olepoloko Fault, and exploring links between granites in the Byrock area and those of the Macquarie Arc further east.

The status of Olepoloko Fault as a suture is not yet clear; however, our results demonstrate that isotopic variations within both the Thomson Orogen and the Lachlan Orogen appear to be larger than any north to south variation across the central section of the Olepoloko Fault. The isotopic data complements geophysical datasets and will inform future investigations, including the current pre-competitive drilling program being run by GA in partnership with GSNSW and GSQ. The drilling program will also provide samples from under cover to infill the isotopic coverage in the region.

## **Early coastal occupation and maritime resource use on the continental shelf edge, North West Australia.**

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Located on the edge of Australia's North West continental shelf, Barrow Island is optimally located to register early coastal occupation, with luminescence chronologies providing occupation dates of > 50 ka. A range of archaeological, zooarchaeological, and geoarchaeological evidence from Boodie Cave are already presenting unique insights into the changing nature of Indigenous occupation and coastal resource use in response to post-glacial sea-level rise. Faunal data in particular indicate an increasing use of dietary and utilitarian marine resources, including sea turtle and baler shell, from > 41 ka up until island abandonment around 7.5 ka. The marine assemblages reflect a variety of coastal habitats, with a 17,000-year record for the presence of a former tidal marsh or estuary. Here the archaeology is informing the palaeogeography rather than visa-versa - an important point given the high cost of offshore research. At the same time sedimentary analyses show a diagnostic change in quartz-dominated to carbonate-dominated sediments at the terminal Pleistocene, associated with rising sea-levels. Adding to this picture are micromorphological analyses that largely corroborate what is observed at the macroscale in the form of bone and plant remains but additionally provide new insights into the formation history, microclimate and site use of the cave. The Barrow Is. story can be viewed in the wider context of increasing marine resource exploitation in the Carnarvon Bioregion of northwest Australia, indicating the region was not as depauperate as initially thought.

## The Ontong Java Plateau uncovered: evidence for mass wasting on the flanks of Ontong Java and Nukumanu atolls

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The Ontong Java Plateau (OJP) in the western equatorial Pacific is the largest submarine plateau on Earth ( $\sim 1.86 \times 10^6 \text{ km}^2$ ). Despite its immense magnitude and significance to our understanding of mantle processes, submarine sedimentation, and tsunami risk in the western equatorial Pacific region, the plateau remains enigmatic. In October 2014, scientists aboard Schmidt Ocean Institute's *RV Falkor* (FK141015) mapped for the first time the seafloor surrounding Ontong Java Atoll (Solomon Islands) and Nukumanu Atoll (Papua New Guinea), situated atop the OJP.

We use new multibeam bathymetry and backscatter data to (i) characterise the submarine flanks of these atolls and detect volcanic features distinct from the carbonate atolls themselves, (ii) understand how erosional processes have influenced the morphological development of the atolls over geological timescales, (iii) identify regions vulnerable to slumping and slope incision, and (iv) model the impact of tsunamis generated by submarine slope failures. In the context of the Ontong Java and the Nukumanu atolls, a tsunamigenic submarine landslide could cause inundation of these low-lying inhabited atolls (max. elevation of Ontong Java ~13 m, and Nukumanu ~2 m).

The irregular morphology and distinctive boomerang shape of the Ontong Java Atoll suggest extensive submarine erosion, sector collapse of an antecedent subaerial volcanic edifice, or morphology of the original volcanic island. Sizeable lobate aprons (~4 km across) on the southern and eastern flanks and bights around the entire atoll indicate active erosional processes and submarine mass wasting, potentially providing energy and sediment downslope to Kroenke Canyon. Multibeam sonar reveals that the steep flanks (30-50° in the upper 500 m) of Ontong Java and Nukumanu atolls are characterised by slump scars and have hummocks at the base of the atoll slope - evidence for submarine mass wasting. In addition, we observe evidence for submarine slides on Ontong Java Atoll as convex contour lines directly downslope from bights in the atoll rim. Atolls are prone to submarine landslides and/or edifice failures, due to over steepening of flanks (especially in regions of high carbonate production), sediment instabilities, erosion of the slope toe, and earthquakes, all of which can cause tsunamis. The location of these atolls in the western equatorial Pacific Ocean makes them vulnerable to earthquakes and tsunamis related to circum-Pacific subduction zones. High-resolution bathymetric maps are essential to understand of how catastrophic wave energy propagates shoreward across the plateau, to identify regions prone to slope failure, and to assess potential tsunami risk to island communities.

## Dynamics of the Main Central Thrust: insights from the Alaknanda valley, Garhwal Himalaya

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During the Himalayan orogeny, a deep crustal wedge of high grade rocks comprising the Greater Himalayan Sequence (GHS) was emplaced atop cold Proterozoic rocks of the Lesser Himalayan Sequence (LHS). At present, there is no clear consensus on the mechanism by which this emplacement occurred. Part of the problem is that we do not understand enough about the shear zone facilitating the tectonic transport: the Main Central Thrust (MCT). The position and architecture of the MCT across the wider Himalaya is highly contentious, and the many criteria used to define it are often in direct conflict with one another. Moreover, because we lack a clear understanding of the MCT structure, we are as yet unable to gather insights on its dynamics and mechanical behaviour.

In the Alaknanda Valley, the MCT is thought to be split into two parallel high strain thrusts separated by a thick quartzite. We have used quartz textures and microstructural analyses to gather empirical observations across the MCT, and to better constrain the stress, strain and strain rate. We have found that quartz CPOs shift from weak rhomb-< $\alpha$ > slip to stronger prism-< $\alpha$ > slip up-sequence suggesting increased temperatures (>550°C). Quartz CPO strength, indicative of strain magnitude, peaks in a quartzite unit between two thick mylonites, and subsequently weakens into the GHS. The distribution of strain along strike suggests that the MCT is a single high strain zone, ~6km in thickness that includes the high strain quartzite. Our paleopiezometric measurements suggest a gentle decrease in stress from 27MPa in the cooler rocks of the LHS to 15 MPa in the hot rocks of the mid-region of the GHS. When combined with published P-T estimates, as well as the thickness estimates derived from our texture analyses, a velocity profile of the MCT can be constructed, from which strain rate can be derived and the rheological parameters of quartz during deformation can be calculated independently. The position of the shear zone is in the temperature region where rock viscosity is most sensitive to the thermal gradient. This work lays out the basis for the use of thermochronology studies to constrain the timing and duration of this tectonic event, which will in turn help us understand the rate of GHS emplacement and the thermal evolution of the shear zone.

## **High-temperature normal movement on the Main Central Thrust, Sikkim Himalayas**

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The Miocene-age Main Central Thrust (MCT) is a 2000 km shear zone that placed hot rocks of the Greater Himalayan Sequence above the Lesser Himalayan Sequence creating an inverted metamorphic sequence. In Sikkim, India, the MCT has been folded around a central duplex of Lesser Himalayas rock in its footwall, forming a 50-km wide domal feature. We found that in the western side of this dome, the MCT has been reactivated as a 3km-wide normal shear zone, inferred from asymmetric kinematic indicators. Normal movement overprinted thrust-related structures within the high-grade migmatites and gneisses of the Greater Himalayan Sequence, but generally erased evidence of thrusting in the structurally lower metasedimentary rocks. The metamorphic mineral parageneses indicate that normal movement started close to peak metamorphic conditions and continued as the sequence cooled. These findings have two significant implications: they establish a) that thrusting and metamorphic inversion occurred while the rocks were still hot, a point contested in this region; and b) that normal movement interrupted thrusting before significant cooling occurred. We compared the spacing between isograds. We found that the spacing is only one third of those where only thrusting is recorded from which we conclude that normal movement telescoped the isograds. This is the first normal reactivation recorded on the MCT anywhere along its length. The fact that it occurred at the margin of a large domal feature suggests a causal relationship: doming of the MCT caused by duplexing on the footwall forced a partial relaxation of the southward thrusting of the Greater Himalayan Sequence in the hanging wall. This is an ideal area to combine high and low-temperature geochronology to determine the impact of movement inversion on the thermal evolution of the package, and to determine the time of the switch, and by inference the time of doming of the MCT around the duplex.

## **Geochemical and Sm-Nd isotope constraints on the origin of the ca 1780 Ma high heat producing Napperby Granitic Gneiss, Aileron Province, central Australia**

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Large regions of Proterozoic Australia contain extraordinarily elevated levels of U and Th compared to global averages. In comparison with global norms, the contemporary heat flow from Proterozoic Australia is around 60% higher. While a number of studies have focused on the implications of elevated U-Th contents for the tectonic development of the continent, there has been less attention focused on the origin of the continental-scale U and Th enrichment.

The ca 1780 Ma protolith to the Napperby Gneiss (Napperby Granite) is one of these high heat producing granites, outcropping over a length scale of 100km through the southeastern part of the Reynolds Range, in the Aileron Province of central Australia. It intrudes the ca 1800 Ma Reynolds Range Group, and by stratigraphic inference, the slightly older Lander Rock Formation (ca 1840 Ma), which forms basement to the Reynolds Range Group. The Napperby Granite was a mica bearing granite. Geochemically it is relatively homogeneous and slightly less SiO<sub>2</sub> rich (68 to 76%) than the older ca 1800 Ma high heat producing granites that intruded metasedimentary packages in the central Aileron Province. Like those suites, it is also slightly to moderately peraluminous. As with the ca 1800 Ma suite, the Napperby Granite is depleted in Nb, Ti and Zr. In contrast to the 1800 Ma suites, it has a slightly less negative Eu anomaly, and a steeper REE pattern. Its calculated heat production rate averages about 5.5  $\mu\text{W/m}^3$ , and ranges from about 3 to 25, although most samples are between 3 and 11.

Sm-Nd isotope constraints indicate a dominant crustal source, although available isotope data for exposed metasedimentary rocks of the Lander Rock Formation and overlying Reynolds Range Group indicate these metasedimentary rocks are too evolved to produce the isotopic composition of the melts that formed the Napperby Granite. As in the case for the ca 1800 Ma granitic suite, a more juvenile source component is required.

## Quantification of Ochreous and Vitreous Goethite using Reflectance Spectroscopy

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With the decrease in current, high-grade hematitic iron ore resources in Australia, mining companies are increasing their use of alternative, lower grade ores, such as the goethite-rich Marra Mamba ores. These iron ores contain more alumina, higher loss on ignition (LOI) and finer particle size that significantly impact on the sinter quality and sintering performance of iron ore fines (<6.3 mm) material. This is particularly relevant for the softer, limonitic or ochreous goethite (OG) ores. Distinguishing these ore types from the more competent, vitreous goethitic (VG) ores would be beneficial in improving ore sorting and maximise ore processing efficiency.

Ochreous and vitreous goethite are spectrally distinct in the visible to near-infrared wavelength (380–1100 nm) range, and can be routinely identified in drill core and RC chips using, for example, the CSIRO HyLogger™. Vitreous goethite shows a broad, asymmetric crystal field absorption (CFA) feature at 900 nm (CFA900), whereas the absorption feature for ochreous goethite is relatively sharper and more symmetric. A spectral index, the full width half maximum (FWHM) of the CFA900 feature separates OG from VG: OG has a low FWHM value of 1.1–1.2, compared to VG with a FWHM value of 1.25–1.4.

Representative examples of OG and VG ores (5 samples each) from an operational iron ore mine, were dry sieved to +16 mm, +9.5 mm, +6.7 mm, +4.75 mm, +2 mm, +1 mm, +150  $\mu\text{m}$  and -150  $\mu\text{m}$  size fractions. Reflectance spectra of each size fraction, covering the visible, near-infrared and shortwave infrared wavelength range (380–2500 nm) were used to assess the influence of particle size on the spectral discrimination of OG from VG. Despite the loss of some textural information, spectral distinction of OG and VG ores was possible for all size fractions, including the finest, -150  $\mu\text{m}$  sized material.

To establish a spectral method for quantifying the ochreous/vitreous goethite content, a series of OG-VG ore mixtures were prepared, in 10 wt% increments, using the -150  $\mu\text{m}$  size fraction. Using the spectral FWHM value, estimates of the OG content to +/- 6 wt% at 95% confidence limit (CL) were achieved. However, the accuracy of the spectral model was dependent on the absence of other ore and contaminant phases in the mixtures. The presence of kaolinite induced asymmetry to the CFA900 feature resulting in ochreous goethite showing a more vitreous spectral signature. Similarly, hematite in amounts > 10 wt% also resulted in ochreous goethite showing a more vitreous spectral signature. In combination, the presence of hematite in moderate amounts ( 10–20 wt%) appeared to counteract the effect of kaolinite in OG-VG mixtures where both phases were present.

The findings of this work highlight the importance that composition exerts over the spectral nature of ochreous and vitreous goethite and the extent to which reliable identification of these goethite types can be made. More broadly, these results emphasize the importance of understanding fully the physical and chemical compositional characteristics of iron ore in selecting the most appropriate characterisation and sorting methodologies to optimise performance.

## Newly discovered occurrences of the Paney Rhyolite and associated volcaniclastic deposits, Narlaby Well area, Gawler Range Volcanic Province

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The Mesoproterozoic Upper Gawler Range Volcanics succession is dominated by felsic coherent facies interpreted as silicic lava flows hundreds of meters thick. Rare volcaniclastic facies locally overlie the Paney Rhyolite Member and thus provide potential stratigraphic markers. The Geological Survey of South Australia (GSSA) recently undertook geological field mapping along the southern margin of the Gawler Range Volcanic Province complimenting a large regional drilling program run by the GSSA (Mineral Systems Drilling Project - MSDP).

During field work, previously unrecognised occurrences of the Paney Rhyolite were discovered on Hiltaba Station in the vicinity of Mount Friday and Eurilla Hill (Narlaby Well area) in the northwestern part of the Gawler Ranges. These newly discovered occurrences currently represent the northwesternmost known outcrops of the Paney Rhyolite, extending its lateral extent to ~200 km.

On Hiltaba Station, the quartz- and feldspar-phyric Paney Rhyolite occurs as two NW-trending series of outcrops and is represented by flow-banded coherent facies occurring at the northern margin of the plagioclase-phyric Eucarro Rhyolite lava flow. Of particular interest are the outcrops near Mount Friday as here the coherent facies of the Paney Rhyolite is locally overlain by volcaniclastic deposits. The upper part of the Paney Rhyolite is typically veined by cryptocrystalline chalcedonic silica. This coherent but fractured volcanic facies grades upwards into coarse breccias characterised by highly angular rhyolite clasts and clast-supported texture. The latter facies is interpreted as the autoclastic carapace of the underlying lava flow.

These autoclastic breccias are overlain by matrix-rich, poorly sorted, coarse volcaniclastic breccias characterised by angular to subrounded rhyolite clasts. These rocks are succeeded by finer grained and moderately sorted volcaniclastic breccias and pebble-granule conglomerates interbedded with massive medium- to coarse-grained volcaniclastic sandstones and laminated fine-grained sandstones to siltstones. This fining-upward succession is interpreted as fluvially reworked volcaniclastics sourced from the underlying autoclastic rhyolite. This reworked volcaniclastic facies records surface water runoff on top or along the margin of the Eucarro-Paney lava flow with local deposition and preservation in shallow palaeo-depressions.

The newly discovered volcaniclastic deposits at the northern margin of the Paney Rhyolite are of regional significance as the only other known volcaniclastic rocks within the Upper Gawler Range Volcanics, the Mount Double Ignimbrite near Paney and silicified sandstones near Nonning, occur at the same stratigraphic level forming an important marker horizon. Recently drilled holes in the region intersected volcaniclastic rocks from the same stratigraphic position and provide a valuable comparison to field exposures. Drill cores enable the study of clast shapes and textures, bedding structures, contact relationships and depositional trends in great detail and provide more continuous and better quality records of these volcaniclastic successions than natural outcrops. The combined information from drill core and outcrop enhances characterisation and interpretation of these deposits and improves the picture of their lateral distribution and variation.

## From migmatites to fayalite-bearing, ferroan granites: how does the Palaeoproterozoic Arnhem Province fit into the North Australian Craton?

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The North Australian Craton (NAC) comprises rare Neoarchean basement inliers overlain by Palaeoproterozoic metasedimentary and metaigneous rocks with evidence of collisional orogenesis at ca. 1875–1855 Ma in the Halls Creek and Pine Creek orogens. The Arnhem Province, an isolated Palaeoproterozoic inlier of the NAC located ~300 km east of the Pine Creek Orogen, comprises previously poorly understood succession of gneisses, migmatites, and voluminous S- and A-type granitic rocks. Similarities in the timing of geologic processes to other Proterozoic terranes in the northern NAC are evident; however the nature of these events can be markedly different.

The Melville Bay Metamorphics within the Arnhem Province comprise migmatitic metapelite and metapsammite previously interpreted to be part of extensive turbidite deposition covering much of the northern NAC after ca. 1860 Ma. New SHRIMP U-Pb zircon dating indicates the Melville Bay Metamorphics represent an older succession deposited prior to ca. 1895 Ma, with similar detrital zircon provenance and maximum depositional ages for the Cahill Formation and Nourlangie Schist of the Nimbuwah Domain (Pine Creek Orogen) and the Marboo Formation (Halls Creek Orogen).

The sedimentary protoliths to the Melville Bay Metamorphics were metamorphosed to granulite facies conditions (>825 °C and 0.6–0.8 GPa) between ca. 1872 Ma and ca. 1862 Ma. This produced a network of former melt-bearing veins and dykes that preserve evidence of melt formation, migration and pooling to form plutons of Prp<sub>20</sub>-Alm<sub>80</sub> garnet- and cordierite-bearing Drimmie Head and Bawaka S-type granites dated at ca. 1872–1862 Ma. These events in the Arnhem Province are synchronous with collision-related metamorphism, deformation and I-type bimodal magmatism in the Nimbuwah Domain and the Halls Creek Orogen. In the Nimbuwah Domain, metaluminous, calc-alkaline granite, granite–granodiorite, and less abundant diorite and gabbro emplaced during metamorphism at 650°C and >0.9 GPa are interpreted to represent the root zone of a continental arc.

Approximately 40 m.y. later, voluminous fayalite±clinopyroxene-bearing A-type granites of the Giddy Suite intruded the Arnhem Province region. The ca. 1830–1825 Ma Giddy Suite comprises four phases, with cross-cutting relationships coupled with geochemical evolution trends providing evidence of distinct pulses of magmatism. The source of this magmatism is enigmatic and it is noteworthy that coeval magmatic rocks of mafic–intermediate composition are absent at the present level of exposure. Older mafic rocks occur as xenoliths entrained in the S-type granites and rarely exposed mafic dykes are attributed to the much younger Mesoproterozoic Galiwinku Dolerite. Rocks similar in composition and age to the Giddy Suite are not currently recognised in the Pine Creek Orogen.

Though the Arnhem Province shares some similarities with the Pine Creek Orogen, further work is required to examine their relationship and the tectonic setting of metamorphism and magmatism in the Arnhem Province. Such data would also have implications for correlating the Arnhem Province with other Proterozoic terranes in the northern NAC.

## Distinguishing local- and regional-scale metasomatic systems

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Geochemical alteration in mafic rocks of the Fortescue Group around the Prairie Downs Zn-Pb-(Cu-Ag) deposit, Western Australia, is the result of two overprinting metasomatic systems. The first was a regional-scale event recorded widely across the Hamersley Basin to the north and resulted in extensive depletion of alkalis, Mg, and heavier first transition series metals (Mn-Zn), accompanied by the formation of epidote/pumpellyite-quartz rocks. The second, localized event was associated with Zn-Pb mineralization and resulted in Ca-loss accompanied by enrichment in a sedimentary exhalative (SEDEX)-like element suite (Zn-Pb-Sn-Ag-K-Ba-Tl-Sb-Ge-U-Th-Cd-Hg-Se-REE). The second, mineralization-related event was superimposed on the earlier regional-scale system: previously unaltered basalts underwent growth of biotite and Zn-bearing chlorite at the expense of epidote and amphibole; regionally metasomatized rocks now comprise assemblages dominated by quartz, muscovite and baileychlore (Zn chlorite). In all cases, these altered basalts host Zn within chlorite in a broad (km-scale) halo around the main sulphide zones, thereby providing an expanded exploration target. Recognizing and distinguishing the two separate systems is vital for exploration as some observed chemical zonation around the deposit (e.g. Fe and Mn depletion) are related to the earlier regional-scale system and not the later mineralizing event. Geochemical modelling with HCh indicates that the observed alteration assemblages can be generated through interaction of rocks with large volumes of a saline, Zn-K-bearing fluid (fluid/rock ~1000). This study highlights the importance of understanding the regional geochemical background when investigating local metasomatic systems in order to correctly characterize them, determine their origin and position within a regional framework, and to correctly identify vectors towards mineralization to aid future exploration.

## Strongly seasonal Proterozoic glacial climate in low paleolatitudes: A radically different pre-Ediacaran world

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Proterozoic (pre-Ediacaran) glaciations occurred under strongly seasonal climates near sea-level in low paleolatitudes. Metre-scale primary sand-wedges in Cryogenian periglacial deposits in South Australia and elsewhere are identical to those forming, by the infilling of winter thermal contraction-cracks in permafrost by windblown sand, in present-day polar regions with a mean monthly air-temperature range of 40°C and mean annual air temperatures of -20°C or lower [1,2]. Varve-like rhythmites with dropstones in Cryogenian and Paleoproterozoic glacial successions imply an active seasonal freeze-thaw cycle [1,3]. The seasonal (annual) oscillation of sea level recorded by tidal rhythmites in Cryogenian glacial successions indicates a significant seasonal cycle and extensive open seas [1,2]. Paradoxically, paleomagnetic data determined *directly* for Proterozoic glacial deposits and closely associated rocks give low paleolatitudes: Cryogenian deposits in South Australia formed at 10°, most other Cryogenian deposits at <20° and Paleoproterozoic deposits at <15° [1,2,4]. High-paleolatitude pre-Ediacaran glaciation is unknown, whereas Phanerozoic glaciation is circum-polar. Paleomagnetic data show the Proterozoic geomagnetic field approximated a geocentric axial dipole, hence paleolatitudes represent geographic latitudes [4].

The Cryogenian glacial environment included glacier-free permafrost regions, periglacial sand-sheets, extensive and long-lived open seas, and an active hydrological cycle [1,2]. The paleoenvironment, with large seasonal changes of temperature near the equator, cannot be accommodated by the 'snowball Earth' and 'slushball Earth' hypotheses. Consequently, their advocates have downplayed the evidence for strong seasonality by introducing Popperian 'auxiliary assumptions' [1,2]. Non-actualistic arguments that Cryogenian sand wedges indicate diurnal or weak seasonal temperature changes are based on misunderstandings of periglacial processes and are negated by voluminous periglacial research. Modelling of a strongly seasonal climate for a frozen-over Earth is invalidated by the presence of persistent open seas and glacier-free continental regions during Cryogenian glaciations, and gives a mean monthly air-temperature range of only 10°C for 10° latitude.

A strongly seasonal Proterozoic glacial climate in low paleolatitudes, based on *actualistic* interpretations of geological features, accords with a high obliquity of the ecliptic (Earth's axial tilt, now 23.5°) during the pre-Ediacaran [1–3]. The obliquity controls the strength of the global seasonal cycle and the sign of climatic zonation. For an obliquity >54°, low latitudes would receive less solar radiation annually than high latitudes and would be glaciated preferentially, the seasonal cycle would be greatly amplified over continents, and global habitability would be low because of high seasonal stresses. Glaciation could be globally synchronous or diachronous. A high obliquity is a likely result of a giant impact on the early Earth that evidently produced the Moon [2]. Reduction of obliquity to <54° during the Ediacaran, to permit Phanerozoic circum-polar glaciation, reduce seasonality and increase global habitability, may imply major mass-redistribution within the Earth as revealed by Ediacaran true polar wander [4] coupled with 'obliquity-oblateness feedback' [2].

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## Are spatially variable records of overprinting metamorphism related to inherited zones of retrogression and structural weakness? Unravelling polymetamorphism in the Terre Adélie Craton (east Antarctica) and formerly contiguous Gawler Craton (South Australia)

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Polymetamorphic signatures in rocks can be difficult to deconvolve, especially where overprinting events have similar metamorphic grade. In situ and erratic samples from the Terre Adélie Craton, Antarctica, and in situ samples from the formerly contiguous Gawler Craton, South Australia, are examined to deconvolve microstructural, pressure–temperature and geochronological evidence of terrane-scale polymetamorphism. In situ monazite U–Pb geochronology shows that coastal and erratic samples record 1720–1690 Ma and 2450–2400 Ma ages, consistent with known ages of the Kimban and Sleafordian Orogenies, respectively. In situ samples from the Antarctic coast record exclusively 2450–2400 Ma ages, whereas most erratic samples from the glacial moraines at Cape Denison record only 1720–1690 Ma ages. In combination with measured mineral chemistry, phase equilibria forward modelling for the Red Banks Charnockite (southern Gawler Craton; c. 2000 Ma emplacement age) uniquely constrains peak metamorphic conditions of the 1720–1690 Ma Kimban Orogeny to ~4.0–7.5 kbar and 700–950 °C, corresponding to apparent thermal gradients of ~95–240 °C/kbar. Peak metamorphic conditions of the 2450–2400 Ma Sleafordian Orogeny, constrained by in situ samples from the Terre Adélie coast, are ~5.0–8.0 kbar and 720–850 °C, corresponding to apparent thermal gradients of ~100–140 °C/kbar.

Considerable overlap exists between the  $P$ – $T$  results for samples recording the 2450–2400 Ma and 1720–1690 Ma events. However, peak  $P$ – $T$  conditions for the older event are arguably slightly higher pressure and lower temperature than the younger event. Perhaps as a consequence of their similarity in  $P$ – $T$  conditions, the record of polymetamorphism is cryptic and spatially variable in the rock record. Antarctic samples that only record 1720–1690 Ma Kimban ages are interpreted as reflecting either complete overprinting or development subsequent to the older 2450–2400 Ma Sleafordian event. In contrast, rocks recording only 2450–2400 Ma ages are interpreted to have remained unaffected by the Kimban overprinting event despite being witness to it. This study highlights the careful approach required when unravelling the  $P$ – $T$  evolution of polymetamorphic terranes, and argues that a spatially variable record of overprinting metamorphism is possibly related to locations of retrogression and structural weakness occurring either in the waning/exhumation stages of earlier events or between superimposed events.

## New geological and geochronological constraints on the origin of the Prominent Hill hematitic IOCG deposit, Gawler Craton, South Australia

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The Prominent Hill IOCG deposit lies immediately south of a steeply-dipping reverse fault forming part of thrust duplex that juxtaposes two distinct rock associations of the Mount Woods basement domain respectively composed of a metamorphic-plutonic complex (north) and Archean rocks overlain by essentially unmetamorphosed Proterozoic rocks (south). It is also immediately north of (stratigraphically below) an interpreted disconformity/unconformity in the steeply-dipping and overturned stratigraphic sequence in the footwall of the fault. This feature separates a shallow marine siliciclastic-carbonate sequence with a maximum (detrital zircon U-Pb) age of ca 1750 Ma from a package of high energy subaerial sedimentary (maximum age ca 1590 Ma) and predominantly mafic to intermediate volcanic rocks. The latter have primary enrichment of incompatible elements (including the ore-associated elements Ba, LREE and U) compared to mafic Gawler Range Volcanics in other parts of the craton, as do some intrusive rocks in nearby parts of the northern Mount Woods Domain including the large White Hill gabbro complex (U-Pb zircon age 1562±14 Ma).

Relatively unaltered rocks interpreted to be equivalent to the Prominent Hill hosts occur in a similar structural position 10-15km west of the mine. These contain abundant early-formed tectonic breccias derived by fracture boudinage of interlayered mudrock-dolostone. The main Prominent Hill (Malu) orebody includes the same type of breccia whose carbonate matrix is now replaced by hematite. Textural evidence and a Re-Os age of 1734±9 Ma indicate that other Prominent Hill host rocks with a coarse clastic component contain detrital pyrite (now largely replaced by Cu-bearing sulphides) implying that the parent rocks were carbonaceous. Carbonaceous rocks are notably preserved in the host sequence at the discrete Ankata orebody 2km west of the Malu open pit mine.

Deposit-related alteration extends southwards (i.e. stratigraphically-upwards) into the volcanic-sedimentary sequence and geopetal features indicate at least some mineralization occurred after the sequence was tilted into its current orientation. U-Pb dating of hydrothermal monazite from the orebody gave a range of ages between ca 1.6 and 1.1 Ga whereas Sm-Nd isotopic data for Prominent Hill ore samples are consistent with a ca 1.6 Ga age of (REE) mineralization. Epsilon Nd (1590 Ma) values for REE-enriched ore samples are between -5.5 and -3.5 (i.e. distinctly less than published values for Olympic Dam ore and mafic dykes but similar to White Hill gabbro samples (ca -4.1) and published values from magnetite bodies in the northern Mount Woods subdomain).

Prominent Hill differs from the large granite breccia-hosted hematitic IOCG deposits such as Olympic Dam and Carrapateena in the (eastern) Gawler craton in its (a) deformed orogenic foreland margin setting and (b) essentially sedimentary-hosted in rocks whose primary character (coarse clastic, early breccia, labile carbonate and detrital pyrite-carbonaceous components) influenced the localization of the deposit.

Regionally-anomalous (incompatible element-enriched) rocks and/or magmas of the GRV-Hiltaba granite LIP may have been significant sources of ore components and it is entirely possible that mineralization occurred during basin inversion by focussed fluid flow at the regional unconformity beneath the GRV-equivalent sequence

## What lies beneath the western Gawler Craton? Interpretations and implications from deep crustal seismic reflection profile 13GA-EG1

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The eastern section of deep seismic reflection profile 13GA-EG1, here referred to as 13GA-EG1E, starts at Tarcoola in the central Gawler Craton and extends west across the predominantly covered western Gawler Craton, and into the thickly covered Coompana Province. Limited control on the crystalline basement imaged by this seismic transect is available to aid seismic interpretation, as outcrop and drilling are sparse. Neoproterozoic-recent cover thickens to the western end of 13GA-EG1E, with the Neoproterozoic-Ordovician Officer Basin and Cenozoic Eucla Basin combining to provide a cover thickness of up to ~2.5 km. Hence, the seismic profile is a crucial tool for understanding the geology and crustal evolution of this area.

The upper crust of the Gawler Craton can be sub-divided into three distinct domains, corresponding to domains previously defined by aeromagnetics. The Wilgena Domain, at the eastern end of the profile, is characterised by apparent east-dipping structures, whereas the Christie and Nawa Domains predominantly contain apparent west-dipping structures. Some of these upper crustal structures can be traced to greater depths, where they either flatten out in the lower crust, or in several cases, offset the Moho. These structures are interpreted to represent multiple phases of extension and basin development as well as being multiply reactivated during compressive deformation associated with several orogenic events recognised within the Gawler Craton. These include the Sleafordian (c. 2440 Ma), Kimban (c. 1730-1690 Ma), Kararan (c. 1600-1580 Ma) and Coorabie (c. 1450 Ma) orogenies. Viewing this seismic section in conjunction with potential field data, especially aeromagnetic imagery, it is apparent that a significant component of deformation along shear zones in the western Gawler Craton is accommodated by strike-slip movement, particularly in the c. 1450 Ma Coorabie Orogeny. This adds another layer of complexity when resolving apparent offsets of seismic horizons.

Magmatism is recorded as bland zones in the upper crust in the Gawler Craton. Several Kimban-aged (i.e. c. 1730-1690 Ma) granites are recognised as thin, sheet-like bodies in the upper part of the Christie Domain. In contrast, the Mesoproterozoic Hiltaba Suite forms a series of prominent, irregular bland zones that occur throughout the upper crust of the Wilgena Domain. Similar seismically bland zones are associated with Hiltaba Suite intrusions that are known to host iron-oxide copper gold mineralisation at Olympic Dam, further east in the Gawler Craton.

The Gawler middle crust is characterised by a series of bland zones, which are separated by west-dipping reflective layers that correspond to crustal-scale shear zones. The lower crust of the Gawler Craton is characterised by sub-horizontal to shallowly west-dipping reflectors.

Seismic profile 13GA-EG1E offers the first look at the margin of the Gawler Craton with the Coompana Province. This boundary is interpreted to be a west-dipping shear zone (the Jindarnga Shear Zone), which juxtaposes Palaeo- to Mesoproterozoic granitic rocks of the Coompana Province over Archaean-Palaeoproterozoic rocks of Gawler Craton upper-middle crust.

## **War Service and Career of Cecil Charles Morton, GSQ's first economic geologist**

**Withnall, Ian**

Geological Survey of Queensland

Cecil Morton was born in Toowoomba in 1891. He attended the Charters Towers School of Mines and graduated with honours in Mining and Metallurgy in 1911. For the next two years he worked in the Chillagoe and Mount Perry mineral fields as a mining surveyor.

In 1914, he joined the Geological Survey of Queensland (GSQ) as a Field Assistant and was sent back to Charters Towers to work with JH Reid re-mapping the goldfield. This work was interrupted when he joined the AIF in July 1915.

Morton gave his occupation as a mining engineer. Like his colleagues from the GSQ, Leslie Blake and Walter Bryan, he was assigned to the artillery. He embarked for overseas service in November 1915. In July 1916, he was promoted to 2<sup>nd</sup> Lieutenant in the field during the Battle of the Somme. Later that year he was promoted to Lieutenant and transferred to the 105<sup>th</sup> Howitzer battery where he joined his GSQ colleague, Leslie Blake.

He was mentioned in dispatches during April 1918 and in the final phase of the war, during the attack on the Hindenburg Line in late September 1918, Morton was awarded the Military Cross for his actions in commanding his section while under heavy enemy barrage. Just 5 days later, he was present when Leslie Blake was fatally wounded by a stray shell. Morton helped him to the aid station but Blake died the next day. Morton was promoted to Captain just before the Armistice.

He returned to the GSQ in 1919 and for the next 15 years was employed as a geologist in mining fields in various parts of Queensland and again assisted JH Reid in geological mapping in the Brisbane Valley and the Bowen River coalfield. Morton was the first GSQ geologist to make economic geology a speciality, undertaking detailed studies of individual deposits, paying attention to the structures and their controls on mineralisation.

In 1934, the GSQ decentralised, and Morton was sent back to north Queensland, where for 11 years he was based at the Charters Towers District Office, forming close relationships with the mining and prospecting community.

Morton was appointed Chief Government Geologist in 1946 and faced staff shortages and inadequate office accommodation at a difficult time in the GSQ's history. Nevertheless, his tenure saw the introduction of two important initiatives in 1950. The first was the joint regional mapping with the newly formed Bureau of Mineral Resources, a programme that was to run for the next 25 years and underpinned the development of Queensland's resources industry. The second was the foundation of a Coal Section following recommendations of the Powell Duffryn Report. Diamond drilling commenced on the West Moreton and other coalfields and eventually led to the discovery and development of much of Queensland's significant Bowen Basin coal resources.

Morton suffered a serious accident in 1950, which led to a decline in his health. He returned to work full-time in late 1955, but died from a heart attack two weeks later.

## Sapphires, rubies, and the Wilson cycle

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Sapphire and ruby deposits are clustered in certain geographic areas and are often associated with major tectonic belts such as the Pan-African and Himalayan Orogens, observations that point toward potential links with plate tectonic processes. This study uses oxygen isotope data ( $^{18}\text{O}$ ) from sapphire and ruby to investigate this link.  $^{18}\text{O}$  from a global compilation of sapphire and ruby geochemical data define four groups. The first group (low  $^{18}\text{O}$  rubies) is associated with rocks of mafic to ultramafic compositions that mainly occur in Madagascar, southern India, and Sri Lanka. The second group consists of sapphires with  $^{18}\text{O}$  centred on the mantle value of 5.5‰, presumably reflecting mantle involvement in their formation. Sapphires of the third group (high  $^{18}\text{O}$  sapphires) are spatially restricted but occur, primarily, on islands or continental margins with a history of orogenic events. The final group, which is made up of rubies with high  $^{18}\text{O}$ , occur in marbles and are restricted to the Himalayas.

We propose that  $^{18}\text{O}$  differences that define the four groups are fundamentally related to the plate tectonic processes of subduction and continental collision. Group 1 rubies (low  $^{18}\text{O}$ ) are concentrated in the East African Orogen and may be associated with hydrothermal circulation during continental collision. The largest accumulation of Group 2 sapphires ( $^{18}\text{O}$  ~5.5‰) is in eastern Australia, suggesting that this group is associated with long-lived subduction and Al-enrichment of the mantle wedge. Both Groups 3 and 4 (high  $^{18}\text{O}$  sapphires and rubies, respectively) are associated with metamorphism during continental collision. High  $^{18}\text{O}$  rubies occur in metamorphosed platform carbonates that are prevalent in the Himalayan region, whereas high

$^{18}\text{O}$  sapphires are formed by later metasomatic events and are relatively restricted. On a global-scale, therefore, sapphire and ruby formation is associated with key stages in the Wilson cycle, with the exception of continental break-up. This important omission illustrates that Al-enrichment and/or metamorphism, processes that are not generally associated with rifting, are key in the generation of sapphire and ruby.

## The role of fluorine in the formation of the giant Olympic Dam Iron Oxide-Cu-Au deposit

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The importance of fluorine for understanding the genesis of the Olympic Dam (OD) supergiant Fe-Cu-Au-U-REE deposit has been recently postulated by a number of studies that noted the abundance of this element at the OD deposit. The extracted ore contains ~2.5 wt% of fluorite ( $\text{CaF}_2$ ), adding up to ~106 Mt fluorine. McPhie et al. (2011) linked the high concentrations of fluorine in the OD ores to the flow of fluids through the F-rich Mesoproterozoic Gawler silicic large igneous province, and suggested that fluoride complexing of metals may be important in explaining the metal contents at OD. We investigated this hypothesis using thermodynamic modeling, and also performed experiments to evaluate the stability of  $\text{Fe}(\text{II})\text{-F}$  complexes at elevated temperature.

One hypothesis is that the Fe-rich nature of the OD ores is related to the transport of Fe as fluoride complexes. The current consensus is that Fe is transported as  $\text{Fe}(\text{II})\text{-chloride}$  complexes in most crustal fluids. However, at room temperature, the  $\text{FeF}^+$  complex is more stable than the  $\text{FeCl}^+$  complex. No experimental data is available on Fe-F complexing at high temperature, but some extrapolations suggest that  $\text{Fe}(\text{II})\text{-F}$  complexes become stronger with increasing temperature. Our *in situ* X-ray absorption spectroscopy (XAS) data show that although  $\text{Fe}(\text{II})$  fluoride complexes predominate in F-rich solutions at low temperature (~100°C), increasing temperature causes precipitation of  $\text{Fe}(\text{II})$  fluoride solids from F-rich solutions, so that above 200°C there was no detectable Fe left in the solution. Hence, fluoride is unlikely to play a role in base metal transport at OD.

We investigated the potential of granitic rocks as a source for (at least some of the) REE and U using thermodynamic calculations. The simulated rock assemblage consists of muscovite-quartz-microcline-annite (biotite)-hematite-uraninite- $\text{LaF}_3$  (as a proxy for REE fluorocarbonate minerals)-fluorite and fluorapatite. Lanthanum concentrations show a minimum at temperatures ~300°C, but saline fluids have the capacity to carry high REE concentrations (>10 ppm) either at relatively low (<200°C) or high (>400°C) temperatures. REE are carried as chloride complexes and possibly as hydroxide complexes at high temperatures, and REE fluoride complexes do not contribute significantly to REE mass transfer. Our results also show that U solubility is mainly controlled by temperature. Again U(IV/VI) fluoro-complexes do not appear to carry significant amounts of U. Uranium mobility at low temperature requires the presence of ligands such as carbonate and sulfate.

The REE contents are closely associated with the hematite content in the OD breccia, with increasing hematite contents accompanied by higher REE abundances. Therefore, an oxidized, relatively low temperature (150-300°C) chloride-bearing fluid may be responsible for the REE leaching and transporting at OD and felsic magmas may be the source for REE. Fluorine may not be important as a complexing agent for metal transport, but may be a factor causing iron-oxide and REE to precipitate.

## **Twenty-four development models of geotourism**

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Research on geotourism can be conducted in six different areas. These include natural landscape, geological heritage interpretation and protection, geographical characteristics of tourist destinations, special interest tourism, geoscience popularisation for mass tourism, geological tourism and tourism geology. This paper defines the concept of geotourism and the resources associated with it. Geotourism is considered as a temporary departure from a person's residence to acquire spiritual satisfaction and enjoyment through experiencing and appreciating geological heritage and natural landscape. There are nine major types of geological heritage which can be classified under stratigraphy, structural geology, petrology, mineralogy, paleontology, geological hazards, geomorphology and hydrogeology. They can further be expanded into forty-seven sub-types to cover all geological features. By assessing the values of geological heritage and the degree of visitors' encounter, three different forms of geotourism could be identified, namely random, incidental and continual forms of geotourism. However, when based on the functions of geological heritage, geotourism can be categorised into eight types: sightseeing, learning-oriented, exploratory, metaphorical, leisure, entertaining, food/accommodation and shopping. The combination of these three forms and eight types of geotourism creates the twenty-four scenarios which can be taken as the development models of geotourism. Three Chinese geoparks are then studied in detail to test the models and to provide a better understanding of their geotourism development. The models are used for setting directions and strategies for development of tourist destinations.

Keywords: geosciences, geotourism, geological heritage, models, geoparks

## Mineral chemistry mapping within an IOCG system, Olympic Cu-Au Province, South Australia

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The Iron Oxide Copper Gold (IOCG) mineral province of the eastern Gawler Craton plays host to economically important large to giant mineral deposits and has potential to host additional, as yet undiscovered resources. Exploration in the province is hampered by deep cover and has relied on sparse drilling into potential field geophysical anomalies, which are proxy measures for IOCG systems at best (measuring hematite and magnetite rather than copper and gold). This study is focussed on characterising the mineralogy and chemistry of these sparsely distributed drill holes and understanding how this can be used as an indicator of the nature and size of IOCG mineralising systems. In turn, this can be used to decrease the risks of exploration.

We present the results of optical microscopy, SEM, Electron Microprobe (EM) and Laser Ablation ICPMS analyses on selected samples from the Olympic Cu-Au Province. We use these data to comment on the mineralogical deportment of trace pathfinder elements that hold potential to map 10s of kilometre scale exploration vectors within an IOCG system. Both petrographic observation and mineral chemistry mapping indicate that K-feldspar, chlorite, oxide minerals and sulphides controlled the distribution of key elements in the system. K-feldspar controlled enrichment of Rb and Ba and depletion of REE (less than PAAS). Chlorite was found to contain elevated concentrations of Cu and S. Petrologic observations provide evidence for two stages of chlorite, both containing Cu and S in their structure. The first chlorite stage has relatively low concentrations of Cu (7.5-80 ppm) and S (167-470 ppm) compared to the second stage that has generally higher concentrations of Cu (128-195000 ppm) and S (220-20500 ppm). Of the oxide minerals, hematite consistently overprints magnetite in the petrogenesis. Hematite has >7 times Cu, Th, U, Mo, Nb, Ba, Ta, Pb and REE content compared to magnetite. Chalcophile pathfinder elements (eg. Ag, As, Bi, Cu, Sb, Se) are dominantly deported in sulphides which overprint these assemblages. Pyrite is the most common sulphide, with chalcopyrite increasing in abundance closer to mineralisation. Co/Ni ratios in pyrite range from 0.18 to 9.75 with the majority ranging from 1.43 to 9.75, indicating a hydrothermal origin. The n-type pyrite ( $\text{Fe/S}_{\text{atom}}$  0.49-5.0) has 0-0.02 wt% Cu and p-type pyrite ( $\text{Fe/S}_{\text{atom}}$  0.56-0.71) has stable 0.1-0.11wt% Cu. At elevated concentrations, within altered rocks, REEs are deported in hydrothermal apatite. This indicates the high capacity of the hydrothermal system to mobilise, and locally accumulate, even the most refractory elements. It was found that REE enrichment can be used as a good proximity indicator to ore, since it only occurs at high concentrations in the centre of the system.

## Hainan Island (south China) in the Nuna breakup and Rodina assembly

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Hainan Island in the southernmost China has the unique 1.43 Ga crystalline rock package as one of the two oldest Proterozoic basement rocks for the Cathaysia Block. Understanding the Proterozoic tectonics of Hainan Island is thus essential for constraining the paleogeographic positions of the Cathaysia Block in the Precambrian supercontinents Nuna and Rodinia. We report here new geochronological and Hf–O isotopic results for Mesoproterozoic gneisses, metavolcanic and metasedimentary rocks from Hainan Island. Together with published data from the region, we divide Mesoproterozoic rocks on Hainan Island into three major tectonostratigraphic units: (1) the amphibolite-facies Baoban Complex, consisting mainly of 1.43 Ga volcanic/plutonic rocks and minor sediments formed in a continental rifting setting and were subsequently highly metamorphosed during the 1.3–1.0 Ga Sibao orogeny; (2) the greenschist-facies Shilu Group, consisting of 1.43 Ga rifting sediments with 1.44–1.43 Ga tuffs in the fifth layer and 1.0 Ga foreland fold-and-thrust sediments in the sixth layer, all of which underwent greenschist metamorphism during the 1.3–1.0 Ga Sibao orogeny; (3) the unconformably overlying Shihuiding Formation, consisting of 1.0 Ga sediments probably deposited in a distal foreland basin. Continental-wide provenance and magmatism correlations amongst Hainan Island, western Laurentia, Tasmania and western Yangtze suggest of a united Cathaysia–Laurentia landmass, and it was neighboured with Tasmania during the ~1.43 Ga. The Hainan Baoban–Shilu groups, the Tasmania lower to middle Rocky Cape Group and the western Laurentia Belt–Purcell Supergroup probably all received commonly-sourced rifting sediments from the Cathaysia basement rocks during the ~1.43 Ga Nuna breakup. The Hainan 1.43 Ga magmatism was probably the extension of the 1.50–1.35 Ga trans-continental granite–rhyolite province. Later on during the ~1.0 Ga Rodinia assembly, the Sibao orogeny which welded the Yangtze and Cathaysia blocks to form the united South China Block probably brought Tasmania, Yangtze and the Cathaysia–Laurentia together, and shed the uplifted orogenic detritus to foreland basins such as the local Hainan Shihuiding Formation, the western Yangtze Kunyang Group, the Tasmania upper Rocky Cape Group and the western Laurentia Deer Trail Group.

## The Ediacaran–Silurian Nanhua foreland basin in South China: response to the Gondwana assembly

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This study presents the temporal and spatial tectonostratigraphic and provenance evolution of the Ediacaran–Silurian Nanhua basin in South China and explores the relationship between clastic sedimentation in the basin and evolution of the adjacent Wuyi–Yunkai orogen. Sedimentary facies in the basin comprises, in an ascending order, turbiditic marine, shallow marine and fluvial-dominated deltaic facies, featuring a lateral migration from southeast to northwest. We interpret the Ediacaran–Silurian Nanhua basin as a foreland basin with a three-stage tectonostratigraphic evolution history. Stage 1: the Ediacaran–Cambrian stage, recording the start of tectonic subsidence with turbiditic marine siliciclastic deposition, fed by exotic orogens outboard South China; Stage 2: the Ordovician to earliest-Silurian stage, characterised by a migrating depocentre with dominant shallow marine and deltaic siliciclastic deposition, fed by the local and northwestward propagating Wuyi–Yunkai orogen; Stage 3: the Silurian stage, showing the arrival of depocentre in the Yangtze Block during the waning stage of the orogeny with deltaic deposition in the remanent foreland basin. The Wuyi–Yunkai orogen remained the dominant sedimentary source region during Stage 3.

Furthermore, in-situ U–Pb and Hf isotopic analyses of detrital zircons from sixteen Cambrian–Silurian siliciclastic samples across the Nanhua foreland basin are conducted for provenance studies. Together with published data from Ediacaran–Silurian sandstones in the region, we establish the temporal and spatial provenance evolution across the basin. Except for samples from the northeast part of the basin, all other Ediacaran–Silurian samples exhibit a prominent population of 1100–900 Ma, moderate populations of 850–700 Ma and 650–490 Ma, and minor populations of 2500 Ma and 2000–1300 Ma, grossly matching that of crystalline and sedimentary rocks in northern India. Zircon Hf isotopes further reveal four episodes of juvenile crustal growth at 2.5 Ga, 1.8 Ga, 1.4 Ga and 1.0 Ga in the source regions. Utilizing the basin history and late Neoproterozoic to early Paleozoic paleogeography of South China, we conclude that the Ediacaran–Cambrian sediments in the Nanhua foreland basin were mainly sourced from northern India and adjacent orogens, and the Ordovician–Silurian sediments were derived from both locally recycled Ediacaran–Cambrian rocks and eroded Cathaysian basement. The Wuyi–Yunkai late-orogenic magmatic rocks also contributed to the Silurian sediments in the basin. The upper-Ordovician to Silurian samples in the northeast part of the basin received higher proportions of local Cryogenian (850–700 Ma) magmatic rocks which were uplifted during late-Ordovician to Silurian time.

We speculate that there was an Ediacaran–Cambrian collisional orogen between South China and northern India during the assembly of Gondwana, shedding sediments to the early Nanhua foreland basin, and Stage 1 was likely related to this collision. Far-field stress during the late stage of this collisional orogeny triggered the Ordovician–Silurian intraplate Wuyi–Yunkai orogeny in South China, and erosion of the local Wuyi–Yunkai orogen further provided detritus to the late Nanhua foreland basin. Stages 2 and 3 recorded sedimentation during the northwestward propagation and subsequent orogenic root delamination/collapse of the Wuyi–Yunkai orogen.

## Elastic Properties of Lacustrine Hydrocarbon-bearing Shale using core analysis data

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Unconventional reservoirs are keys to oil and gas exploration and development, especially shale gas reservoirs. Discriminated shale gas reservoir lithofacies are, in particular, a primary problem in shale gas reservoir engineering. The mineral composition and microstructure will affect both absorbed and free gas contents, and hydraulic fracturing operation. Therefore, their identification is important. This paper takes Chinese lacustrine shale gas reservoir as an example, proposes the standard of lithofacies classification and a method to discriminate them which are suitable for shale gas reservoir.

Typical test analysis for lacustrine shale gas reservoir rock include: X-ray diffraction (XRD), rock-eval, thin section microscopy (TSM), triaxial stress test. The mineral composition is one part of lithofacies, and the contact relations of mineral crystal are also important. Base on XRD and rock-eval, mineral composition and total organic carbon (TOC) are obtained. Clay mineral contents are around 22.5%~68%, the average value is 48.44%. Quartz contents are around 7.3%~30.8%, the average value is 17.36%. Feldspar mineral contents are around 22.5%~68%, the average value is 48.44%. And the average of pyrite and carbonate is 2.0%, 6.94%. TOC varied significantly from 1% to 13%. From triaxial rock mechanical test, compressive strengths of rocks are obtained from the differences between axial pressure and confining pressure through the relationship between strains and stresses. The compressive strengths of lacustrine organic shale are around 36~124Mpa, the average value is 68Mpa. The static elastic parameter, Young's modulus, is calculated from load increment, deformation, samples' size in elastic range. The results shows that Young's modulus varies significantly under isotropic stress conditions with respect to the organic matters, clay content and pores. Young's modulus is around 8707~25485Mpa. According to the feature of the shale samples, the standards of lacustrine shale are established following: clay content 50%, TOC 4%, compressive strength 50Mpa and 100Mpa, the ratio of Young's modulus and compressive strength 230.

We form a mathematical method and apply it to shale gas reservoirs to discriminate lithofacies. Decision tree is used here. However, there were too many well logs to discriminate all lithofacies precisely. Principal component analysis PCA is a technique used to reduce multidimensional data sets to lower dimensions for analysis. This technique can be useful in petrophysics and geology as a preliminary method of combining multiple logs into a single entity or two logs without losing information. Combining PCA and a decision tree algorithm, the lithofacies of a shale gas reservoir were accurately discriminated.

## Coupled plate tectonic reconstructions and mantle convection models of the eastern Tethys

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Plate tectonic reconstructions have played a central role in explaining regional and global geological evolution. However, classical “plate” reconstructions typically do not fully embrace tectonic principles, which require consideration of the entire plate rather than “drifting” continental fragments. Major advances have been made over the last decade in coupling plate tectonic reconstructions to numerical models of mantle convection. We apply a modern methodology, using the *GPlates* open-source and cross-platform plate reconstruction tool, to model the evolution of entire plates that reconciles seafloor spreading histories with the continental geological record in a post-Pangea timeframe. Where oceanic lithosphere has been lost to subduction, the synthetic portion of plates is inferred from assuming seafloor spreading symmetry from preserved oceanic crust, or from geological indicators of past ocean basin opening and closure from evidence of terrane rifting and accretion. We apply the plate velocity fields from the plate reconstructions as surface boundary conditions for global numerical mantle flow models using the finite element *CitcomS* code. To validate the plate reconstructions, we compare the predicted present-day distribution of slab material to fast seismic velocities in P- and S-wave seismic tomography. This is especially important considering the complexity of subduction in a spherical mantle shell that cannot be untangled from the present-day snapshot from seismic tomography alone. The numerical models capture the temperature- and pressure-dependence of viscosity and end-member mantle radial viscosity profiles, and assimilate oceanic lithospheric thicknesses and subduction zone locations. In addition, we test competing plate reconstruction scenarios where the geological constraints are vague, such as in the successive Tethyan ocean basin opening and closure driven by the northward transfer of Gondwana-derived terranes.

We test end-member interpretations of the latest Jurassic rifting event from northern Gondwana, which included the enigmatic Argoland (likely to be East Java and West Sulawesi), as well as the continental and arc fragments of the Sepik terrane on PNG and the embryonic fragments of the Philippine Arc, respectively. The global nature of the mantle flow models requires the application of reasonable numerical model parameters to reproduce slabs at the expected depths and lateral distributions, rather than fine-tuning parameters to fit a single subduction zone in a regional numerical model.

The results indicate prolonged intra-oceanic subduction in the NeoTethys, and our models for the first time reproduce the enigmatic Proto South China Sea slab at approximately transition zone depths north of Borneo. The refined plate reconstructions for PNG suggest that an Early Cretaceous back-arc was subducted in Late Cretaceous to Eocene times, which can account for a slab interpreted beneath Lake Eyre on the Australian continent at a depth of ~800 km. Importantly for Australia, the geodynamic evolution of the circum-Gondwana margins play a significant role in understanding the formation of hydrocarbon and mineral resources, as well as the evolution of topography, ocean circulation, climate and sea level changes, as well as faunal and floral exchanges.

## Mantle flow controlling the advance and retreat of shallow seas in Southeast Asia

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The Sundaland continental promontory, as the core of Southeast Asia, has recorded a complex tectonic history of convergence between Eurasian, Tethyan, Pacific and Australian plates. Both geodynamic models of mantle convection and inferences of seismic tomography point to the existence of a 'slab burial ground' beneath this region. The sinking slabs explain the long-wavelength low-lying topography where almost half of the overriding continental area is flooded by a shallow sea. If dynamic topography, as the surface expression of mantle convection, plays a significant role at present-day, then the ephemeral nature of this mechanism suggests that the region may have also experienced dynamic uplift at some time in the past.

Southeast Asia is a mosaic of accreted continental and arc fragments, delineated by a complex network of sutures representing ancient ocean basins that have since been lost to subduction. Not only is it difficult to reconstruct the regional plate tectonic evolution, Southeast Asia's paleogeography has also been punctuated by extended periods of submergence and emergence that are out of sync with eustatic sea level changes. Most notably, the Late Cretaceous to Eocene regional unconformity marks a prolonged period of erosion and non-deposition that cannot be explained by tectonic or flexural mechanisms alone. The regional nature of the missing sedimentary sections has been previously explained as the effect of long-wavelength mantle-driven topography. However, so far no attempts have been made to model or test this mechanism of Southeast Asia flooding and emergence that link deep Earth and surface processes.

We synthesise seafloor spreading histories with continental geology to assemble plate reconstructions of Southeast Asia embedded in a global plate motion model, using the cross-platform and open-source *GPlates* tool. We build seafloor age-grids and evolving plate boundaries that are assimilated into numerical models of mantle convection using *CitcomS*. Mantle flow is driven by plate velocities and subducting slabs that are applied as surface boundary conditions, with heating applied at the core-mantle boundary. The predicted mantle structure is validated using interpretations of P- and S-wave seismic tomography, and estimates of residual topography are compared to the predictions of dynamic topography at present-day.

We demonstrate that a ~10-15 Myr hiatus in subduction, caused by the accretion of the Woyla Arc and Argoland continental fragment (East Java and West Sulawesi) onto southern Sundaland at ~80 Ma, led to broad dynamic uplift of the region. Renewed subduction from ~60 Ma caused strong dynamic subsidence and flooding from ~40 Ma, even during periods of significant long-term sea level falls. This pattern of flooding in the mid-Cretaceous, emergence in the Late Cretaceous and Eocene, and renewed subsidence since the late Eocene is supported by paleogeographic reconstructions of the region, and highlights the dominance of deep Earth processes controlling the advance and retreat of shallow seas in Southeast Asia

## **Long-wavelength mantle structure and supercontinent evolution since the Palaeozoic**

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The Earth's lowermantle structure, as revealed by seismic tomography studies, is best characterized by two large low shear velocity provinces (i.e., LLSVPs, or superplumes) beneath Africa and the Pacific, and the surrounding, circum-Pacific fast shear velocity anomalies (i.e., a globally spherical harmonic degree 2 structure). Two competing ideas have been proposed to explain this degree 2 structure. The first is that the African and Pacific superplumes have remained largely unchanged for at least the last 300 Myr and possibly much longer. In contrast, the other proposes that the African superplume has been dynamically coupled with the formation and breakup of the supercontinent Pangaea, and did not until sometime after the formation of Pangaea at ca. 320 Ma. According to the latter idea, the mantle in the African hemisphere was predominated by cold downwelling structures during the assembly of Pangaea, whereas the Pacific superplume could have been in existence before the Pangaean superplume. Our global geodynamic simulation results are consistent with the latter idea. A cold downwelling is predicted for the African hemisphere during Pangaea assembly using a classic plate reconstruction model. The model predicted surface dynamic topography evolution, and frequency of geomagnetic polarity reversal, are also consistent with observations. Further examinations of these and other hypotheses are ongoing using higher-resolution plate reconstructions and extending to deeper geological time.

## The Hainan flood basalts: a deep plume origin prompted by the encircled subductions at Southeast Asia

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The Hainan flood basalts, locating at The Hainan province of China, are a paradigm of the volcanic activity in Southeast Asia. Beneath this region, geophysical investigations identified a plume-like seismic structure with azimuthally 500 km size, as well as deep-subducted slabs down to the lower mantle or near the core-mantle boundary (CMB). Therefore, a plume named with Hainan is proposed to be responsible for popularly spreading volcanic activities in this region. A special character of the Hainan plume is that it is isolated within the Eurasian mantle downwelling zone and almost encircled by Indo-Australian and Pacific subduction zones. This character is very different from other large number of classic plumes that occur dominantly above either African or Central Pacific superplumes. Without the superplume origin, the generation mechanism of Hainan plume is enigmatic. Recent geochemical study discovered these basalts with deep mantle origin and age to the late Cenozoic. A young, and Lower Mantle-root plume is therefore very possible.

Here, we use a geodynamic model to explore the origin of Hainan plume as well as its driving force. Our study aims to test whether encircled subduction zones could produce a deep plume as geophysical and geochemical observables. Our geodynamic model has a high resolution regional domain embedded in a relatively low resolution global domain, which is set up in an adoptive-mesh-refined, 3D mantle convection code ASPECT. The top mechanic boundary condition of the global domain uses the latest plate motion reconstruction from GPlates project. In a series of experiments, we explore the effects of various important mantle parameters on the mantle plume generation. The experiments suggest that the west Pacific subduction promotes the initiation of Hainan plume 50 Ma ago. The plume initiated from the CMB. As the head rising, the plume head moves toward to west, and finally situates beneath the South China Sea. The Indo-Australian cold slab acts like a cold wall from the southwest side in the mantle since 80 Ma ago. We also find that the fossil slab from much older north Tethys subduction plays a moderate role in blocking the deep mantle hot structure escaping to north side. Our model results are not sensitive to whether a chemical layer (possible D'' layer) on the CMB.

## **Investigation the supercritical CO<sub>2</sub> injected in carbonated rocks with X-ray tomography analysis**

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Injected CO<sub>2</sub> in the reservoirs is green and efficient choice for the enhanced oil recovery operations, and also could be suggested for the carbon storage to reduce the warmhouse gas in the atmosphere. However, the reservoir condition is always at high pressure and high temperature (HTHP) environment: the CO<sub>2</sub> is at supercritical condition and with the formation water could be treated as acidic fluid with pH values as low as 3~4. At the same time, the carbonate reservoirs are wildly presented around the world, it is also known that the carbonates could react and dissolve in the acid environment. Therefore, the CO<sub>2</sub> injection in the carbonated reservoirs could result in rock dissolution and associated series of problems such as rock layer collapse or earthquake.

We thus have conducted core flooding tests on the typical carbonated rock - Savonnières limestone at reservoir condition (15 Mpa confining pressure and 50°C temperature). Several technical equipment (e.g. stress sensor, and ultrasonic tools) were used for monitor the changing characteristics on the limestone core plug exposed to supercritical CO<sub>2</sub>, like porosity, dynamical permeability and elastic modulus acquired before and after the flooding process. The X-ray scanning also was applied to "see" the structure inside the rock.

We indeed observed a significant dissolution (wormholes formed) of the plug sample from the x-ray tomography associated with porosity increase; permeability increase and elastic modules decrease. The wormholes formed could strongly influence the rock mechanical behaviour, which explained by the elastic modules reduced.

## Iron isotope behaviour during mineralization and K-feldspar alteration: A case study of two types of gold deposits from the Jiaodong Peninsula, East China

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Mechanisms for Fe isotope fractionation in hydrothermal mineral deposits and in associated K-feldspar alteration remain poorly constrained. Two types of gold deposits have been recognized in the Jiaodong Peninsula, East China: the Linglong-type (L-type), comprising auriferous quartz veins; and the Jiaoja-type (J-type) of gold-bearing sericite-altered rocks. Both types of gold deposit belong to the same metallogenic system and are directly comparable in terms of geology, geochronology and geochemistry. L-type gold deposits are hosted within narrow open fracture systems, and the J-type deposits are in relatively closed regional ductile-shear fracture systems. The well-documented geological settings of these deposits and the good constraints on the composition and physical-chemical parameters of the ore-forming fluids make them a natural laboratory amenable to study fractionation mechanism of Fe isotopes in a hydrothermal system.

We have analyzed a suite of bulk samples of granite displaying K-feldspar alteration, Precambrian metamorphic rocks and pyrite by multi-collector inductively-coupled mass spectrometry. Pyrites from the J-type ores show a  $^{56}\text{Fe}$  variation from 0.00 to +0.63‰, which overlap with the signature of the host granites (+0.22 to +0.56‰). In contrast, pyrites from the L-type quartz veins show a wide range of Fe-isotopic composition from -0.78 to +0.79‰. Note in particular the negative values which are not seen in the J-type pyrites. The Fe isotope signature of the host granite with K-feldspar alteration is significantly heavier than that of the bulk silicate Earth. The Fe isotopic compositions of Precambrian metamorphic rocks across the district display a narrow range between -0.17‰ and +0.18‰, which is similar to most terrestrial rocks.

The concentrations of major and trace elements in bulk samples were also determined, so as to evaluate any correlation between Fe isotope composition and degree of alteration. We note that during progressive K-feldspar alteration to rocks containing >70 wt.% SiO<sub>2</sub>, >75 ppm Rb, and <1.2 wt.% total Fe<sub>2</sub>O<sub>3</sub>, that the iron isotope composition of the granite changes systematically. The Fe isotope signature becomes heavier as the degree of alteration increases.

The extremely light Fe isotopic compositions in L-type gold deposits may be explained by Rayleigh fractionation during pyrite precipitation in an open fracture system. We note that the sulphur isotopic compositions of pyrite in the two types of ores are also different. Pyrite from J-type ores have a systematically 3.5‰-higher  $^{34}\text{S}$  value (11.2‰) than those of pyrite from the L-type ores (7.7‰). There is, however, no correlation between Fe and S isotope signatures. The isotopic fractionation of sulphur is used to constrain the change in  $f\text{O}_2$  of the hydrothermal fluids responsible for pyrite formation.

This work demonstrates that the Fe isotope composition of pyrite displays a significant response to the pyrite precipitation process in a hydrothermal systems and that systematic fractionation of iron isotopes occurs during K-feldspar alteration of granite. The implications of the results are that processes of mineralization and fluid-rock reaction, which are ubiquitously observed in porphyry-style Cu-Au-Mo and other hydrothermal deposits, may be readily traceable using Fe isotopes.

## **Methane adsorption capacity investigation of gas shale formations in Canning Basin, Western Australia**

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Adsorbed gas cannot be neglected in the evaluation of shale gas reservoirs, since a significant proportion of gas is stored in the form of adsorbed gas. Gas adsorption capacity is an essential parameter to assess adsorbed gas in shale gas reservoirs. In this study, high pressure methane isotherm approach has provided some insights into the characterization of methane adsorption capacity of gas shale in the Canning Basin, Western Australia. Gas adsorption capacity of the shale samples from Canning Basin were measured by the high pressure volumetric analysis (HPVA) apparatus. The effects of organic composition and clay minerals on methane adsorption capacity were analysed. Correlation of methane adsorption capacity with total organic carbon (TOC) has been shown to establish a linear regression equation. The ratio of TOC to methane adsorption capacity is affected by clay minerals, such as illite in clay-rich shale samples as well. In addition, low pressure N<sub>2</sub> and CO<sub>2</sub> adsorption were also employed to provide information of pore volume, surface area and pore size distribution of the shale samples. Pore structure information offers reasonable explanations to the relationship between methane adsorption capacity and TOC. The study results contribute to the development of adsorbed gas evaluation of shale gas reservoirs in the Canning Basin.

## **Occurrence of Potential Harmful Elements (PHE's) around abandoned mines in South Africa: A case study at Albert Silver Mine, Mpumalanga Province**

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The study focused on the occurrence of potential harmful elements (PHE's) within and around the abandoned Albert Silver mine. The work involved sampling and analysis of soil, sediments, and waste rocks. The samples were analysed in-situ using portable X-ray fluorescence spectrometry (XRF-Delta Professional Model) set at soil mode. As, Cu and Pb were high in both waste rocks and soil with maximum values (ppm) of 567 and 433 As, 5738 and 5682 Cu, 4002 and 2614 Pb respectively. High concentrations (ppm) of Cr (91), Ni (59) and V (89) were recorded in waste rocks; however Zn (817) and Se (12) recorded high concentrations in soil. From the XRF results, it is evident that the soil around Albert Silver mine is high in As, Cu, Zn, and Se. Consequently, high concentrations (ppm) of As (90) and Cu (205) were recorded in sediments. This study recommends the rehabilitation of the waste rocks dumps in order to minimise the dispersion of PHE's into the environment.

**Keywords:** Abandoned mines, potential harmful elements, Albert Silver Mine, Mpumalanga, South Africa

## Unravelling multi-stage ore formation from a mineralogically zoned deposit to determine the validity of geochemical footprints

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Mineralogical and geochemical zonation in sedimentary base-metal deposits evolve through space and time due to changes in host rock chemistry, fluid sources and structural influences. Lateral zonation and alteration haloes can extend into distal, unmineralised rock providing a far-field signal of mineralisation that can be used as a vector towards the ore deposit. These geochemical ‘footprints’ are tools to pinpoint resources in under-explored or covered areas during mineral exploration.

Abra is a buried Fe-Pb-Cu-Zn-Ba-Ag-Au deposit hosted within the 1620 – 1485 Ma Edmund Group in the Capricorn Orogen, Western Australia. It sits in a regional network of reworked crustal fault systems that follow the suture zone between the Pilbara Craton and Gascoyne Complex. Mineralisation is confined to shallow marine siltstones and dolostones, unconformably overlain by deltaic sandstones recording several events of subsidence and uplift. Vertical mineral zoning follows stratigraphy but vertical zoning of Pb, Zn, Cu, Ag and Au does not. All the zones are cross-cut by later mineralised veins.

SEM texture and phase imaging illustrates the spatial phase distribution in overprinting textures, providing a temporal context for quantitative geochemical analysis. In-situ LA-ICP-MS indicates trace element correlations between lead and Sb, Tl, Bi, Ag, zinc and Cd, Ag, copper and Au, Ag, gold and Cu, Ag, As, Sb, and silver and Au, Cu, Zn, Sb, As. SIMS stable isotope analysis on oxygen in quartz, and sulphur in pyrite, track the changes in fluid and sulphur source during growth, alteration and shearing of generations of grains. The results are applied to a deposit-scale framework of bulk-rock analysis on core samples from correlating sedimentary bodies, away from the ore-body. Oxygen and hydrogen isotopes from all zones in mineralised and unmineralised cores plot within the sedimentary to metamorphic range (9-15  $^{18}\text{O}$ ; -37-95 D), consistent with mineralising fluid derived from the sedimentary basin. Bulk-rock XRF data has identified geochemical footprints with enrichment of MgO and  $\text{Fe}_2\text{O}_3$ , and a depletion in  $\text{TiO}_2$ ,  $\text{CaO}$ ,  $\text{K}_2\text{O}$ , Y, and V towards the mineralisation zone. Pb, Zn and Cu decrease away from the deposit whereas Ba is high throughout. High values of Pb, Zn, and Cu occur in faulted areas or in particular sedimentary bodies.

Evidence point to the zonation at Abra being primarily a result of lithological variation as basinal fluids circulate to form the deposit. Later hydrothermal and faulting events have remobilised and concentrated ore minerals, altering their distribution in zones. Enrichment and depletion haloes surrounding the deposit provide distal vectors towards mineralisation but must be traced laterally along a correlating sedimentary body to avoid variation due to lithology.

## The Future of Mineral Exploration in the Cloud

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The global mining industry seeks reduction in the cost and risk in its search for new mineral resources – the intelligent use of geoscience big data to drive discovery of buried objects. A Mineral Exploration Cloud Laboratory is a vision for a future virtual laboratory in ‘big data’ science that will directly support these needs, advancing the integration of physical, chemical and dynamic properties of the Earth needed by the Exploration Industry and Research sectors. The opportunity is to connect five frontier developments into a breakthrough, low-cost cloud-based technology designed for Australian and global mineral prospecting (1) Seeing beyond what the eye can see using high-resolution geophysical images reflecting physical properties beneath the Earth’s surface; (2) Big Data technologies to interrogate Petascale data; (3) Automatic image analysis: deep Earth objects can be detected automatically by linking currently-dispersed collections of satellite and airborne-survey images, trained with “ground-truth” data and advanced machine learning. (4) Spatial-temporal data analysis: combined spatial-temporal analysis of big, time-dependent geoscience data will drive the search for undiscovered ore bodies beneath the surface. (5) Online services: inexpensive services would give users the ability to analyse data in the cloud across entire data collections. Mineral Exploration in a Cloud Laboratory could aggregate global geoscience imaging data sets, initiate new ones, and build a large scale cloud-data collection for use in Mineral Exploration and Geoscience Research. It could offer a series of web-based services that offer derivative products such as ore-targeting maps derived from cloud-held big data. Dramatically reduced costs and increased capabilities, from affordable remote sensing and big data in the cloud, will enable advanced and affordable online services.

We illustrate this concept with a “small data” case study for South American subduction-related porphyry ore deposits, using an iPython Notebook running on the cloud-based GPlates Portal ([portal.gplates.org](http://portal.gplates.org)). Using the recently released pygplates software ([www.gplates.org](http://www.gplates.org)), we apply spatio-temporal analysis to age-dated ore deposits to isolate the tectono-magmatic parameters leading to the formation of metalliferous copper deposits during subduction. We focus our analysis on plate convergence rates and directions, the age of the downgoing plate through time and ore deposit proximity to the plate boundary. We test two machine learning techniques, the ‘random-forest’ ensemble and ‘support vector machine’ classification methods to identify and quantify tectonic parameters that are robust predictors of Andean ore deposit formation. We find that a combination of rapid convergence rates (~100 km/Myr), subduction obliquity of ~15°, a subducting plate age between ~25-70 Myr old, and a location far (>2000 km) from the boundary of a subducting trench represent favorable conditions for porphyry magmatism and related ore deposits to occur. This allows us to broadly predict where and when ore deposits may have likely formed along the Andes, creating a foundation for predicting ore deposits along other (paleo-) subduction zones. The ideas outlined here represent an opportunity for a future Virtual Geophysics Laboratory, building on previous investments by AuScope, Nectar, NCI and a SIEF-funded Big Data Knowledge Discovery project.

## Reconstructing the formation of the Ninetyeast Ridge, Indian Ocean

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Late Mesozoic to Early Cenozoic Indian Ocean seafloor reveals complex patterns of crustal accretion attributed to both tectonic and mantle plume processes. The Ninetyeast Ridge (NER) is an aseismic, linear volcanic chain running near parallel to the 90°E meridian from the Bay of Bengal to Broken Ridge in the eastern Indian Ocean. Previous interpretations of the NER suggest it formed through the interaction between plate tectonic motion and plume processes, across three tectonic plates – India, Australia and Antarctica. However, interpretations of magnetic anomalies west of the NER have not been incorporated as constraints into plate reconstructions of the adjacent basins.

We use (1) new satellite altimetry data (Sandwell *et al.*, 2014) allowing the identification of previously unidentified seafloor structures, including a series of extinct propagating ridges in the Central Indian Basin, (2) new  $^{39}\text{Ar}/^{40}\text{Ar}$  age dates from the NER, and (3) existing magnetic anomaly data to provide temporal constraints to develop a new reconstruction for the Central Indian Basin, NER and Enderby/Southern Ocean Basin from 73.6 – 40.1 Ma. Our new reconstruction reconciles all the available evidence and accounts for all ocean crust created at mid-ocean ridges - i.e. no gaps or overlaps in oceanic crust at modeled times. This study reveals the extensive influence that the Kerguelen plume has had on shaping the Indian Ocean.

Our results show that overall the Central Indian-Wharton Ridge migrated northwards away from the Kerguelen plume from 73.6 – 40.1 Ma; however the spreading ridge segments closest to the Kerguelen plume location remain further south. We interpret this pattern to be a result of plume-ridge interaction. Further, our results show that the influence of the Kerguelen plume on seafloor spreading is more dramatic to the west than to the east. Central Indian Ridge segments (west of the NER) repeatedly jump southward (towards the Kerguelen plume) initiating propagating ridges. In contrast, the Wharton Basin, east of the NER, there is no evidence of ridge jumps observed in the seafloor fabric or magnetic anomalies. Instead, a series of large transform faults accommodate the offset created by the mid-ocean ridges segments pinned to the Kerguelen plume.

Seamount ages along the NER younging to the south indicate that these ridge jumps are small-scale southward ridge jumps. In contrast, magnetic anomaly patterns reveal that the ridge jumps occurring within the Central Indian Basin are large-scale southward ridge jumps, resulting in observable reverse age segments of oceanic crust being transferred to the Indian Plate. These different modes of accommodating ridge-plume interaction causes the change in shape of the Central Indian-Wharton Ridge geometry from an approximate SW-NE orientation at 73.6 Ma to an asymmetric acute angle with a centre point situated at the base of the NER by 40.1 Ma.

The results of this study demonstrate a geological feasible spatio-temporal reconstruction of the central Indian Ocean, outlining the formation of the NER. We anticipate the result of this study will be a platform for understanding the dynamic process of deep mantle interaction with crustal accretion during the formation of the Indian Ocean.

## An insight into the tectonic history of the Lomonosov Ridge, Arctic Ocean

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The Arctic Ocean region is of great interest in a number of scientific fields. It plays, and has played in the geological past, a key role in Earth's climate and oceanic circulation. Investigating its tectonic formation and the implications for paleoclimate and –oceanography is essential. Despite this, previous investigations and current knowledge are limited due to the predominant heavy ice conditions that make it difficult to reach this remote and harsh region. Open questions in regards to fundamental issues still exist, e.g. related to the complex tectonic formation of the Arctic Basins and the opening of the Atlantic-Arctic Gateway.

The Lomonosov Ridge, a huge elongated mountain range extending more than 1500 km across the entire Arctic Ocean, plays a significant role in the investigation of the region's tectonic and sedimentary history. The ridge acts as a double-sided continental margin where its flanks underwent various rift processes during the formation of the ocean's basins. After the Mesozoic formation of the Amerasia Basin, shaping the Lomonosov Ridge's structure, the ridge itself started to unzip from the Barents and Kara shelves during the formation of the Eurasia Basin in Early Cenozoic time (~ 64 Ma).

During RV *Polarstern* Expedition ARK XXVIII/4 in the summer of 2014, sea ice conditions were optimal for the collection of a comprehensive network of multichannel seismic reflection data along the Lomonosov Ridge between 80°N and 85°N. Depending on the sea ice conditions and required resolution of the data, different survey set-ups were used. The focus of this study is on seismic data collected with a 3000 m long streamer for the first time in this region. These seismic profiles provide a new insight into the deeper structure of the ridge that can be used to interpret the tectonic origin and possible age of the deeper seismic sequences.

The sedimentary strata on top of the ridge are subdivided into four prominent sequences; three upper sediment units and an underlying sequence likely metasedimentary in composition. An approximate age model, as well as a projection of the part of the ridge between 83°N and 84°30'N to its conjugate, the Severnaya Zemlya Archipelago at the Eurasia margin, is revealed. It is suggested that the sediment sequences underlying the prominent High Amplitude Reflector Sequence (HARS) formed well before the ridge separated from the Barents and Kara shelves. The projection to the Eurasian margin is realized based on characteristic seismic parameters and internal structures of the sediment sequences. Therefore, the part of the Lomonosov Ridge between 83°N and 84°N might be correlated to a former conjugate area around the October Revolution and Komsomolets Islands in the Kara Sea. Parts of it are dated as Ordovician/Devonian with fold structures of Triassic/Jurassic age. Further south, the metasedimentary unit shallows and comes into contact with the lower HARS boundary. This part of the ridge might be correlated to the Upper Proterozoic/Early Palaeozoic metamorphosed complexes exposed on the Bol'shevik Island.

## The electrical resistivity of the Australian lower crust

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Crustal silicate rocks at sub-solidus temperatures are expected to have very high electrical resistivities. However, although the upper crust is typically more than 1000  $\Omega\text{.m}$ , it is not unusual for the lower crust to have resistivity of less than 100  $\Omega\text{.m}$ , and in places lower than 1  $\Omega\text{.m}$ . That the lower crust (below 15 km to the Moho) can be as electrically conducting as seawater in some locations is remarkable, and indicates a substantial and highly connected mineral, melt or aqueous phase. To date, the temporal and spatial mechanism giving rise to the low resistivity is speculative and poorly constrained by both observation and laboratory measurement.

In our project, we assess current knowledge of the resistivity of the Australian lower crust. The project addresses the primary question as to whether the low resistivity is primary in the formation of the crustal profile, or is an overprint due to melt and fluid migration that post-date the formation of the crust. A secondary question is how such regions of low resistivity from an interconnected phase can be preserved through time-scales of millions to billions of years. Observational data are drawn from a variety of sources, including: the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP); detailed transect magnetotelluric (MT) data, legacy MT and geomagnetic depth sounding (GDS) data collected in smaller surveys over the last thirty years. Three types of modelling have been undertaken: a thin-sheet inversion of thousands of GDS data to yield constraints on regional crustal electrical conductance; 3D inversions of subsets of MT data; and detailed 2D MT inversions that provide more detail on the Moho to upper crustal connectivity.

Our research demonstrates a strong spatial correlation of lower crustal resistivity with major tectonic domains in Australia. For example, the Archaean core of the Gawler Craton is, in places, orders of magnitude more resistive than the Proterozoic crust on the eastern margin. From the 2D profiles, the lowest resistivities are often imaged at the rheological boundary between the upper and lower crust at about 10-15 km. Below this depth, the resistivity is imaged as a broad zone, tens of kilometres wide and thick, but above the boundary the regions of low-resistivity appear as narrower pathways in a broadly resistive upper crust. We find evidence of a strong spatial correlation between zones of lowest crustal resistivity and major mineral provinces.

Results suggest that zones of lower crustal anomalies appear to be associated with an event that results in fluxes of fluids and potentially melt from the upper mantle and the lower crust.

## **Hypogene Alteration as a Precursor to Supergene Enrichment – a New Style of Iron Ore Mineralisation in the Pilbara, Western Australia**

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Exploration at BHP Billiton's Marillana and Mindy deposits in the northern Hamersley Province identified a number of atypical features in the normally consistent Hamersley Group rocks. These anomalous features included reduction in natural gamma response of the rocks, extensive silicification (manifested as quartz breccias), siderite alteration, and variations in whole rock geochemistry from the typical Hamersley Group characteristics.

Investigation of these deposits through surface mapping, drill hole logging, geochemical analysis, petrographic examination, structural interpretation and 3D modelling revealed a geological history distinctly different from the rest of the Hamersley Province.

Following the main tectonic events in the Hamersley Province, it is interpreted that hydrothermal fluids moved along the regional scale Poonda Fault. Initially the fluid silicified the Hamersley Group rocks with the development of extensive hydrothermal silica-rich breccias which are possibly related to the development of other chert-rich breccias in the Eastern Pilbara. Following the initial silicification the fluid evolved, possibly through interaction with underlying carbonate-rich units, resulting in extensive siderite, and minor pyrite, alteration of rocks adjacent to the Poonda Fault. These events often resulted in complete alteration of the rocks in the Brockman Iron Formation, Mt McRae Shale and Mt Sylvia Formation to the point where the primary lithology (banded iron-formation, shale or chert) is unrecognizable.

Later supergene fluids, likely during the Mesozoic, resulted in weathering of the siderite altered rocks into massive, relatively homogenous bodies of goethite with only minor hematite. This is in addition to the more typical martite-goethite enrichment developed in the banded iron-formations, combining to make BHP Billiton's Marillana Deposit one of the largest iron deposits in the Pilbara.

Supergene enrichment formed from massive whole rock siderite alteration has not been previously identified in the Hamersley Province and represents a new style of iron deposit for the region.

## From greenstones to gabbros: insights into gabbro and granitoid petrogenesis from the Lachlan Orogen, southeastern Australia.

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The nature and role of mafic end-members in granitoid petrogenesis is poorly constrained in the Lachlan Orogen of southeastern Australia. Most previous studies have focussed on intermediate-felsic magmas and attempted to model the nature of their primitive precursors. Ordovician–Devonian magmatic rocks of gabbroic composition are exposed as volumetrically minor intrusions throughout the Lachlan Orogen, and are temporally and spatially associated with voluminous granitoids. Chronologic data indicate that gabbro magmatism was contemporaneous with I-, S- and A-type magmatism, with a marked increase in gabbro emplacement at the Silurian–Devonian boundary when felsic magmas switched from dominantly S-type to dominantly I-type. A detailed study of tholeiitic and alkali gabbros of the Arte Igneous Complex in the Kuark Zone of eastern Victoria provides new insights into gabbro petrogenesis and the source regions of such magmas which in turn have implications for the generation of granitoids, throughout the Lachlan Orogen.

Variations in whole-rock major- and trace-element contents, Sr, Nd, Hf and O isotope compositions, coupled with zircon and titanite age dating suggest that the Arte Igneous Complex represents a number of magma batches which locally preserve their cumulate piles. An initial and volumetrically minor alkali gabbro magma, produced through a small degree (10–20%) of partial melting of isotopically heterogeneous greenstone basement was followed by a more voluminous tholeiitic magma produced through greater degrees of partial melting (>50%). Both magmas underwent subsequent fractional crystallisation. Locally, evidence is preserved for plagioclase-rich assemblages, coupled with enriched HFSE that indicate plagioclase and zircon accumulation also contributed to compositional variation, however these processes would have occurred at the site of emplacement. Gabbros of the Arte Igneous Complex record considerable Sr-Nd isotopic heterogeneity and form two distinct arrays; (1) a shallow array defined by the tholeiitic gabbro and tonalite, in which initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ranges from 0.703258–0.708575 and  $_{\text{Nd}}$  ranges from +5.77 to +2.74, and (2) a steep array defined by alkali gabbro and cumulate rocks, in which initial  $^{87}\text{Sr}/^{86}\text{Sr}$  ranges from 0.702970–0.705199 and  $_{\text{Nd}}$  +6.04 to -7.54. However, at least in the case of array 1, significant assimilation and/mixing can be ruled out as quartz  $^{18}\text{O}$  values of between 5.0 and 6.0‰ can accommodate less than 10% crustal input. Partial melting of a heterogeneous source represented by Cambrian greenstone basement can account for the observed chemical and isotopic variations in the Arte Igneous Complex

Remarkably, the isotopic heterogeneity preserved in the Arte gabbros mirrors that preserved in other gabbro occurrences in the Lachlan Orogen, and in Cambrian greenstones, now exposed as rare fault-bounded belts throughout the orogen. This requires that the source heterogeneity is present on a local- and regional-scale. Moreover, the same isotopic heterogeneity is observed in I-type granitoids of the Lachlan Orogen. The implication is that I-type magmas may also be generated by partial melting of greenstone basement rocks, thus mafic and I-type magmas image their source region. The Arte Igneous Complex example provides an opportunity to re-examine the petrogenetic models for I-type magmas of the Lachlan Orogen in light of this new information.

## **Ten Years of Building High Performance Computational and Data Infrastructures to support the next generation of World Class Earth Science Research**

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In 2006 AuScope aimed to build a world-class infrastructure to assist Australian researchers in monitoring and understanding the structure and evolution of the Australian Continent. Initially computation was undertaken with on-premise infrastructures, using some online data from the Geological Surveys. The 2009 Super Science budget invested significantly in eResearch infrastructures (petascale computers and data repositories, research clouds, data registries and services). However, the earth science community has been slow to utilise opportunities these new HPC facilities offered: the showstoppers were access to data and suitable software. In the last 10 years, as earth science data volumes reached petascale, there was a growing realisation that data have reached a tipping point for a change to sustainable, centralised large-scale data infrastructures that are co-located with High Performance Computing (HPC) facilities. There are many ‘Big Data’ earth science collections, which mostly comprise heterogeneous files that are fragmented and non-standardised. Researchers are now collaborating on such datasets to reorganise them into self-describing ‘High Performance Data’ (HPD) collections that can be programmatically accessed *in situ*, as well as over the network.

In 2006, very little geoscience software could take advantage of cloud and HPC infrastructures: rewriting to use HPC systems is non-trivial and requires both scientific and computational science skills to understand the existing algorithms and then rewrite to use scalable, parallel algorithms. AuScope researchers have been developing open source codes (eScript, GPlates, Underworld, iEarth) that are shared online and take advantage of the new infrastructures.

This scaling-up of earth science infrastructures has been most prominent at the National Computational Infrastructure (NCI), Canberra. Over 10 Petabytes of data spanning the geosciences, geophysics, environment, climate and elevation have been co-located with a 1.2 Petaflop supercomputer and a HPC class 3000-core OpenStack cloud system. Since 2010 Geoscience Australia has been exploring HPC techniques at NCI and has proven that much larger datasets could be analysed at higher resolution and in faster timeframes (e.g., it now takes 10 hours to conduct a variable reduction to the pole over the whole of the magnetic map of Australia).

However, these hybrid HPC/HPD systems are a complex environment and there is a significant skills barrier to entry. Online Virtual Laboratories have been seen as one approach of enabling online processing to take place across distributed software, data and compute resources. The Virtual Geophysics Laboratory (<http://vgl.auscope.org>) provides geophysicists with integrated online access to geophysical data and to tools to process that data, whilst the Virtual Hazards Impact and Risk Laboratory is for researchers in geoscientific hazards.

It is hoped that changes in practices undertaken by collaborations between researchers in AuScope and on the Super Science computational infrastructures, will enable the realisation of 2006 AuScope vision of the 3D/4D Whole Earth Model. To fully utilise the last decade of developments, the next generation of scientists will need to be more computer literate on the use of models, data analysis techniques and good data management practices, with an increased emphasis on sharing and collaboration, particularly on developing partnerships around data, software, tools and infrastructures.

