Government of **Western Australia**
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RECORD 2017/17

SGTSG DENMARK 2017 ABSTRACT VOLUME

BIENNIAL MEETING OF THE SPECIALIST GROUP IN TECTONICS AND STRUCTURAL GEOLOGY, GEOLOGICAL SOCIETY OF AUSTRALIA, 8–12 NOVEMBER 2017, DENMARK, WESTERN AUSTRALIA

compiled by
MA Pearce

Geological Survey of Western Australia

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Perth 2017

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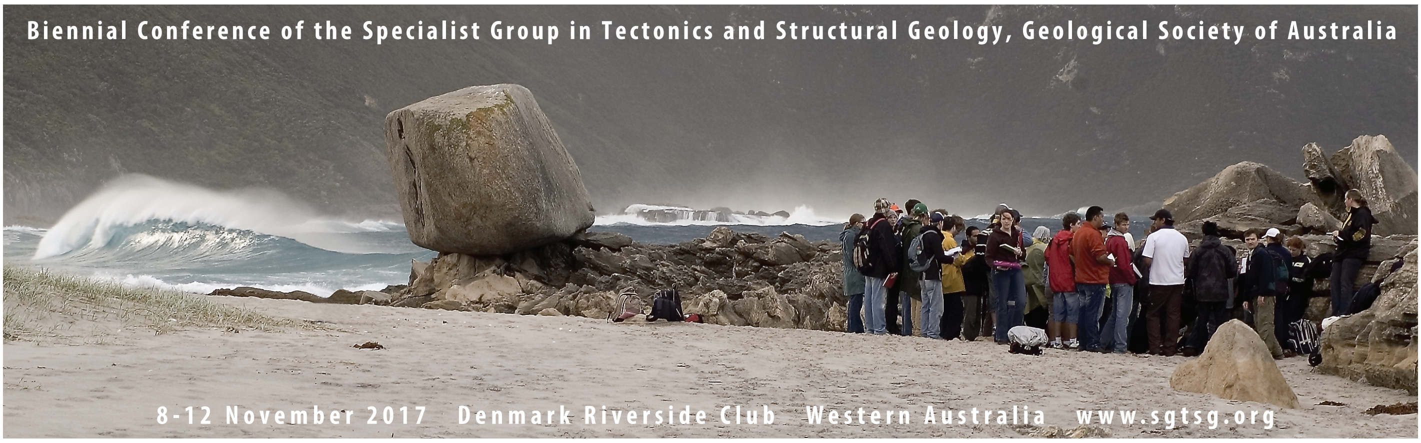
Cover image: Elongate salt lake on the Yilgarn Craton — part of the Moore–Monger paleovalley — here viewed from the top of Wownaminya Hill, 20 km southeast of Yalgoo, Murchison Goldfields. Photograph taken by I Zibra for the Geological Survey of Western Australia

Denmark 2017
Abstract Volume

Biennial Meeting of the Specialist Group in Tectonics and Structural Geology
Geological Society of Australia

8-12 November 2017, Denmark Riverside Club, Denmark, Western Australia

SGTSG Denmark 2017 - Abstract Volume



Welcome to SGTSG Denmark 2017!

This conference aims to bring together the research community in structural geology and tectonics within Australia and internationally to discuss the latest research and developments in these fields. We plan to maintain the relaxed, informal atmosphere of previous SGTSG conferences, with strong encouragment of student attendance and presentations.

Situated on the gneisses of the Albany–Fraser Orogen on the south coast of Western Australia, Denmark is a small town with a lot of character nestled within spectacular tall forest, rural and coastal landscapes of the Great Southern wine region. The conference is held at Denmark Riverside Club in the town centre.

This volume is designed to be used in conjunction with the Scientific Program, which is available as printed copy at the conference, electronically on a USB stick within your registration pack, and can be downloaded from www.sgtsg.org.

We hope that you enjoy the conference.

Kind regards,

Nick Timms (on behalf of the SGTSG Committee)

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Jump Straight To The Day's Events

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Wednesday 8th November

The Lithosphere, Subduction & Continental Assembly

The Earth's Lithosphere: A Modern View

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The lithosphere is the most accessible zone of the Earth's interior. Interest in the lithosphere has been intense since the advent of plate tectonics because the mobile lithosphere constitutes the tectonic plates. Given its accessibility and significance it is no surprise that the study of the lithosphere is one of the largest fields in solid Earth Sciences. I estimate that about 1,000 research papers are published each month in over 100 journals that focus on the physical properties and evolution of the lithosphere. Given this extensive research, it is not surprising that today virtually every scientific concept about the lithosphere is currently under challenge. Here I review several outstanding issues in lithospheric studies: (1) Secular variations in lithospheric properties. My new calculation is that the Archean crust comprises 13% of the continental crust. Early studies indicated that Archean lithosphere was thicker and compositionally distinct from younger lithosphere. However, recent geophysical and geochemical studies show significant diversity in the physical properties of Archean lithosphere, indicating that a there isn't a uniform mechanism of formation of Archean lithosphere. The formation of Paleo- and Neo-Archean lithosphere may differ, and the Neo-Archean lithosphere may have a multi-genetic origin, just as crust and mantle lithosphere is forming today is multi-genetic and is being created above subduction zones, at mantle hot spots, and within continental rifts. (2) The lithospheric mantle was first identified some fifty years ago using seismic surface waves. In the last twenty years considerable progress has been made in determining the fine structure of lithospheric mantle. Very deep penetrating seismic reflection profiles have identified sub-horizontal reflections at depths of 80 to 120 km. These have been interpreted as eclogite within oceanic lithosphere what has underthrust the Proterozoic. This provides powerful evidence for sea floor spreading and horizontal tectonics during the Proterzoic (post-2.5 Ga). Equally importantly, it indicates that horizontal stacking of oceanic lithosphere is one process for forming continental lithosphere. S-wave seismic receiver functions have been used to detect the lithosphere-asthenosphere boundary (LAB), but even more importantly they also see a mid-lithosphere discontinuity (MLD) at around 100 km depth. The S-wave velocity decreases up to 10% below the MLD. This discovery is consistent with evidence from xenolith petrology, magneto-tellurics, and studies of seismic anisotropy that show that the lithosphere is layered. However the physical explanation for the MLD is debated. Looking deeper, there is evidence that the lower thermal lithosphere is sheared due to basal drag from the underlying asthenosphere. Recently reported studies suggest that the lower lithosphere of the Superior Province (Canada) is dragged and displaced lateral several hundred km to the southwest. I review these and other new insights into the structure, composition and evolution of the lithosphere.

Our Blind Side – Aligning Structural Geology, Tectonics, and a Whole of Lithosphere Reality

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More than 70% by volume of continental lithosphere is sub-continental lithospheric mantle (SCLM). Isotopic studies indicate that about 60-70% of today's continental crust is material extracted from the convecting mantle in the Archean (e.g. Belousova et al., 2010). Relatively little of this may still exist as Archean crust – much of it has been repeatedly reworked into successively younger rocks. This explains the tendency for average Nd and Hf crustal model ages to be typically hundreds of millions of years older than the age of the rocks, irrespective of the age of terrane considered. i.e. repeated reworking also results in a gradual dilution of the old crustal component.

As a result of technological developments in the last 20 years, mapping of the architecture and tectonothermal evolution of the entire approximately 80-280 km thick continental lithosphere is now a reality. Multi-disciplinary (petrographic, geochemical, geophysical, geochronological and isotopic) studies of both SCLM and overlying crust tell us that a) most (likely >70%) of the SCLM is of Archean origin; b) the best preserved, oldest, and generally thickest, SCLM is the most depleted (Mg-rich, Fe-poor, low Al, Ca); c) The dominant process affecting the SCLM over time is refertilisation (Griffin et al., 2009) resulting from the interaction with magmas from the convecting mantle, dominantly in magmatic arc settings.

Therefore time's arrow is one of overall gradual refertilisation and thinning of the SCLM, resulting in lower observed seismic velocity, increased density, and lower relative elastic thickness. Old cratonic areas are simply the best preserved pieces of a universally old lithosphere with Mg-rich depleted SCLM acting as the buoyant life-raft. The continued existence of large regions of such thick ancient SCLM, despite 4 supercontinent cycles, is a testament to its durability.

This opens up a potentially revolutionary understanding of continental structure and evolution. However, is there a disconnect with these findings and the manner in which geoscientific data are being interpreted? The disciplines of tectonics and structural geology were developed before this revolution, whilst the field of numerical modelling is relatively immature. There is a general failure to account for all this old lithospheric material, and its structural architecture, in typical tectonic models for the evolution of the continents.

As a result of 3 billion years of plate tectonics, the SCLM has been fractured and segmented, including the formation of continental ribbons by subduction rollback. This in turn affects the partitioning of deformation during tectonic events. Detailed seismic tomography is now telling us that the SCLM is highly heterogeneous, with mixed domains on the scale of 10s of km, and most likely also at finer scales. There is also a clear relationship between discrete, linear zones of lower velocity and the presence of translithospheric faults. This supports the notion that the SCLM is structurally complex.

The challenge is now to grapple with the this new understanding of lithosphere evolution and a segmented, compositionally and structural heterogeneous SCLM, and to re-evaluate how to interpret our geoscience data in a way that satisfies all of the information.

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Mechanism and Responses of Lithospheric Delamination in Continental Collisional Orogens: Thermomechanical Modeling

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Lithosphere delamination is believed to have played a major role in mountain building; however, the mechanism and dynamics of delamination remain poorly understood. Using high-resolution thermo-mechanical models, we systematically investigated the conditions for the initiation of lithosphere delamination during orogenesis of continental collision, and explored the key factors that control the various modes of delamination. Our results indicate that the negative buoyancy from lithosphere thickening during orogenesis could cause delamination, when the reference density of the lithospheric mantle is not lower than that of the asthenosphere. In these cases, compositional rejuvenation of depleted continental lithosphere by magmatic/metasomatic plume- and/or subduction-induced processes may play crucial roles for subsequent lithosphere delamination. If the reference density of the lithospheric mantle is less than that of the asthenosphere, additional promoting factors, such as lower crust eclogitization, are required for delamination. Based on systematic numerical simulations, three basic modes of lithosphere delamination are predicted: pro-plate delamination, retro-plate delamination, and a transitional double-plates (both the pro- and retro-plate) delamination. Pro-plate delamination is favored by low convergence rates, high lithospheric density and relatively strong retro-plate, whereas retro-plate delamination requires a weak retro-plate. The Northern Apennines and Central-Northern Tibetan plateau are possible geological analogues for the pro-plate and retro-plate delamination modes, respectively. Our model also shows significant impact of delamination on the topographic evolution of orogens. Large-scale lithosphere delamination in continental collision zones would lead to wide and flat plateaus, whereas relatively narrow and steep mountain belts are predicted in orogens without major delamination.

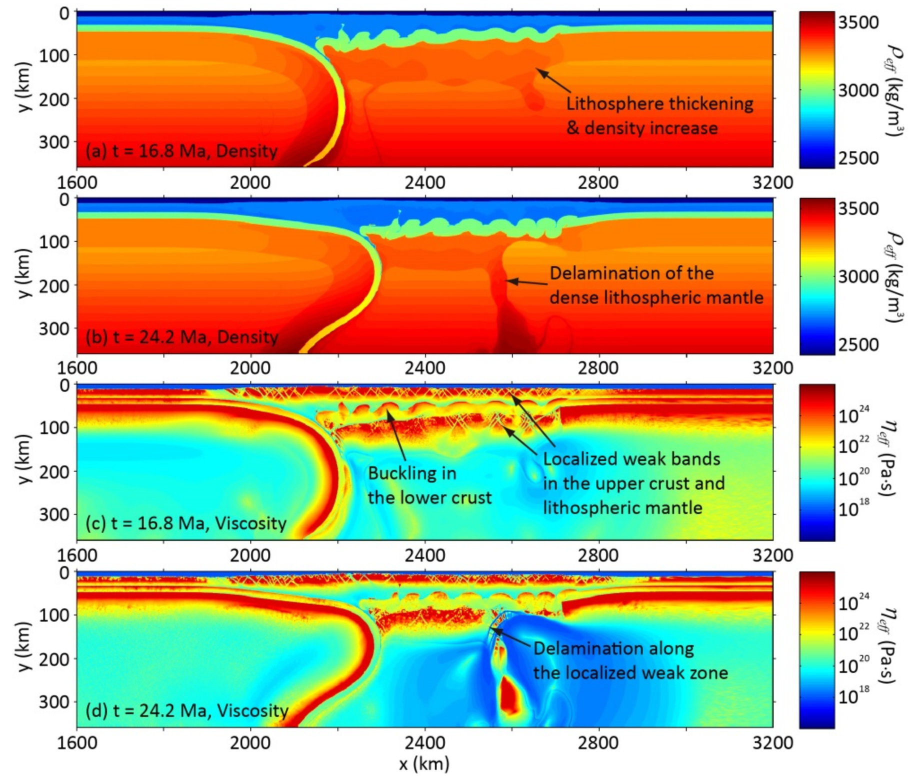

Fig. 1: Density (a-b) and effective viscosity (c-d) profiles during the continental collision and lithospheric delamination.

The Earth's Biggest Kink - in the Nazca Slab beneath South America

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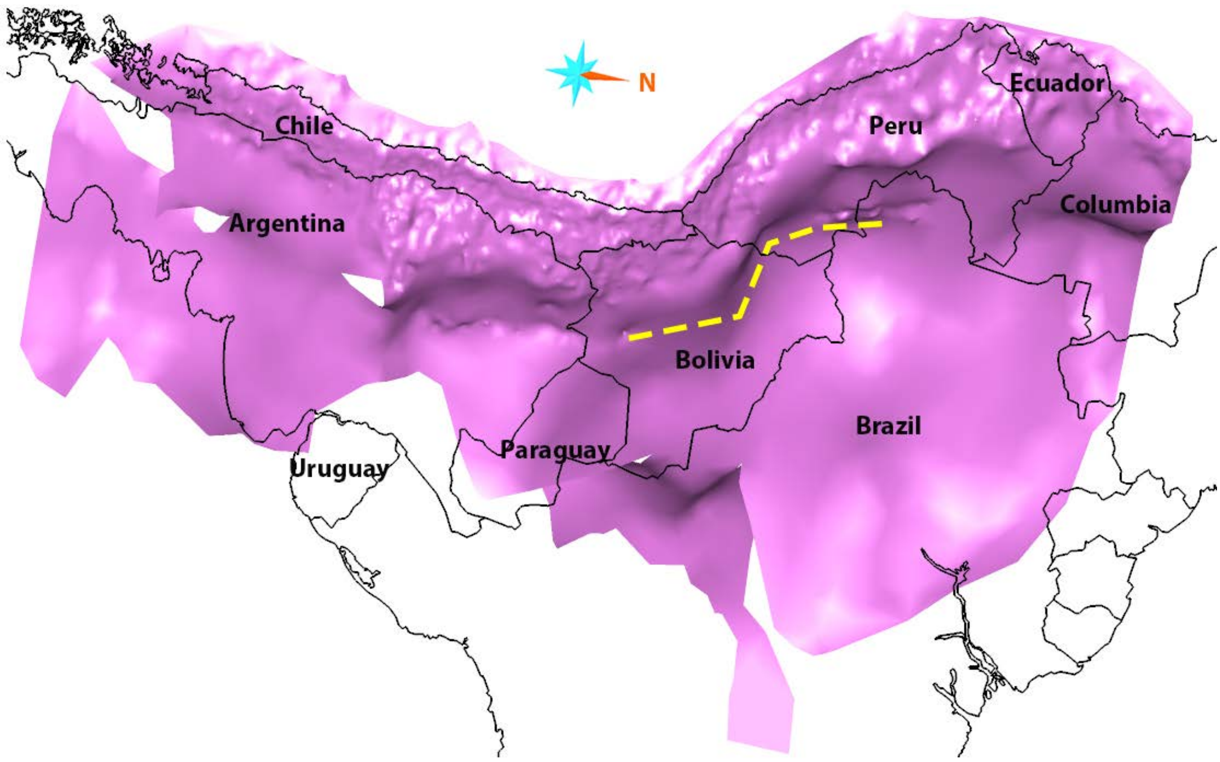
The Peru-Chile trench off the western coast of South America marks the trace of active subduction of the Nazca Plate beneath the overriding South American Plate. The Bolivian Orocline recorded the evolution of the trench as a result of rollback of the subducting slab, and continues at depth into a giant kink that plunges orthogonally through the transition zone. The variations in the steepness of subduction, especially the existence of flat slab subduction regions, influence the volcanic gap in the Andean Volcanic Belt. Although the subduction geometry in the upper mantle is widely studied and well understood, little is known about the subducted lithosphere in the lower mantle. Local seismicity and tomography both show a kink that accounts for approximately 10% along-strike shortening of the subducted slab through the mantle transition zone (Fig 1), which is consistent with the 10% horizontal shortening expected because of the planet's spherical geometry. The along-strike shortening is a mechanism to accommodate the reducing lateral space as the lithosphere descends into the spherical Earth. Through 4D (*i.e.*, 3D + time) reconstruction, we hope to demonstrate whether or not the kink in the transition zone translates to a stagnation point in the rollback process, which could hence define the Bolivian Orocline. We aim to demonstrate the crucial link between subduction structures in the deeper mantle and crustal deformation and the tectonic evolution of South America.



Reverse-engineering subducted oceanic lithosphere in Southeast Asia

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Seismicity and seismic tomography in particular have unveiled the fate of subducted oceanic lithosphere in increasing detail, leading to various inferences of complex slab morphology. Subducting slabs often deform into complex geometries by migration of subduction trenches, slab–mantle interaction, slab tearing, and collision of slabs at depth. Although it is possible to construct three-dimensional models of subducted slabs using earthquake hypocentre locations and tomographic models, it is often not possible to rigorously test their accuracy.

Here we present a method to test the viability of an interpreted slab geometry to assess whether it was ever possible for an oceanic shell, upon being subducted, to have been deformed into its alleged shape. This test is performed by numerical simulation using the programme *Pplates* to mathematically 'unfold' a complex slab model into its pre-subducted configuration – a procedure we refer to in this talk as 'reverse engineering'. A fortunate consequence of this reverse engineering approach is that the process of 'floating' may successfully flag parts of the mesh that are required to have been torn in order that the slab acheived its hypothesized shape.

We illustrate this approach using the Ryukyu and Shikoku slabs, northwest Philippine Sea, simulating these slabs as viscoelastic sheets that we floated to the surface level (Fig. 1). The net strain distribution in the floated mesh indicated parts of the original slab model that are geometrically viable (those that remain unstrained), in addition to parts where additional tears and/or zones of localized ductile extension are required to have enabled the slab to deform during subduction. In the instance of the Ryukyu and Shikoku slabs, the Palau-Kyushu and Gagua ridges are shown to have both acted as planes of weakness that broke into major vertical slab tears. Connecting these subducted ridges we infer a trench-parallel tear that represented the former contact between the Huatung and West Philippine basins, and which tore as the slabs descended. The fossil spreading centre of the Shikoku Basin formed a separate slab window upon subduction along the Nankai Trough.

The methodology presented herein proves a powerful tool in evaluating slab morphologies, inferring the locations of slab tears, and so reconstructing the features of subducted oceans to evaluate the geodynamics of complex subduction.

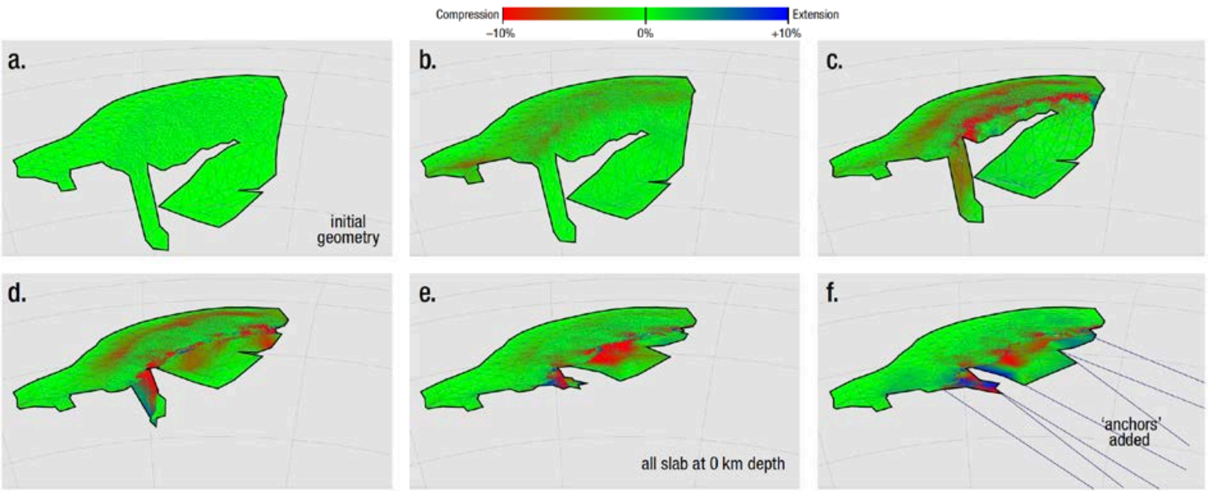

Fig. 1: 'Floating' the Ryukyu and Shikoku Slabs to surface level using *Pplates*.

Micro-continent collision and the dynamics of congested subduction: Lessons from New Zealand

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Accretionary orogenic systems record protracted accumulation of buoyant material transferred from the down-going plate to the overriding plate at convergent margins. Collision of buoyant material locally congests a subduction zone, increasing convergent interplate coupling, which reduces or ceases convergence on the subduction megathrust. Deformation is partitioned into the overriding plate, effectively suturing (or locking) the colliding plates together. Away from the collision zone, plate convergence continues to be accommodated by active subduction. Numerical simulations of congested subduction suggests subduction zones re-establish behind the zones of collision. This is significant because large-scale changes in the lithospheric composition of subducting plates impact the rate and style of deformation along a convergent plate margins.

Oblique dextral Pacific and Australian Plate boundary is a modern Earth example of the changing lithospheric composition along a convergent margin. Unimpeded subduction occurs along the Tonga-Kermadec Trench, whereas the subduction zones is congested where the Hikurangi Plateau has collided with the Hikurangi Trench, and micro-continent collision has occurred along the Alpine Fault. This congested subduction zone has slowed convergence along the megathrust in the eastern North Island of New Zealand, and locked it along the north eastern South Island.

Comparison of GPS data and earthquake moment tensors along the Pacific-Australia Plate Boundary, with numerical models show deformation is a direct result from the lithospheric heterogeneity with an additional component of dextral convergence. Micro-continent collision along Alpine Fault and extrusion tectonics along the Marlborough Fault Zone is driven by west-dipping subduction of the Pacific Plate. This margin is further complicated by the interaction of the Hikurangi Plateau with the convergent margin. The Hikurangi Plateau maintains a strong influence on strain orientation and overriding plate switch from shortening to extension as subduction transitions to continental collision. Re-establishment and migration of the mega-thrust activity has promoted asymmetric trench retreat and increasing rates of extension northward along the plate boundary, and increases both the shear strain and vorticity through the North Island.

The Marlborough Fault Zone is located at the lateral edge of the indenting Campbell microcontinent. The Marlborough Fault Zone represents a migrating plate boundary that has translated 120 km SE from the Wairau to Hope Faults, accreted ~700,000 km^3 of crust from the Pacific to the Australian Plate since the mid-Miocene.

Using sub-horizontal pressure (P)-axis orientation derived from the recent Kaikoura earthquake-aftershock sequence, historical seismicity, ad fault lineation data we demonstrate the P-axis has rotated clockwise from 68° to 116° since ca. 16 Ma. We explain this rotation by the southward unlocking of the Hikurangi Megathrust during simultaneous roll-back induced rotation of the Hikurangi Slab. The gradual unlocking of the Hikurangi megathrust is interpreted to be linked to the southward relocation of the plate boundary since the mid-Miocene, and in doing so have identified a previously undescribed mechanism of accretion, which we term “Subduction propagation accretion”.

Building Blocks of the Tasmanides

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The Tasmanides occupy the eastern third of Australia and provide an extensive record of the evolution of the eastern Gondwanan convergent plate boundary from the Cambrian to Triassic. Previous studies in the Tasmanides have mainly focused on individual “orogens” and “orogenies”, and relatively little attempt has been done to describe spatio-temporal relationships across the whole system. To address this issue, I subdivide the Tasmanides into approximately 70 “building blocks”, each represents an igneous province or a sedimentary basin. Spatio-temporal patterns of these building blocks, combined with information on the timing and extent of contractional and extensional deformation, unravel key features with regards to the evolution of the convergent plate boundary. In particular, it is recognised that the northern and southern parts of the Tasmanides are separated by major crustal-scale structures, which likely represent an original segmentation of the plate boundary. This segmentation likely played a fundamental role in controlling the origin of oroclines during periods of trench retreat and overriding-plate extension.

Crustal structure of the Capricorn Orogen of Western Australia and its role in Paleoproterozoic craton assembly and reworking: a high-density passive seismic receiver function study

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The Capricorn Orogen records the punctuated Paleoproterozoic amalgamation of the Western Australian Craton. Regional geological, geochemical, and geophysical studies revealed a prolonged tectonic history in craton assembly and subsequent intraplate reworking, which significantly re-shaped the orogenic crust. In this study, a high-density seismic receiver function study targeted the Glenburgh Terrane, an exotic late-Archean to Paleoproterozoic crustal block in the core of the orogen. Prominent Moho and intracrustal discontinuities are present, replicating the overall trend and depth range interpreted from a previous deep crustal seismic reflection survey. Low Vp/Vs ratios (~1.70) are mapped terrane-wide, indicating a felsic bulk crustal composition. However, significant lateral variations in the seismic signal are present across the terrane, showing a relatively thin crust (<40km) with small Vp/Vs ratios (~1.70) in the centre of the terrane, compared to thickened crust (>40km) with elevated Vp/Vs ratios (>1.76) along the margin. Within the shallow crust, a fast-velocity intraplate is present indicating significant modification of the crust during post-cratonization magmatic differentiation processes. Based on existing age, isotopic, chemical and conductivity data, and the absolute shear wave velocity data presented here, the Glenburgh Terrane is interpreted as an Archean microcontinent that was significantly modified during Paleoproterozoic orogenesis. This is supported by the presence of significant seismic variations across the terrane boundary. The crust of the Glenburgh Terrane has preserved a unique seismic signature which was inherited from processes associated with crust formation in the Archean and significant reworking processes in the Paleoproterozoic. These results illustrate that multi-disciplinary datasets provide complementary resolution and texture information allowing for tighter constraints on Proterozoic cratonization processes.

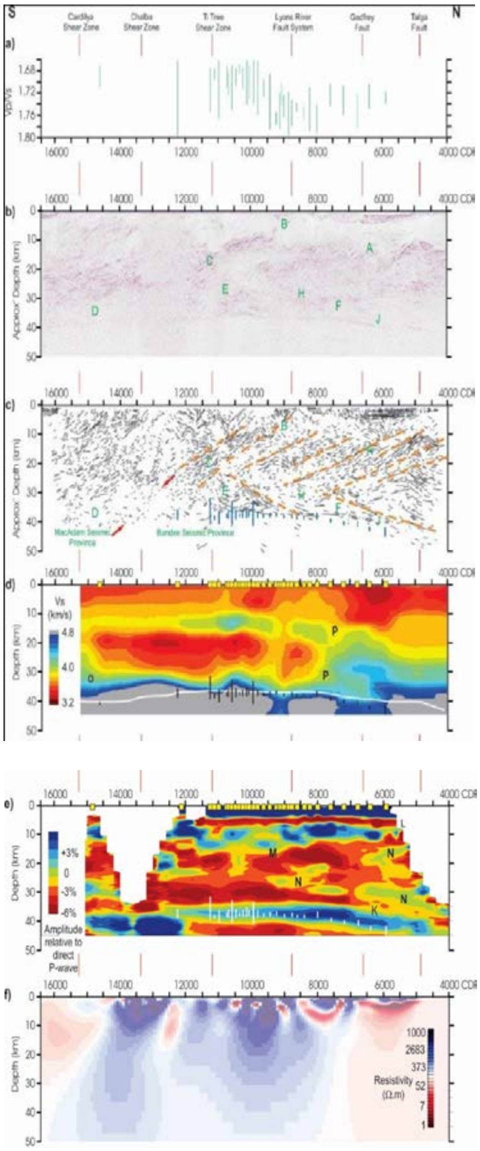

Fig. 1: Crustal scale geophysical sections along seismic profile 10GA-CP2. A) Vp/Vs from H-k analysis; b) seismic reflection section; c) line drawing of (b); d) shear wave velocity section from ambient noise tomography; e) Common-conversion-point (CCP) velocity contrast section; e) conductivity section from Magnetotelluric data. Modified form Dentith et al., submitted to Geophysics.

High-*T*, low-*P* c. 1.7 Ga tectonism in the West Australian Craton triggered by magma flux into the crust

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Identifying the forces that drive intracontinental tectonism is a necessary step in understanding the evolution of the continental crust. The Capricorn Orogen records nearly 1 billion years of intracontinental reworking within the West Australian Craton, but the processes responsible for reworking remain unclear. One of the least understood of the major tectonic events that shaped the orogen is the 1680–1620 Ma Mangaroon Orogeny, mainly due to a lack of direct ages for metamorphism, an absence of pressure (*P)*–temperature *(T)* data, and uncertainty about the duration of granitic magmatism. In this study we define the *P*–*T*–time (*t*) conditions of this event, based on *in situ* SHRIMP U–Pb monazite, xenotime and SHRIMP U–Pb zircon geochronology and calculated *P*–*T* pseudosections. These data provide new insights into the processes driving the metamorphism and magmatism. New *in situ* phosphate geochronology from pelitic migmatite, granofels, gneissic migmatite and schist constrain the timing of peak metamorphism at c. 1695 Ma with an estimated duration of 20 Myr. Pelitic migmatite in close association with a regional-scale granite batholith preserves a peak assemblage of cordierite–sillimanite–biotite–K-feldspar–magnetite–plagioclase–quartz–ilmentite,which defines peak conditions of 655–755 °C and 2.7–4.3 kbar (~250 °C/kbar). The onset of metamorphism during the Mangaroon Orogeny coincides with the oldest ages for granitic magmatism in the region at c. 1710 Ma, confirming that these elevated thermal gradients correspond to regional contact metamorphism. A sample of pelitic schist 80 km to the north has a peak assemblage of garnet–epidote–biotite–quartz–muscovite–plagioclase–ilmenite (+ inferred H_2O). The *P*–*T* conditions retrieved from this sample are 535–635°C and 5.4–11.4 kbar, defining a maximum thermal gradient of 100 °C/kbar. The higher thermal gradients at shallow crustal levels are interpreted to record the emplacement of large granite plutons near the brittle–ductile transition, whereas the slightly deeper levels exposed to the north may record the thermal effects of melt transfer from the source region at depth. New $^{40}Ar/^{39}Ar$ muscovite ages of c. 1640 Ma, from the c. 1.7 Ga granite, likely reflects uplift and cooling of the crust and provide a minimum age for deformation and metamorphism of the Mangaroon Orogeny. Our results emphasise the benefit of monazite geochronology, combined with other techniques, for establishing of the *P*–*T*–*t* conditions of an orogenic event. Our study implies that unlike many Proterozoic orogenic events in Australia, this 1.7 Ga thermal event cannot be explained by a thermal lid model but, rather, is more compatible with a model in which anomalous geothermal gradients in the crust were triggered by intrusion of massive volumes of magma.

Tectono-Metamorphic Evolution of the Georgetown Inlier, NE Australia and its Implications for the Assembly of the Supercontinent Nuna

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Recent tectonic reconstructions for the Proterozoic supercontinent Nuna have suggested connections between eastern Australia and western Laurentia (Betts et al., 2015). Palaeoproterozoic sedimentary–volcanic sequences exposed in the Georgetown Inlier (NE Australia) were deposited until 1.6 Ga and metamorphosed during regional-scale shortening events ca. 1.6 to 1.55 Ga (Betts et al., 2015). These tectonic events were ascribed to NE Australia and NW Laurentia continental collision during the assembly of Nuna, as suggested by palaeomagnetic record after 1580 Ma (Pisarevsky, et al., 2014). However, the central and eastern domains of the Georgetown Inlier recorded low-*P*/high-*T* metamorphic imprint associated with partial melting events and emplacement of S-type plutons, which are not characteristic features of crustal thickening, generally associated with regional medium *T/P* gradients.

The Georgetown Inlier has non-deformed and non-metamorphosed, *ca.* 1.55 Byr–old volcanic rocks in the west, while the central, and eastern domains preserve poly-deformed and -metamorphosed sedimentary and mafic rocks (Boger and Hansen, 2004). Three progressive deformation events (D1, D2 and D3) have been described, during which successive generations of planar fabric developed (S1, S2 and S3). Conflicting interpretations amongst previous work in the region (Hills, 2003; Cihan et al., 2006) reflect the critical lack of geochronological constraints on minerals which are part of equilibrium microstructures of specific metamorphic stages.

In this study, we present a multi-scale analytical approach (Gosso et al., 2015) that combines petro-structural field mapping with microstructural analysis, *P–T* estimation, and geochronology (U–Pb in monazite and zircon; Lu–Hf in garnet) in order to reconstruct multi-point pressure–temperature–deformation–time (P–T–d–t) paths for different sectors of the Georgetown Inlier.

The first field campaign suggested that during D2, S2 is the dominant planar fabric at the regional scale. It developed as slaty cleavage in the west and as pervasive schistosity defined by greenschist- to upper-amphibolite mineral assemblages in the central area. The eastern domain is characterised by paragneiss, amphibolite and calc-silicate, where the dominant migmatitic foliation is defined, crosscutted and locally obliterated by successive generation of leucosomes. During D3, macro- to micro-scale, E–W trending folds (F3) were associated with the development of a retrograde crenulation cleavage (S3) superimposed on S2.

Forthcoming microstructural, petrological, and geochronological work shall allow identifying different tectono-metamorphic units within the Georgetown Inlier, which will thus provide new insights into the tectonic processes that the Inlier recorded at different structural levels, and well as their significance in therms of supercontinent cycles.

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Secular evolution of orogenic processes during the Palaeoproterozoic assembly of the West African Craton

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The Palaeoproterozoic Eburnean Orogeny of the West African Craton (WAC) represents the earliest stage of worldwide collisional orogenesis between 2.1 and 1.9 Ga, heralding the amalgamation of the supercontinent, Nuna. As one of the youngest juvenile granite-greenstone terranes in the world, the Palaeoproterozoic domain of the West African Craton offers the unique opportunity to investigate orogenic processes active in the early Earth, superimposed on a juvenile accretionary orogenic event. We investigate the tectono-metamorphic history of multiple high-grade terranes throughout the craton to compare and contrast the processes responsible for the assembly of the craton.

Investigation of the geodynamic setting through geochemical and isotopic studies suggest southwest Ghana represents an intra-oceanic arc, subsequently dismembered and reassembled during the Eburnean Orogeny. Sporadic preservation of HP-LT or HP-MT metamorphic conditions combined with cold apparent geothermal gradients documented within the craton suggest that the lithosphere was sufficiently cold and strong to accommodate heterogeneous crustal thickening. Furthermore, contrasting exhumation mechanisms preserved within the craton suggests non-unique tectonic styles and changes in the driving mechanism active during the Eburnean Orogeny, some of which are reminiscent of Phanerozoic exhumation mechanisms, and the assembly of the West African Craton. This contrasts with collision orogenic processes recorded within younger Palaeoproterozoic terranes and those involving collision of older Archean cratonic domains. We therefore suggest that the Eburnean Orogeny and the corresponding Transamazonian Orogeny indicates localised and episodic collisional orogenesis of juvenile continental fragments.

Hence, we suggest the amalgamation of the West African Craton can be characterised by episodic collisional events between discrete fragment of juvenile continental blocks during the Eburnean Orogeny, culminating with the collision of the Archean nucleus and the assembled Palaeoproterozoic blocks at ca. 2030 Ma (Kouamelan et al., 1997). Illustrating the increased metamorphic and structural diversity of the early Proterozoic relative to Archean provinces, the Eburnean Orogeny of the WAC potentially provides crucial evidence for understanding the secular evolution of orogenic processes early in the Palaeoproterozoic prior to the appearance of hallmark subduction-related petro-tectonic indicators. Within this model, we are better able to elucidate the geodynamic setting of juvenile crust generation and the subsequent tectonic settings responsible for amalgamation of the alternating, juvenile granite-greenstone terranes of the WAC.

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An Australian source for Pacific-Gondwanan zircons: Implications for the assembly of northeastern Gondwana

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Detrital zircons in Neoproterozoic–Paleozoic basins of the Pacific-Gondwana region contain a distinctive 700–500 Ma population conventionally considered to be derived from Antarctica. However, the 700–600 Ma age component of the population predates major peripheral orogenesis (Terra Australis orogen), which began at ca. 580 Ma, and the highly evolved εHf(t)-in-zircon values (to −40) require an Archean source, which is not proximal to the Terra Australis active margin. To assess the provenance of Pacific-Gondwanan zircons, we analyzed zircons from granites of the Paterson orogen, then compared these with compiled zircon U-Pb and Lu-Hf data from the Terra Australis margin of Australia and Antarctica.

The late Neoproterozoic Paterson and Petermann orogens have traditionally been treated separately, yet are linked via the Anketell gravity ridge, and have coeval 600-530 deformation histories. We consider the Paterson-Petermann orogenic belt as a transcontinental system, with a length of >2000 km, and width of at least 500 km including ca. 560 Ma thrust systems of the King Leopold orogen. We argue that Lu-Hf zircon data from the Paterson-Petermann orogen, along with magmatism, metamorphism and regional deformation indicate that it was a continuous late Neoproterozoic magmatic belt associated with south-dipping subduction. Convergence began at least by ca. 680 Ma, but terminated in the Paterson-Petermann orogen at 550–530 Ma when the North Australian Craton collided with Gondwana.

Based on similar εHf(t) arrays defined by Neoproterozoic granites in Western Australia and detrital zircon populations from the surrounding basins, we suggest that Pacific-Gondwanan zircon grains were partially derived from the >2000-km-long, late Neoproterozoic Paterson-Petermann orogen, which sutured northern and southern Australia at 550–530 Ma. The rising Paterson-Petermann orogen distributed a vast swathe of sediment eastward into evolving early Cambrian backarc basins of the Tasmanides. Following inversion of these Tasmanide basins during the ~500 Ma Delamerian-Ross orogen of Australia and Antarctica, detrital zircons were recycled into adjacent, outboard, basins.

We propose the North Australian Craton was a crustal block connected to now-dispersed southeast Asian terranes during the Neoproterozoic. The Himalayan-style Paterson-Petermann orogen was responsible for amalgamating Southeast Asian terranes into northeast Gondwana, thereby constraining the paleogeography of the northern Gondwanan margin at the Precambrian-Cambrian boundary. Remarkable isotopic similarity of zircon grains with the Lhasa terrane of Tibet suggests that the Paterson-Petermann orogen was the eastern sector of the developing circum-Gondwana subduction system from ca. 700 Ma (Fig. 1).

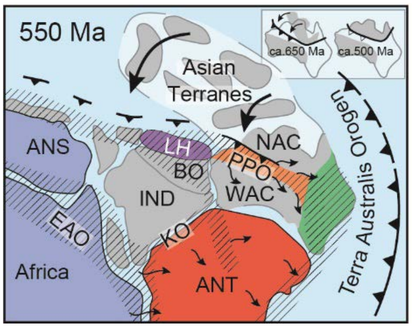

Fig. 1: 550 Ma reconstruction of NE Gondwana

The long road to plate tectonics

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The case of the solar system suggests that active tectonics is fairly rare on planetary bodies, and there is active whether Earth possessed plate tectonics, or another archaic tectonic regime early in its history. On Earth today, active tectonism is powered largely by mature subduction zones, and facilitated by both unduly weak faults, and a fairly cold mantle which permits congruous slabs within the upper mantle, and facilitates stress coupling between the mantle and lithosphere. Failure of any of these components (strong faults, weak, hot mantle) can lead to the complete cessation of tectonic activity, and the interplay between them is highly non-linear, requiring advanced 3D numerical models to resolve.

Here I review recent work on the rheology of active plate-bounding fault zones, from laboratory experiments, recent ocean drilling, and numerical models, and present models demonstrating the effect fault rheology has on intra-plate stress and tectonic activity. I also present models demonstrating the effect the internal temperature evolution of a planet has on its subsequent tectonic activity, and the importance of initial planetary conditions. Finally, I will address the paradox of the difficulty of sustaining early Earth tectonics, with clear evidence of recycling of the oldest crust (which is no longer exposed), and evidence for tectonism in some of the earliest rock record.

Reactivation of an Archean craton margin – Albany–Fraser Orogen numerical case study

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Lithospheric thinning and reactivation through extension and rifting, and implications for the destruction of craton margins have been addressed in several studies (e.g.: North China Craton, NE-Atlantic, SW Greenland and West Iberia margins). Reactivated passive margins can be divided into two categories – volcanic and non-volcanic. Volcanic passive margins are distinct in origin and evolution from non-volcanic hyper-extended margins. Consequently, they should not be integrated into a single evolutionary process, and do not necessarily represent the ultimate stage of hyper-extension. Volcanic passive margins usually form in tectonic zones between cratonic nuclei, and may have been subjected to lengthy periods of divergence and convergence or strike-slip tectonics. Here we present a 2D numerical case study on the Albany–Fraser Orogen to provide insight into volcanic passive margin evolution.

The Albany–Fraser Orogen records Proterozoic modification of the southern and southeastern margin of the Archean Yilgarn Craton margin through coeval basin evolution and magmatism, which included variable additions of juvenile mantle material. Recent extensive geological mapping, geophysical, geochronological and geochemical analysis provides the necessary constraints for numerical studies to help establish best fit geodynamic scenarios for Albany–Fraser Orogen evolution.

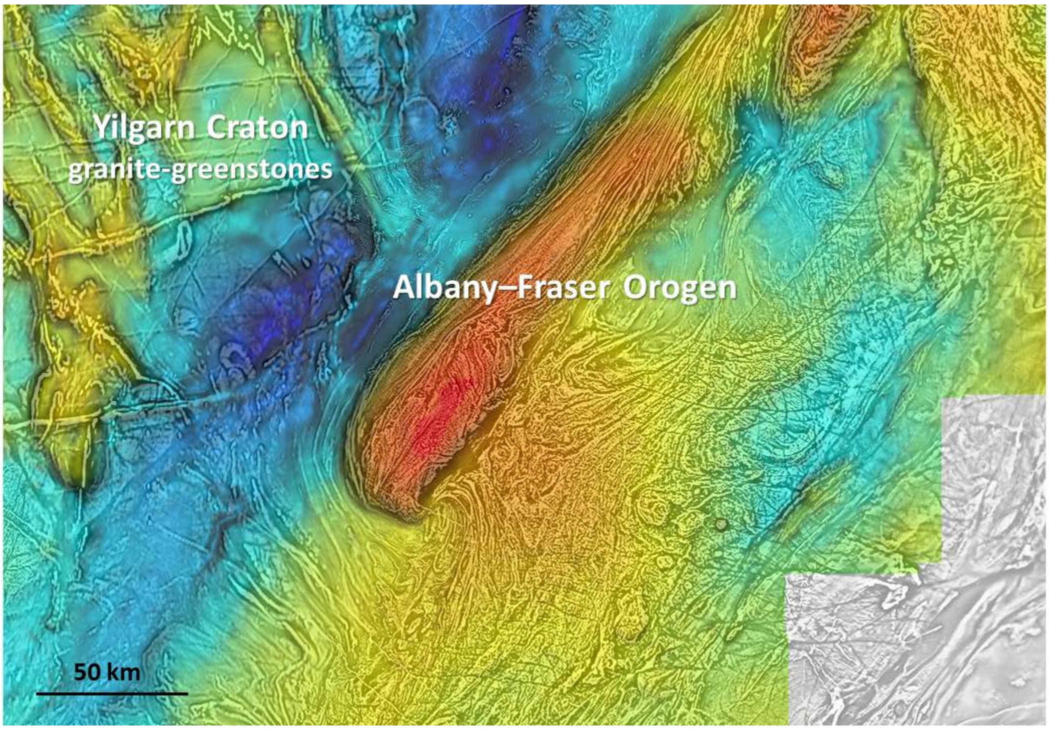

Fig. 1: Gravity (colour) with 1VD aeromagnetic (greyscale) draped image of the Yilgarn Craton and east Albany–Fraser Orogen interface. These data have facilitated GSWA mapping and sampling in the region.

Spatial and temporal relationships in rocks of the Leeuwin Complex, and their setting within the Pinjarra Orogen of Western Australia

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The Gondwana supercontinent formed between 550 and 500 Ma through the collision of several smaller continental blocks. The mountain belts produced by this collision had a profound effect on Earth's evolution, with the least understood belt now occurring as poorly exposed metamorphic rocks of the Pinjarra Orogen. This metamorphic belt is found along the western margin of Australia, and is exposed as basement inliers in the Leeuwin, Northampton and Mullingarra Complexes, and also recovered from drill core that intersects Perth Basin basement. The Pinjarra Orogen is situated in a critical position for reconstructions of both Rodinia and Gondwana, however, its evolution is controversial with poor exposure and a complex tectonic history. The Leeuwin Complex is the least understood basement inlier with existing geochronology indicating two granitic domains with protolith ages of c. 1090 and 780–680 Ma (Nelson, 1996, 1999), but the relationship between these domains is uncertain (Janssen et al., 2003). More recently, geochronology of drill core samples has identifed 1090 Ma granite protoliths beneath the northern and southern Perth Basin (Bodorkos et al., 2016). In this study, we collected samples of garnet-bearing granitic rocks from the Leeuwin Complex and Perth Basin basement, with the aim of integrating field and petrological observations with zircon U–Pb, Lu–Hf and rare earth element (REE) data to constrain the crustal history of these rocks.

Our SHRIMP U–Pb zircon data indicate that granite protoliths of garnet-biotite felsic orthogneiss in the central Leeuwin Complex (Redgate beach) were emplaced at 1092 ±13 Ma (magmatic cores) and metamorphosed at 554 ±36 Ma (a single low Th/U rim analysis), while granite protoliths of garnet-bearing biotite-hornblende felsic orthogneiss in the southern Leeuwin Complex (Cape Leeuwin) were emplaced at 692 ±7 Ma (magmatic cores) and metamorphosed at 532 ±11 Ma (two low Th/U zircon rim analyses). A more precise age of 524 ±6 Ma for the timing of metamorphism in the Leeuwin Complex is provided by abundant low Th/U overgrowths on zircon in garnet-bearing felsic migmatite from Skippy Rock. Garnet-bearing felsic rock from the bottom of Allanooka No. 2 exploration well in the northern Perth Basin yields an age of 1102 ±11 Ma from zircon cores, comparable to the Redgate Beach orthogneiss of the Leeuwin Complex. These data confirm protolith ages determined in previous studies of the Leeuwin Complex (Nelson, 1996, 1999) and support the correlation of Perth Basin basement with the Redgate Beach orthogneiss (Bodorkos et al. 2016). Work is now underway on collecting Lu–Hf data from the same zircon grains to establish the crustal history of c. 1090 and c. 690 Ma Leeuwin Complex domains, determine whether their protoliths were derived from similar or different crustal units, and further test the correlation of Redgate Beach with Perth Basin basement.

These results will further constrain the geochronological framework for the various Pinjarra Orogen components, and test whether these multiple events reflect repeated reworking of an orogen that had already assembled by 1090 Ma, or distinct spatial domains that evolved separately before their juxtaposition at c. 525 Ma during Gondwana assembly.

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Building the S-bend: the structural evolution of a key crustal-scale feature in the east Albany–Fraser Orogen, Western Australia

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The Albany–Fraser Orogen of Western Australia (Fig. 1a) is an economically-prospective example of Archean craton margin deformation and modification. Within the eastern section of the orogen, the S-bend (Fig. 1b) is a regional-scale S-fold interface between four tectonic units that record various styles of craton reworking: Archean rocks of the Northern Foreland, Paleoproterozoic orthogneiss-dominated rocks of the Biranup Zone, Paleoproterozoic gneisses with abundant Mesoproterozoic intrusions of the Nornalup Zone, and Mesoproterozoic interlayered mafic, felsic, and sedimentary gneisses of the Fraser Zone. We interpret the S-fold geometry to have developed during the overprinting of multiple sets of structures at high angle to one another, rather than a typical sinistral shear history.

The prominent northeast-trending structural grain of the Fraser Zone represents relatively old, but at least second generation, structures that refold earlier isoclinal folds of layering. On the western side of the Fraser Zone, the northeast-trending Fraser Shear Zone, that marks the boundary with the Biranup Zone, preserves dominantly dextral strike-slip kinematics. At the southwestern termination of the Fraser Zone, the Fraser Shear Zone and parallel structures in the Biranup Zone were subsequently folded into a northwest-trending orientation. This deformation phase also affected rocks of the Northern Foreland in this region, and its thrust boundary with the Biranup Zone. Along the southern margin and termination of the Fraser Zone, compositionally variable, northeast-trending metagabbros are overprinted by an east-trending, north-dipping shear zone-hosted fold and boudin system. The northwest- to east-trending structures of the Biranup Zone that truncate those of the Fraser Zone are in turn refolded about a series of younger northeast-plunging folds southeast of the Fraser Zone.

Displacement along the Newman Shear Zone, on the eastern margin of the Frazer Zone, involved southeast-side-up and sinistral relative motion. This motion was associated with the development of a subvertically-plunging regional-scale drag fold that deformed the bounding shear zone system between the Biranup and eastern Nornalup Zones, accentuating the S-bend geometry.

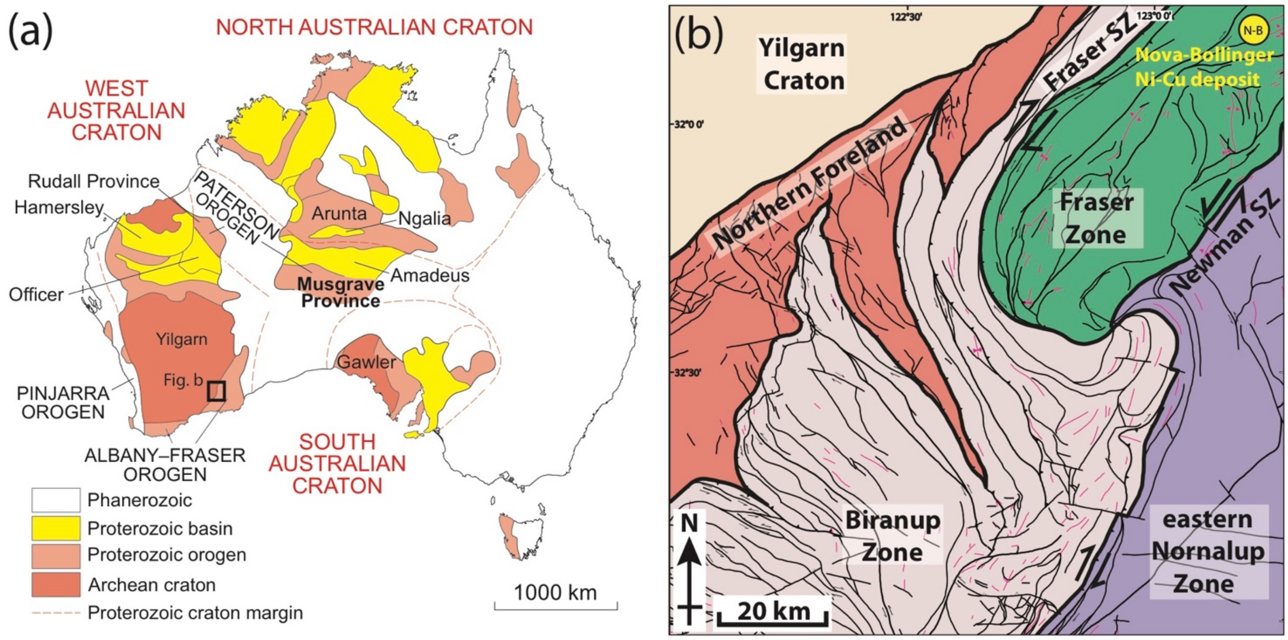

Fig.1: (a) tectonic unit map of Australia showing the location of the Albany–Fraser Orogen, with position of figure b marked. (b) map of the S-bend area showing key tectonic units and structural form lines.

Poster Session 1

Evidence for Devonian crustal stretching in northeastern Australia and implications for the origin of the Tasmanides

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The margin of eastern Gondwana records a prolonged history of convergent tectonism that initiated with the Late Neoproterozoic to Cambrian Ross-Delamerian Orogen and continued throughout the whole of the Paleozoic and early Mesozoic. Remnants of the Ross-Delamerian Orogen are preserved in South Australia, northwestern New South Wales, Tasmania and Antarctica, but the continuation of this belt farther north is less clear. The majority of the northern Tasmanides, in the area of the Thomson Orogen, is unexposed, but a number of Neoproterozoic and Cambrian inliers (Anakie, Charters Towers, Greenvale, Barnard and Iron Range provinces) record evidence for Middle to Late Cambrian deformation equivalent to Delamerian Orogeny. The link between these provinces and the Delamerian Orogen *sensu stricto* has hitherto not been clear, but the availability of new geophysical and well data from the unexposed basement of the Thomson Orogen provides an opportunity to tackle this problem and to shed light on the fundamental geodynamics of eastern Gondwana during the Paleozoic.

Interpretation of new seismic reflection profiles indicates that a large portion of the northern Tasmanides is characterised by a highly extended crust and the occurrence of widespread fault-bounded Devonian basins. These observations are in stark contrast to the southern Tasmanides, where rocks show evidence for prominent Devonian contractional deformation. These contrasting tectonic styles may have been controlled by along-strike variations in the rate of plate boundary migration (trench retreat or advance), accommodated by slab tear faults.

Structural mapping and kinematic analysis based on geophysical data interpretation suggest that the boundary between the southern and northern Tasmanides is a crustal-scale dextral shear zone which was active in the Early Devonian and likely accommodated along-strike variations in trench retreat. It is therefore suggested that crustal stretching in the northern Tasmanides was associated with Early Devonian back-arc extension in response to trench retreat, bounded in the south by a zone of slab-tearing and crustal segmentation. The dextral translation along this boundary may explain the origin of the bend in the Ross-Delamerian Orogen, from the Koonenberry Belt to the northeastern Thomson Orogen.

Palaeozoic ribbons and rollback in 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. In north Queensland the Lucky Springs Island Arc developed at ca. 455 Ma above a retreating east-dipping subduction zone along the western edge of a continental ribbon (basement to Hodgkinson Province) which consumed the oceanic back-arc region separating the eastern margin of Gondwana from the Hodgkinson Province. The remnants of this arc and associated back-arc region are preserved as the Everetts Creek Volcanics and Carriers Well Formation in the Broken River Province (Fig. 1). These rocks were entrained between the Gondwana and the re-accretion of the Hodgkinson Province basement ribbon at ca. 450-440 Ma. Tectonic melange, 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 at ca. 450 Ma. 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 this suture zone and suggests that the region forms a Late Silurian to early Devonian oroclinal structure (Fig 1). This is supported in the geological record where Cambrian and Ordovician sedimentary and volcanic successions within the Charters Towers Province trend E-W, at a high angle to the N-S to NNE-SSW trends of correlative successions in the Broken River and Greenvale Provinces to the north, and the Anakie Inlier to the south. Palaeomagnetic constraints from the Charters Towers Province (McElhinny et al., 2003) suggests a polar shift of 120° for the Charters Towers Province with respect to the Gondwana margin between ca. 425 and 400 Ma. We support the interpretation by Musgrave et al. (2015) that this shift is related to the formation of the Late Silurian to early Devonian Charters Towers orocline which we suggest resulted from initiation and subsequent rollback of a west-dipping subduction zone to the east of the accreted Hodgkinson Province in the early Devonian.

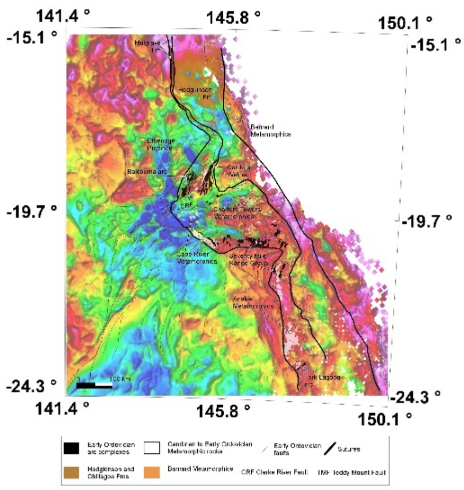

Fig. 1: Bouguer gravity anomaly grid of north Queensland with the location of Cambrian to Ordovician arc rocks, continental ribbons and major Palaeozoic sutures.

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Deep density structure of the Albany-Fraser Orogen and Yilgarn Craton margin from constrained 3D gravity modelling

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Constrained 3D gravity modelling has been used to investigate the density structure of the east Albany-Fraser Orogen. The geometry of the model is constrained from three 2D interpreted reflection seismic profiles and interpolated in 3D, using modelling software Geomodeller. The Moho has been constrained by passive seismic P-wave reciever function analysis (Sippl et al., 2017). These constraints allow us to more accurately model the density of units interpreted in reflection seismic profiles. The advantage of 3D work compared to 2D is that we can model trends along strike of the orogen as well as perpendicular to strike. The margin has a distinct Bouguer gravity anomaly with an orogen parallel long wavelength gravity low and a high amplitude gravity high, produced by the metagabbro dominated Fraser Zone. Using constrained 3D gravity forward modelling this anomaly, to a first order, can be fit with a model containing: 1) a 10 km northeast trending Moho trough along the margin of the orogen, 2) a dense upper crustal Fraser Zone, 3) a dense unit in the Moho trough, and 4) a dense Gunnadorrah Seismic Province in the lower crust of the Albany-Fraser Orogen and 5) a mid crustal mafic material in the Nornalup Zone. Another feature of the model is a sparsely constrained, broadly northwest trending step in the Albany-Fraser Orogen Moho. The Moho step is orthogonal to the strike of the orogen but has a similar orientation to the terrane boundaries of the Yilgarn Craton, specifically the Kalgoorlie/Kurnalpi Terrane boundary. This feature, possibly inherited from the Yilgarn Craton, is coincident with the southwest termination of the Fraser Zone, and may have a role in controlling intrusion of c. 1300 Ma Fraser Zone metagabbros, and possibly earlier c. 1600-1800 Ma Biranup aged juvenile material. Densities from 2D and 3D gravity modelling, and velocities from an active seismic refraction study (Tassel and Goncharov, 2006) are compared with laboratory measurements of density and seismic velocity to suggest compositions for the lower crustal units. The composition of these lower crusal units helps constrain the tectonic processes during which they formed.

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Insights into the kinetics of dehydration of solid gypsum from in-situ small- and wide-angle Synchrotron X-ray scattering

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Fluids liberated through the dehydration of hydrous minerals play a major role in the occurrence of earthquakes, metasomatism and metamorphism in the lithosphere. Because the anhydrous solid product is generally denser than its hydrous counterpart, dehydration reactions often create porosity. The liberated fluids then drain through the newly established pore network. Pore pressure can build up when fluids are released faster than drainage occurs. This over-pressure can result in hydraulic fracturing, weakening the solid phase. Gypsum is an ideal experimental analogue for hydrous minerals found in fault zones and subducting slabs due to its relatively low dehydration temperatures (~100°C). Previous studies on gypsum dehydration use 'black-box' experimental set-ups where reaction progression is assessed using proxy measurements. We present a unique set of novel in-situ dehydration experiments performed on polycrystalline gypsum discs (Volterra alabaster) using X-ray scattering techniques performed at the Australian Synchrotron. We track the dehydration reaction in-situ in real-time using: [1] Wide-angle X-ray Scattering (WAXS), which monitors in-situ changes in mineral phase; and [2] Small-angle X-ray Scattering (SAXS), which monitors in-situ changes in nano-porosity. Here, we report WAXS results for four different dehydration temperatures (120/135/145/170˚C) recorded at two different constant axial strains under radially drained conditions. These data show that [1] solid polycrystalline gypsum generally dehydrates faster than finer-grained powder; and [2] an increase in axial strain enhances reaction rate. Both results are counterintuitive and will be discussed critically. Implications for tectonic processes involving dehydration reactions will be considered.

Capturing the first millisecond of earthquake slip

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The Paterson-type triaxial apparatus was originally built to investigate the strength, deformation and rheological properties of geological materials within a viscous flow regime (Paterson, 1970). A key feature of this apparatus is its mechanical sensitivity arising from the use of a gas confining medium and internal load cell, allowing exploration of confining pressures (P_c) up to 300MPa, pore fluid pressures equivalent to (P_c – 30MPa) and differential stresses of up to ~1GPa. Although study of earthquake slip was not the original intent of the apparatus, its mechanical sensitivity and the ability to store elastic strain energy that is released into a sample upon failure makes it valuable for use in the study of small seismic events during stick-slip. These rapid slip events can be produced on pre-ground 'fault surfaces' at pressure and temperature conditions equivalent to those estimated for the crustal seismogenic regime.

Traditionally mechanical measurements on the Paterson apparatus have involved the use of sensors such as pressure transducers, strain gauges and displacement transducers. These types of sensor produce a voltage output that is sampled at frequencies up to 1000Hz and recorded at a rate of 1-100 samples per second. Fundamental limitations in sensor response time, signal conditioning requirements, and electromagnetic interference prevent data acquisition rates being increased to levels sufficient to capture seismic slip events.

This poster presents a new sensor that we have designed and built for measuring slip displacement at sampling speeds sufficient to capture fault rupture (estimated to be equivalent to the shear wave velocity of the sample (e.g. ~3500m.s^{-1}). We utilise a 1550nm fibre-based Mach-Zehnder optical heterodyne system coupled with a digital phase lock loop to provide non-continuous, triggered acquisition at a rate of 1 million samples per second. The use of an optical interferometer alleviates the effect of electromagnetic interference, allows flexibility in measurement configuration and achieves a system capable of a large dynamic range (multiple centimetres of axial displacement), high displacement resolution (10^{-9}m/$\sqrt{Hz}$ above $2Hz$), and high velocity tracking capabilities (up to ~30m.s^{-1}). The beam path is located internally within the piston assembly above the sample. A micro-collimator, located within the pore-fluid conduit, reflects the beam off an optically flat, highly polished tungsten carbide disc at the top of in the sample assembly, allowing the first direct measurements of the sample displacement during rupture propagation.

Interferometry-based displacement measurement is combined with in-situ stress measurement using strain gauges glued directly onto the sample. The combined results provide new insights into dynamic weakening and fault behaviour during the first millisecond of seismic slip.

Tectonic evolution of Macquarie Arc from geologically constrained geophysical interpretation

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Using geologically constrained potential field (aeromagnetic and Bouguer gravity data) interpretation we investigate the evolution of Ordovician-Silurian Macquarie Arc. We map the concealed and exposed geology and related structures to test if the evolution of Macquarie Arc architecture is consistent with recently developed tectonic models for the evolution of Lachlan Fold Belt. In particular, we test the Cayley and Musgrave, 2011 and Moresi et al., 2014 orocline model which is interpreted to have formed in response to the collision between Vandieland microcontinent and East Gondwana during the Late Ordovician to Early Silurian. Field work observation on major fault reveals kinematics that lack large strike-slip displacement, which is predicted by the orocline tectonic model.

The mapping reveals parasitic folding in the Ordovician-Silurian litho-packages of the Molong and Rockley-Gulgong Volcanic belts preserved on the flanks of Devonian Rift Basin of the Hill End Trough. Preliminary interpretation of geophysical data combined constrained with geologic maps suggest that the northern part of the basin is a fold hinge with Ordovician-Silurian arc-related rocks converging to the fold hinge on both side of the Devonian basin. Field mapping and ground gravity and magnetics are planned to test this models and accentuate our understanding of the eastern belts of the Macquarie Arc.

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Late Mesoproterozoic Metamorphism in Tasmania: Rifting or Rodinia-forming Collision?

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The collision of Australia-Antarctica with western Laurentia in the late Mesoproterozoic or early Neoproterozoic is hypothesised marks the final assembly of the supercontinent Rodinia. Evidence for metamorphism or deformation along the eastern margin of Australia-Antarctica and the western margin of Laurentia that might be attributed to this Rodinia-forming collision is equivocal. One of the few places in eastern Australia where Late Mesoproterozioc metamorphism is recognised is King Island- a small island located approximately 100 km northwest of Tasmania. Based on its record of Late Mesoproterozoic metamorphism, some workers interpret King Island to be a fragment of the collisional suture between Australia-Antarctica and Laurentia within Rodinia. However, the tectonic setting of Late Mesoproterozoic metamorphism on King Island has not been studied in detail and the interpretation that it reflects collisional processes has not been demonstrated.

This study presents results from recent field-based mapping on King Island and a reassessment of the pressure-temperature-time history of the Late Mesoproterozoic metamorphic event recorded here. Mesoproterozoic strata exposed on the west coast of King Island comprise sandy turbidites of the Surprise Bay Formation. The Surprise Bay Formation is intruded by a series of northeast trending dolerite dykes with MORB and within-plate basalt geochemical affinities. Probable mafic volcaniclastic rocks are locally interlayered with turbdites in the Surprised Bay Formation and are compositionally similar to the dolerite dykes. Both the Surprise Bay Formation and dolerite dykes record deformation assigned to D_1, which produced a subhorizontal fabric and tight recumbent folds that were subsequently rotated into an upright position during Neoproterozoic—Paleozoic deformation. Metamorphism was pre- to syn-kinematic with respect to D_1 with the peak garnet- and andalusite-bearing assemblages equilibrating in the low-pressure amphibolite facies at *ca.* 1290 Ma.

Integrating field and microstructural observations suggests that sedimentation, mafic magmatism, deformation, and low-pressure medium-temperature metamorphism on King Island may have been broadly contemporaneous. We suggest that Late Mesoproterozoic metamorphism on King Island occurred in a mature continental rift setting, where mantle upwelling and voluminous mafic magmatism drive low-pressure medium—high-temperature metamorphism in thinned continental crust. Late Mesoproterozoic tectonism on King Island may therefore to be unrelated to orogenesis associated with the assembly of Rodinia. Instead, *ca.* 1290 Ma rift-related metamorphism on King Island overlaps with the final stages of the breakup of the supercontinent Nuna, which is also recorded by widespread basin formation throughout mainland Tasmania at this time.

Microstructural and microchemical evidence for deep crustal melt-rock interaction in mass transfer zones, Finero Complex, Ivrea Verbano Zone, Italy

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The deep crustal section of the Ivrea-Verbano Zone (IVZ, western Alps) has been the study of numerous structural, geophysical and geochemical studies which have attempted to better understand lower crustal processes (P = 10 – 12 kbar) and the magmatic and tectonic evolution of the area. The Finero Complex, in the northern IVZ, is characterized by the occurrence of a pervasively metasomatized mantle unit comprising 8 km^2 of phlogopite-bearing ultramafic rocks called the Phlogopite-Peridotite (after Siena & Coltori, 1989). This unit is surrounded by a nested suite of mafic-ultramafic intrusions which forms a pseudo-antiformal structure with the Phlogopite-Peridotite at the core. The core is surrounded by a 100 m thick unit of interlayered garnet gabbros and hornblendites (the Layered Internal Zone), a 600 m thick cumulus amphibole peridotite (Amphibole-Peridotite), and a 450 m thick garnet gabbro (External Gabbro). The Finero Complex is bordered by the boundary of the European and Adriatic plates (the Insubric line) to the N-NW and the metasedimentary Kinzingite unit to the S-SE. Contacts between the Phlogopite-Peridotite and units within the mafic complex are consistently characterized by dm-scale mylonitic shear zones. The hydrous metasomatism in peridotite and structural features at the margins of peridotite are absent from the other mafic complexes of the central and southern IVZ (Balmuccia and Baldissero), suggesting that the Finero Complex experienced a more complex geodynamic evolution involving extensive metasomatism. This study aids in understanding (i) the metasomatic processes involving melt-rock interaction at upper mantle and deep crustal conditions, (ii) the relationship of different types of metasomatism in different units, (iii) the age of igneous protoliths and timing of metasomatism throughout the complex, and (iv) the formation of high variance assemblages exposed in the Layered Internal Zone. Preliminary results suggest that the microstructures and microgeochemical data can be explained by a model of both widely distributed and channeled diffuse porous melt flow which occurred through the peridotite and along the deforming boundaries with the other lower crustal units. By gaining a better understanding of the reaction and deformation textures formed by the interaction between silicate melts and previously established frameworks of protoliths, similar areas of mass transfer can be recognized in the field.

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Reconstructing the Trace of Mesozoic Subduction and Its Implication on Stratigraphy Correlation between Deep Marine Sediment and Granite : Case Study of Garba Complex, South Sumatra

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Garba hill, located in Tekana Village, South Sumatera Province is comprised to South Sumatra Basin and classified as back arc basin. This area is entered as an active margin of Sundaland which experiences subduction several times since Mesozoic to recent time. The traces of Mesozoic subduction in the southern part of Sumatra island are exposed in Garba hill area. The aim of this investigation is to study the tectonic changes in the first phase in Mesozoic era at the active margin of Sundaland which causes the rocks assemblage in Garba hill consist of continental and oceanic plate rocks which the correlation between those rocks show indistinct relation. This investigation is conducted by field observation in Tekana village and Lubar Village, Muara Dua, South Sumatra along with laboratory analysis included fossil and geochemistry analysis of radiolarian chert, petrography analysis of granite and basalt, and structural modelling. Fossil and geochemistry analysis of radiolarian chert and geochemistry of granite rocks shown the relation between the two rocks and Mesozoic subduction of Woyla terrane on western margin of Sundaland. Petrography analysis from granite and basalt depict the tectonic afinity of rocks. Moreover, Structural analysis shown the changes of lineation direction from N-S to WNW-ESE.

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Toward a Greater Kerguelen large igneous province: Cretaceous magmatism along the rifted margin of Western Australia

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The link between the Kerguelen Large Igneous Province and magmatic occurrences emplaced on the continental lithosphere of Western Australia (WA) in close temporal and spatial proximity to the breakup triple junction of eastern Gondwana remains tentative. Tholeiitic Cretaceous magmatism along the margin was poorly investigated until recently and the involvment of the Kerguelen mantle plume was speculative due to the lack of reliable geochronological data. Here we report new ages from three key locations: the Wallaby Plateau (off-shore, NW Australia), the Bunbury Basalt (SW Australia) and the Naturaliste Plateau (off-shore, SW Australia). Our new plateau ages indicate that (1) on the Wallaby plateau, the magmatic activity occurred at or before ~124 Ma that is at least 6 Ma younger than the oldest oceanic crust in adjacent abyssal plains (~130 Ma); (2) the Bunbury Basalt erupted in three distinct phases, at 136.96 ± 0.43 Ma, 132.71 ± 0.43 Ma and 130.45 ± 0.82 Ma while only two magmatic episodes have been documented so far, and (3) volcanism on the Naturaliste plateau began at or prior to ca. 128 Ma, which is >25 m.y. older than previous estimations. This suggests that this magmatism began during the rifting of the continental lithosphere but lasted after the onset of the oceanic spreading (~130-136 Ma). In addition, this magmatism preceded the emplacement of the Kerguelen plateau by at least 10–20 m.y. These new data led us to re-interpret the currently available Sr–Nd–Pb isotopic dataset. The isotopic data available for the WA Cretaceous magmatism suggests source contributions from the depleted asthenosphere and lithosphere with negligible contribution from the Kerguelen mantle plume. However, heat provided by the Kerguelen deep mantle plume, coupled with edge-driven convection and decompression of the asthenosphere during the rifting, was necessary to melt the asthenosphere and lithosphere. Thus, we attribute the WA Cretaceous magmatic provinces, and equivalent units in Greater India, to the Greater Kerguelen large igneous province.

Fig. 1: Bunbury Basalt lava flows at Black Point, Western Australia, dated at 130.45 ± 0.82 Ma.

Seismic Cycles and Recurrence Plots from Gofar Transform Fault, East Pacific Rise

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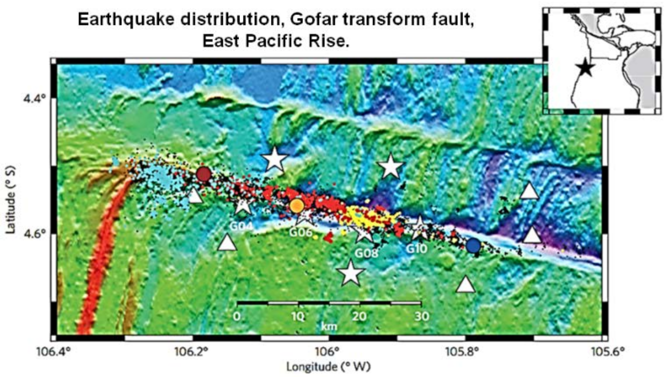
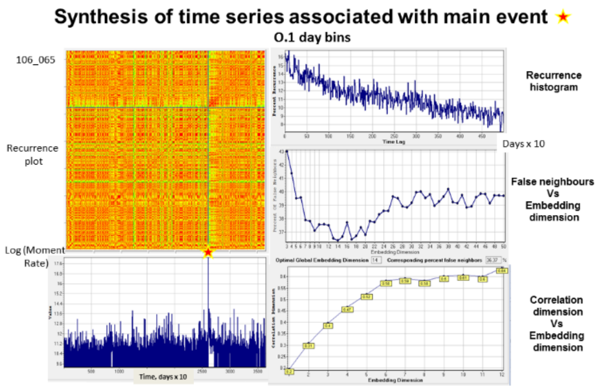
Earthquakes on oceanic transform faults exhibit many of the most systematic and predictable behaviors known in seismology and therefore provide a window into earthquake forecasting on potentially damaging faults. On short time scales (hours to days) earthquakes on these faults display extremely high levels of foreshock activity. On intermediate time scales (years) oceanic transform faults show the clearest evidence of regular seismic cycle behavior in the instrumental record. And on long temporal and spatial scales (decades & 100s of km) the size and frequency distributions of oceanic transform fault earthquakes can be predicted from scaling relations dependent only on transform fault lengths and slip rates. In 2008 the periodicity of oceanic transform fault earthquakes was put to the test when an array of ocean bottom seismometers were positioned on Gofar Transform Fault, located just south of the equator on the East Pacific Rise. The next expected earthquake on this fault occurred right on time and the seismometers recorded an incredible dataset including the magnitude 6.0 earthquake, thousands of foreshocks, and the aftershock sequence. Here we investigate the temporal and spatial patterns of seismicity on Gofar using recurrence plots of microseismicity from 2008. Prior to the magnitude 6.0 earthquake, we find synchronization of chaotic transitions in dynamical behaviour that span 10s of kilometers along strike.





Embedding dimension of attractor somewhere between 6 and 14

The StraboSpot digital data system for field and microstructural data: Application to the Mt Edgar dome, Pilbara Craton

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There is no widely accessible way to digitally archive and share field structural data. In response to this problem, we are continuing development of the Strabo data system for the structural geology and tectonics community. The data system allows researchers to standardize field structural data collection, share primary data, facilitates interaction with other geoscience communities, and allows new types of science to be done. In the future, the Strabo data system will allow users to apply new types of analytical procedures (e.g., statistical analysis). The data system is based on a graph database, rather than relational database approach, to increase flexibility and allow geologically realistic relationships between observations and measurements. Development is occurring on: 1) A field-based application, StraboSpot, that runs on iOS and Android mobile devices and can function in either internet connected or disconnected environments; and 2) A desktop system that runs only in connected settings and directly addresses the back-end database. The field application also makes extensive use of images, such as photos or sketches, which can be hierarchically arranged with encapsulated field measurements/observations across all scales. The system also accepts Shapefile, GEOJSON, KML formats made in ArcGIS and QGIS, and will allow export to these formats as well. StraboSpot uses two main concepts to organize the data: Spots and Tags. A Spot is any observation that characterizes a specific area. Below GPS resolution, a Spot can be tied to an image (outcrop photo, thin section, etc.). Spots are related in a purely spatial manner (one spot encloses another spot, which encloses another, etc.). Tags provide a linkage between conceptually related spots. Together, this organization works seamlessly with the workflow of most geologists. We are expanding this effort to include microstructural data, as well as to the disciplines of sedimentology and petrology. Microstructural data include photomicrographs, scanning electron microscope images (SE, BSE, CL), electron backscatter diffraction (EBSD) and transmission electron microscopy (TEM) data. In this poster, we provide an example of how StraboSpot organizes microstructural data from a recent structural study in the Mt Edgar dome in the Pilbara craton. The study uses data from a variety of scales to investigate the kinematics of dome emplacement.

The recognition of former melt flux through high-strain zones

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High-strain zones are potential pathways of melt migration through the crust. However, the identification of melt-present high-strain deformation is commonly limited to cases where the interpreted volume of melt ‘frozen’ within the high-strain zone is high (> 10 %). In this contribution, we examine high-strain zones in the Pembroke Granulite, an otherwise low-strain outcrop of volcanic arc lower crust exposed in Fiordland, New Zealand. These high-strain zones display compositional banding, flaser-shaped mineral grains, and closely spaced foliation planes indicative of high-strain deformation. Rare segregations of leucocratic material and coarse-grained peritectic garnet grains suggest deformation was synchronous with partial melting. High-strain zones lack typical mylonite microstructures and instead display typical equilibrium microstructures, such as straight grain boundaries, 120° triple junctions, and subhedral grain shapes. We identify five key microstructures indicative of the former presence of melt within the high-strain zones: (1) small dihedral angles of interstitial phases; (2) extremely elongate interstitial grains; (3) small aggregates of quartz grains with xenomorphic plagioclase grains connected in three dimensions; (4) fine-grained, K-feldspar bearing, multiphase aggregates with or without augite rims; and (5) mm- to cm-scale felsic dykelets. We propose that microstructures indicative of the former presence of melt, such as the five identified above, may be used as a tool for recognising rocks formed during melt-present high-strain deformation.

Rapid, semi-automatic fracture and contact mapping for the digital age

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UAV-based photogrammetric and LiDAR techniques provide high-resolution 3D point clouds and orthorectified photomontages that capture surface geology in outstanding detail and over wide areas. Many studies now use these methods to collect primary field information and then extract geological measurements such as structure orientations at a later stage. Automated and semi-automated digital mapping methods are vital to fully utilize these detailed datasets and extract meaningful geological information in practical amounts of time. The nuances of geological structures and materials (natural variability in colour and geometry, soft and hard linkage, shadows and multiscale properties) make this a challenging task.

We present new open-source software tools for rapid, computer-assisted but user-driven interpretation of large point cloud and raster datasets. Integral to the workflow is a least-cost-path solver that can follow geological structures and contacts through both point-cloud and image datasets, reducing interpretation time while simultaneously improving objectivity. Our two open-source implementations of this method, ccCompass and GeoTools, are optimized for 3D point cloud and 2D raster datasets respectively. GeoTools can incorporate a digital elevation model to extract and analyse planar orientation estimates, while ccCompass includes a virtual compass for rapidly measuring structural orientations. ccCompass also creates and maintains a flexible data structure for organising measurements and interpretation into a geological database and associated three-dimensional map (Fig. 1).

ccCompass is a plugin for the popular software package CloudCompare, and is now included in the standard installation, while *GeoTools* is available from the QGIS plugin repository.

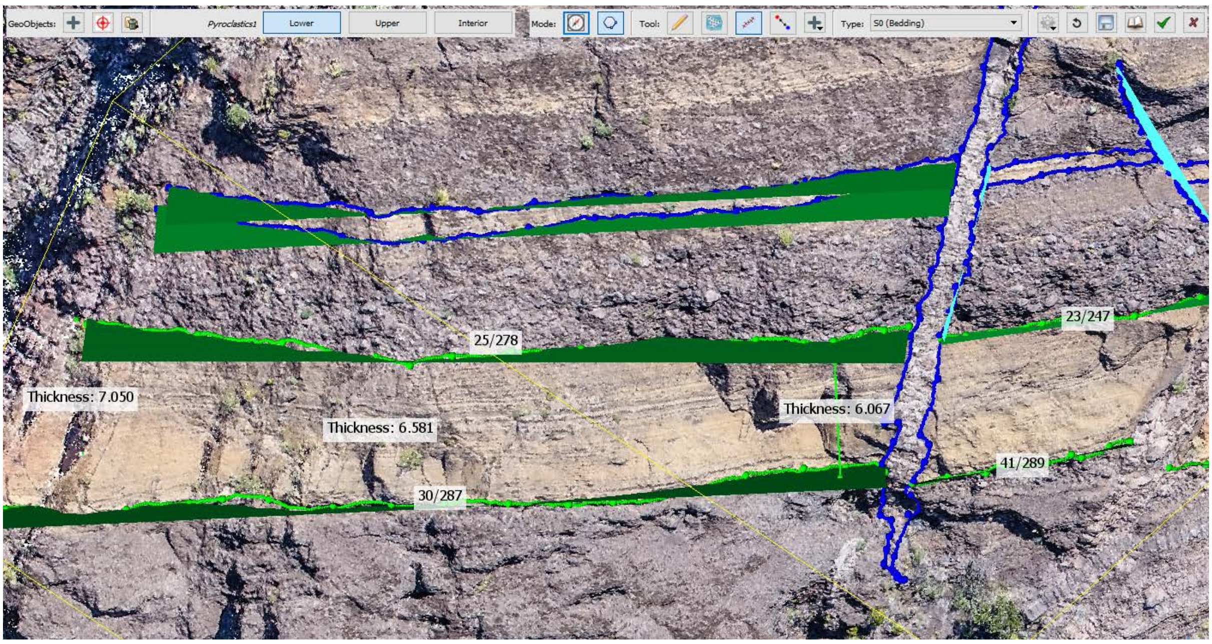

Fig. 1: ccCompass used to map dykes and stratigraphy in a virtual outcrop model of volcanic cliffs on the Canary Islands. Best-fit planes deriving from semi-automatically generated contact traces are shown in green, as are thickness estimates interactively derived from them.

Structural and chemical correlations by multifractal methods in Alpine Fault Drilling Project (DFDP) samples.

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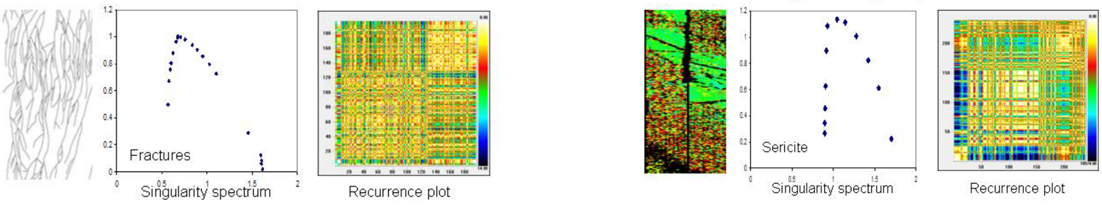
New Zealand's Alpine Fault, Deep Fault Drilling Project (DFDP) has thus far sampled

(i) The shallow Alpine Fault ultramylonites, cataclasites and principal slip zones at Gaunt Creek. Approximately 130 m of drillcore was recovered from this sequence (Toy et al., 2015)

(ii) The protolith amphibolite facies Alpine Schist and the distal parts of the ductile shear zone at depth (protomylonite and mylonite). This material was recovered as cuttings collected over 2 metre intervals (Toy et al., in revision).

A variety of systematic structural and chemical datasets have been collected from these materials. In some cases comparable data have been collected by different methods. For example, we have estimates of quartz grain size in cuttings chips made by linear intercept analysis of thin sections made on the drillsite and EBSD-derived grain size estimates from the same materials. We also documented structures in the core by manual description and by detection from CT scans by both manual and automated methods. Compositional information was acquired by XRD, XRF, thin section analysis, EDS mapping, and will be acquired by Hylogger before the SGTSG meeting.

These datasets provide the opportunity to assess how variations in structure and chemistry correlate within an active, plate-boundary scale fault analogous to extinct mineralising systems. The Alpine Fault Zone hosts a very active hydrothermal system in which circulating fluids tapping heat from rapidly advected rock at depth generate a near-surface geothermal gradient of >125^{O}C/km (Sutherland et al., 2017). We hypothesise that changes in mineralogy in the samples may be related to alteration as these hot fluids circulate in fracture networks, rather than reflecting original lithologic variations or reactions that involved grain-scale diffusion and would have affected the rock mass more uniformly. We are testing this hypothesis through multifractal analyses and recurrence quantification exploring correlations between the structural and chemical variations, such as those illustrated in the following figures.



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Virtual Petrography (ViP) – A virtual microscope for the geosciences

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Virtual Microscopy is a rapidly growing tool in many fields of science with powerful applications in research and teaching. In this presentation we demonstrate the fully functional first high resolution virtual polarising microscopy platform designed for geoscience applications in petrography and microtectonics. It was developed by RWTH Aachen University and Fraunhofer FIT.

The system consists of two parts:

An automated polarisation microscope that scans thin sections in very high resolution under various polarisation and illumination conditions to cover all information available by polarised microscopy (reflected and transmitted light, and Cathodeluminescence). The data is then processed to extract the extiction curve of each superpixel and the data are stored in a format that allows rapid access high compression.

The datasets can then be viewed with a virtual microscopy software (TileViewer) that is user friendly and allows Google Earth - like fluent zooming and browsing through the thin section as well as rotation of the polarisers and switching between illumination conditions. TileViewer software is platform independent and requires no special hardware. Besides visualisation and image adjustments the TileViewer Software offers the possibility to create annotations, visualise the data attributes (for example extinction direction), and offers a basic module for image segmentation. For further analysis the data can be exported to image analysis environments or machine learning applications. The information density of each dataset (including the extinction behaviour) and the high resolution over very large continuous areas allows for multiscale analysis, and offers the potential for automated petrography and nove methods of multiscale, semi-automated analysis that was not possible before.

Virtual Petrography has proven itself as excellent for teaching due to the ease of use and many further advantages to classical microscope based teaching. It is our goal to build a community of geoscience lecturers and professionals in which samples and datasets are shared for teaching and research.

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Thursday 9th November

Microstructures

Deformation Mechanisms and Microstructure Evolution in Mudrocks

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The mechanical and transport properties of mudstones are rapidly gaining importance in many subsurface applications such as finding brittle reservoir sweet-spots, evaluating topseal and fault seal integrity at storage sites and predicting the performance of nuclear waste repositories. Equally important is the understanding of mudrock deformation in fault zones, where the weak detachments and seismic slip are key processes.

There is a rapidly growing knowledge base of the bulk constitutive behaviour of these fine-grained nano-porous materials, showing a wide range of behaviour transitional between rocks and soils with anisotropic plasticity, effective pressure dependent failure envelopes, and strong strain localisation. Time dependent effects can be related to significant organic material and fluid pressure gradients. The microphysical and microchemical basis of this is much less understood because imaging the microstructure at nm resolution over large volumes in these heterogeneous materials is difficult.

This presentation will present results of Broad Ion Beam (BIB) milling followed by Scanning Electron Microscopy (SEM) to image naturally and experimentally deformed mudstones from the underground research laboratories in Europe which provide well preserved and characterised samples from outside the excavation damage zone and from fault zones.

In uncemented mudrocks with increasing effective stress the material's compressive strength increases and the tendency for the formation of dilatant fractures decreases, finally resulting in strongly localized strain in compacting shear zones and kinks in samples shortened parallel to bedding. Shear zones develop strong preferred orientation of clay and we propose an important contribution of the flow of nano-scale clay aggregates. Deformation mechanisms are bending of clay plates, sliding along clay-clay contacts and pore collapse, with shear zones developing in zones anastomosing between strong silt grains. The interaction of these two scales of localisation is in strong contrast to cemented mudrocks where cataclastic deformation is dominant even at high confining pressure. Here, microstructures show a complex interplay of microcracking, bending and kinking of phyllosilicates, and grain refinement. Although with increasing confining pressure the tendency to dilate decreases, there is evidence of micro porosity development even at high confining pressure, until at high strains the development of a clay-rich gouge can re-seal the initial dilatant fractures.

In a small fault in Opalinus clay, incipient faulting shown both dilatancy forming calcite microveins and pore collapse in ductile shear zones. These shear zones develop into scaly clay in fault relays, together with thin zones of strongly deformed clay gouge in the fault core. Here, deformation mechanisms also include solution- precipitation processes which suggests that long-term rheology can not be simply extrapolated from short-term experiments.

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Grain boundary structure of Alpine Fault rocks: what are the implications for shear zone rheology and electrical properties?

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Magnetotelluric models around the inferred down-dip projection of New Zealand's Alpine Fault Zone (AFZ) demonstrate it has anomalously high conductivity (ρ~10-100 Ωm) from 10-20 km depth and high conductivity (ρ~100-1000 Ωm) from 20-30 km depth (Wannamaker et al., 2002). Comparison of laboratory measurements of resistivities of samples of AFZ outcrops with wireline resistivities measured *in situ* to ~820 m depth during the recent Deep Fault Drilling Project (DFDP-2; Sutherland et al., 2017) indicate an order of magnitude variation that is demonstrably not a result of surface conductivity, and cannot be resolved even by considering realistic fluid compositions (Doan et al., in prep).

In exhumed and borehole samples we have characterised the distributions and arrangements of the most conductive phases observed in these rocks – solid graphite, possibly amorphous carbon, and grain boundary pores that would have contained brines or other conductive fluids at depth (Billia et al., 2013; Sauer et al., 2017). These become progressively concentrated onto grain boundaries with increasing total ductile shear strain (Kirilova et al., in review; cf. Craw & Norris, 2003). However, even at high strains they are still diseminated.

Lower strain (proto)-mylonites have a segregated microstructure with interlinked layers of quartz with strong CPOs, that likely deformed by grain size insensitive (GSI) creep in the deeper parts of the shear zone. With increasing shear strain, ultramylonites are generated, within which the constituent phases are more well-mixed/dispersed and CPOs are weaker (Toy et al., 2012; Sauer et al. 2017). There is also evidence retrograde reactions occurred – albeit to limited extent because fluids are not abundant during exhumation of comparatively anhydrous lower crust. For example, there is sporadic chlorite, and sharp albitization fronts extend a few hundred nanometres from grain boundaries. These observations are consistent with dominance of solution-accommodated grain size sensitive (GSS) creep.

In a shear zone that progressively narrows during exhumation the most highly strained rocks should be the product of deformation in the shallower part of the creeping crust. This is also the zone that has the highest conductivity in MT models. Our overall conclusion is that the major source of anomalously high conductivity in AFZ rocks is dynamic interlinking of conductive phases during GSS creep in the mid crust.

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Partially open grain and phase boundaries as fluid pathways in magmatic and metamorphic rocks: new observations and modelling

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Combined TEM and SEM/FIB sequential imaging of quartz grain boundaries from contact and regional metamorphic rocks showed that most of the grain boundaries are open on the nanometre scale (Kruhl et al., 2013). Three types of voids occur: (i) roughly 40 to 500 nm wide, open zones parallel to the grain boundaries; (ii) cavities of variable shape and up to micrometer size along the open grain boundaries; and (iii) cone-shaped, nanometre-sized depressions at sites where dislocation lines meet the open grain boundaries.

The significance of these structures is proven by their wide occurrence, also along phase boundaries between quartz, K-feldspar, plagioclase, amphibole, pyroxene, garnet, and calcite and in a variety of rock types: granitoids, basalt, metagabbro, eclogite, kinzigite, and marble. The voids are partly filled by secondary minerals, such as amphiboles, biotite and chlorite. This argues for dissolution-precipitation processes caused by fluid circulation in a connected network of porosity, partly already under mid-crustal conditions.

The grain- and phase-boundary-parallel open zones are suggested to be generated by thermal contraction at temperatures below the threshold temperatures of diffusion of the involved minerals, and kept open, due to the anisotropy of thermal contraction, even at pressures of several hundred MPa. In addition to imaging by TEM and SEM/FIB methodology (Wirth, 2004), the 3D network of open grain and phase boundaries is investigated by confocal laser scanning fluorescence microscopy and numerically modelled, based on the known pressure-temperature-dependencies of cell parameters (Schrank et al., 2012). The comparison between modelling results and measured 3D fabrics serves to verify the proposed process of fabric widening and its modification if necessary.

The importance of the investigated phenomenon is rooted in the probably large effect of networks of partially open grain and phase boundaries on permeability, reactivity, elasticity, strength, shear resistance, and not least weathering of rocks.

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Retrogression and reworking in relation with deformation microstructures developed in previously hot and dry rocks; an example from the Reynolds Range, Central Australia.

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The occurrence of wide shear zones, in different states of hydration and retrogression, juxtaposed to large granulite grade terranes poses questions about the relation and feedback mechanisms between deformation and metamorphism/metasomatism. At Mt Boothby in the southeastern Reynolds Range, central Australia, ‘dry’ and impermeable orthogneisses have been sheared and metamorphosed into muscovite bearing ultramylonites. The muscovite poor orthogneiss has developed a foliation defined by aligned biotite and elongated megacrysts of optically continuous K-feldspar porphyroblasts showing perthite exsolution. This foliation is crosscut by the shear zone fabric in which remnants of K-feldspar porphyroblasts are found in muscovite bearing ultramylonites retaining perthite exsolution in the core with a recrystallized feldspar mantle. A quartz vein with a hydration halo of a few meters (increased mode of micas) is observed in the center of the shear zone. The quartz body is thought to be a result of primary shearing at high grade and deflects some of the retrogressive fluids retaining an earlier mylonite in its strain shadow.

U-Pb ages from monazite of protomylonite, mylonite, and rocks from the micaceous halo around the quartz body result in metamorphic ages of ~1580 Ma (Chewings age). A Discordia trend is observed to intersect the Concordia plot at around 1000 Ma but uncertainties are large. Highly retrogressed monazite is observed in the transition rock (proto-to ultramylonite) and analysis of such resulted in meaningless U-Pb ages (4.6+ Ga). Rocks with little or no monazite show an increase in apatite and presumably loss of incompatible REE.

Strain free (optically), elongated and aligned perthite from the (muscovite poor) orthogneiss suggests metamorphism and/or recrystallization at high temperatures (i.e. granulite grade). Monazite found within these textures are as young as ~1580Ma. Stable monazite inside the shear zone was only found in close relation to the quartz body and its halo. A mylonite from this halo was dated at 1580 Ma (monazite) indicating that a shear fabric was developed during the Chewings event. The Discordia intercept of 1000 Ma, retrogression of monazite, increase of muscovite together with the finer grained fabric and increase in sodic plagioclase mode suggest this existing fabric has been overprinted by a later deformation event. Preliminary results are interpreted that the shear zone represents a reworked and retrogressed pre-existing structure involving hydration at temperatures of around 350-450°C.

Friday 10th November

Extensional Tectonics & Basins, Structural Processes & Mineralisation

4D evolution of accretionary wedges – examples and models

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Accretionary prisms in subduction systems typically form critically tapered Coulomb wedges with imbricate fans of regularly spaced thrust-related tip-line folds detached on over-pressured shale units. The wedge geometries are controlled by the layer thickesses of the imbricated section as well as by syn-tectonic erosion and syn-tectonic sedimentation. The frontal sections of the wedge form quasi-stable wedges in dynamic equilibrium whereas the hinterland forms a backstop. Changes in wedge topographies or basal friction characteristics perturbs the wedge equilibrium typically producing out of sequence thrust faults. At the thrust front, proto-thrusts are commonly found and these control the initiation of the thrust related folds that form as the wedge progrades into the foreland. Modern high-resolution seismic data from accretionary prisms such as the Makran offshore Iran, the Cascades offshore northwestern USA and Canada, the Hikurangi prism offshore the east coast of New Zealand and the Banda Arc accretionary prism system offshore Timor have provided new insights into their geometries, fault-fold structures and how they form in space and time. Syn-tectonic sedimentation rates in many of these systems are low and the thrust-related folds are emergent on the sea floor such that gravitational collapse of the frontal limbs of the folds is common. Analyses and reconstructions of these deepwater fold and thrust belts have lead to new models for the development of thrust-related folds in these terranes.

Scaled analogue models of thrust wedge systems in 2D and 3D was recorded using DIC monitoring show how these wedges evolve with synchronous thrusting and wedge re-adjustment when syn-tectonic sedimentation or erosion is introduced. The geometries and characteristics of the physical models are strongly controlled by surface processes as well as by basal detachment strengths. The results of the physical models are compared to both accretionary wedges as well as to sub-aerial fold and thrust belts.

3D analogue experiments of rotational extension: how propagating rifts interact with pre-existing linear rheological heterogeneities

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Propagating rifts are a natural consequence of lithospheric plates that diverge with respect to each other about a pole of rotation. Although all major continental breakup events have involved relative rotation between plates, most geodynamic modelling has focused on orthogonal and oblique rifting. We present a series of lithospheric-scale three-dimensional analogue experiments of rotational extension with in-built, variably oriented linear anisotropies to elucidate how propagating rifts interact with pre-existing structures. Surface strain and dynamic topography in the analogue models are quantified by high-resolution particle imaging velocimetry and digital photogrammetry, which allows us to characterise the spatio-temporal evolution of deformation as a function of the orientation of the linear heterogeneities in great detail.

Previous results show that the presence of a weak zone contained in the lithospheric mantle exerts a first-order control on the general evolution of rift propagation and deformation evolution. When the heterogeneity is oriented at low angles with respect to the rift axis, an “unzipping” process prior to continental break up is favoured. In these scenarios, the formation of intra-rift horsts at early stages may lead to microcontinent formation. Alternatively, models with a weakness that is oriented at high angles with respect to the rift axis show strong strain partitioning, providing insights on how propagating rift branches are aborted when strain is relayed onto structures that develop in rheologically weaker areas.

New modelling incorporating linear anisotropies only in the lower crust shows that pre-existing discontinuities and their orientation also control the evolution of the fault network, but to a lesser extent than experiments with a lithospheric mantle weakness. We also report on preliminary results of models incorporating linear anisotropies in both lithospheric mantle and lower crust levels. These new experimental results are compared to previous analogue models, summarised in terms of their evolution and patterns of strain localisation, and compared to ancient and modern examples of rifted margins on Earth.

Basement controls on the evolution of the Outer Basin High, Ceduna Shelf: Integration of seismic and gravity data

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Recent exploration on the outer margin of the Ceduna Shelf has identified an anticline within the Early Cretaceous sequences known as the outer basin high, which is a target for exploration. The outer basin high is 15 to 40 km wide and extends along the southwestern flank of the Ceduna Sub-basin, beneath the outer flank of the Ceduna Terrace. It is associated with structural relief in excess of 2000 m (Figure 1).

The outer basin high underlies a transitional zone of deformation between the thin skinned extensional faulting and outer fold and thrust regions of two overlapping delta systems, the Late Albian to Santonian White Pointer and the Santonian to Maastrichtian Hammerhead delta systems. Detailed mapping using the Ceduna 3D seismic dataset reveals two main episodes of relative uplift, in the Santonian and again in the Maastrichtian to Eocene. The first phase of relative uplift is associated with thinning of the Tiger Supersequence onto the high and is attributed to the formation of a fold forming over a reactivated rift-related basement fault. The second phase is identified as a decrease in thickness of the Hammerhead Supersequence overlying the outer basin high, related to basin-wide uplift and erosion during the Maastrichtian-Eocene, which removed up to 1.5 km of sediment.

Interpretation of the rift-related basement faults is limited by a lack of conventional seismic data below 12 km depth. A regional deep crustal seismic survey by ION Geophysical reaches depths of 40 km and has been integrated with gravity and magnetic data. The locations of rift-related basement fault blocks are constrained by 2D forward modelling of the gravity and magnetic data and reveal the deep basin architecture. This helps to improve understanding of the controls on the deformation of the overlying sedimentary sequences.

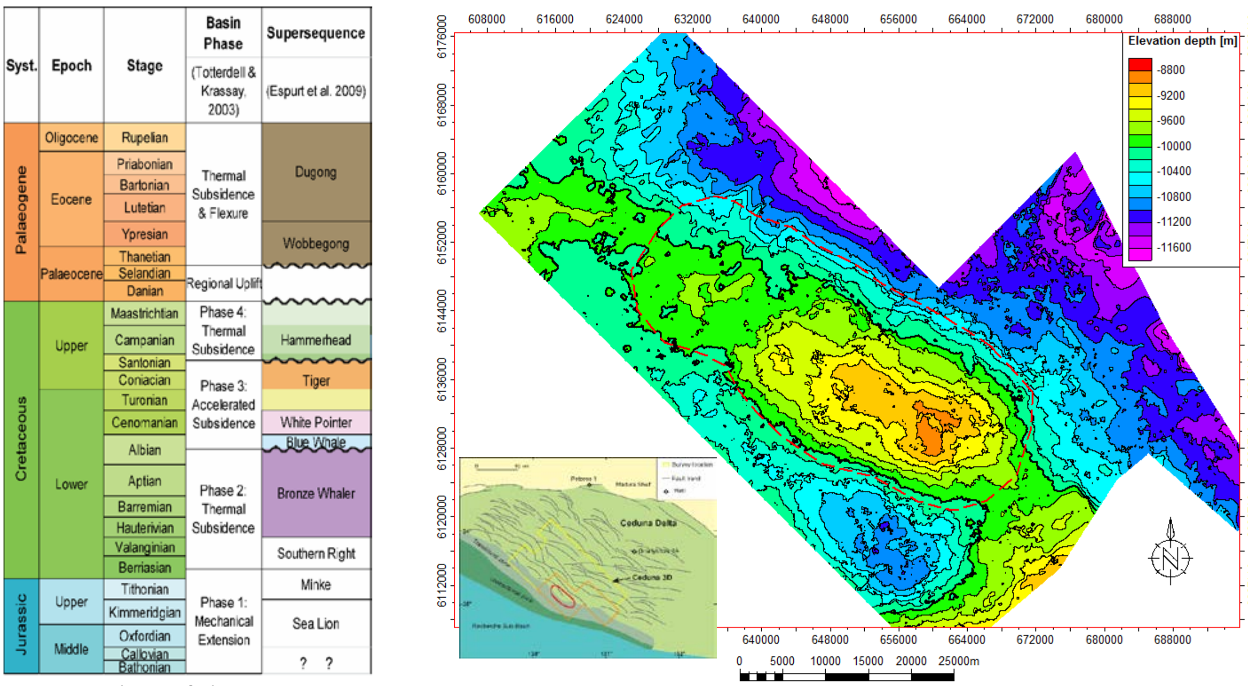

Fig. 1: Outline of the Outer Basin High as seen at the top of the Albian Bronze Whaler Supersequence.

Fault Segmentation, Linkages and Reactivation in Multi-Phase Extension, Rowley Sub-Basin, Roebuck Basin, Australia

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A detailed structural analysis of 3D seismic surveys from the Rowley Sub-basin of the Roebuck Basin, North West Shelf, Australia, has identified a population of generally NW-SE to N-S trending faults, which consists of sinuous segments, extending up to 23 km in length. Fault geometries, displacement and orientation analyses strongly suggest the NW-SE to N-S trending faults are a result of Late Jurassic-Early Cretaceous oblique reactivation (east-west directed extension) of underlying zones of weakness generated by the preexisting highly segmented (-5 km in length) northwest-southeast trending Early Jurassic faults. A population of NE-SW trending Late Jurassic-Early Cretaceous faults are also observed, but were more likely formed in a relatively short-lived northwest-southeast directed tectonic process, with little influence by preexisting structures.

The highly segmented Early Jurassic fault system displays horse-tail en-echelon fault arrays and indicate the control of preexisting NW-SE structural fabrics associated with the development of the onshore Canning Basin in the Triassic and during the Paleozoic.

The identification of the NW-SE to N-S trending Late Jurassic-Early Cretaceous faults suggests the presence of a NW-SE to N-S trending structural domain perpendicular to the northeast-southwest trend of the passive margin that has significantly influenced fault development in the Roebuck Basin. The formation of this transverse structural domain indicate the way in which pre-rift crustal structural fabrics can influence structural development in rift process.

Salt Tectonics in the Petrel Basin, Australia

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Neoproterozoic and Lower Palaeozoic salt occurs in a number of Australian sedimentary basins. Although salt structures are associated with hydrocarbon occurrences in a number of these basins, the Lower Palaeozoic Petrel Basin on the North West Shelf is by far the most prolific. However, despite the large number of salt structures, the number of discoveries in the Petrel Basin is relatively small.

The Petrel Basin is a NW-SE trending graben, orthogonal to and most likely older than the NE-SW trending structures that dominate the North West Shelf. The development of salt structures is closely related to the complex multi-phase evolution of the basin and the adjacent passive margin. Although not penetrated by wells, seismic stratigraphy clearly shows that salt was deposited as part of the syn-rift sequence, most likely of Devonian age. A significant phase of widespread mini-basin formation ensued and was terminated by the end of rifting. Hyper-extension during the Lower Palaeozoic resulted in the development of a thick Carboniferous to Triassic sag sequence during which some of the early formed structures evolved into high-relief point-sourced diapirs by a combination of early salt withdrawal and subsequent passive growth. Extensional fault reactivation in the Middle Jurassic, associated with more widespread rifting further outboard on the continental margin, resulted in accelerated subsidence in the basin centre, with extension on the basin margin being balanced by tightening of compressional salt cored folds and daipirs in the basin centre. A phase of compression, most likely associated with the collision of Australia with SE Asia in the Neogene, resulted in inversion of segments of the basin bounding fault system and a final phase of diapir growth.

Most hydrocarbon occurrences are associated with broad salt cored anticlines that developed during Jurassic extension, rather than high relief diapirs that experienced Cenozoic growth. The complex multi-phase growth of these latter structures most likely resulted in seal breach.

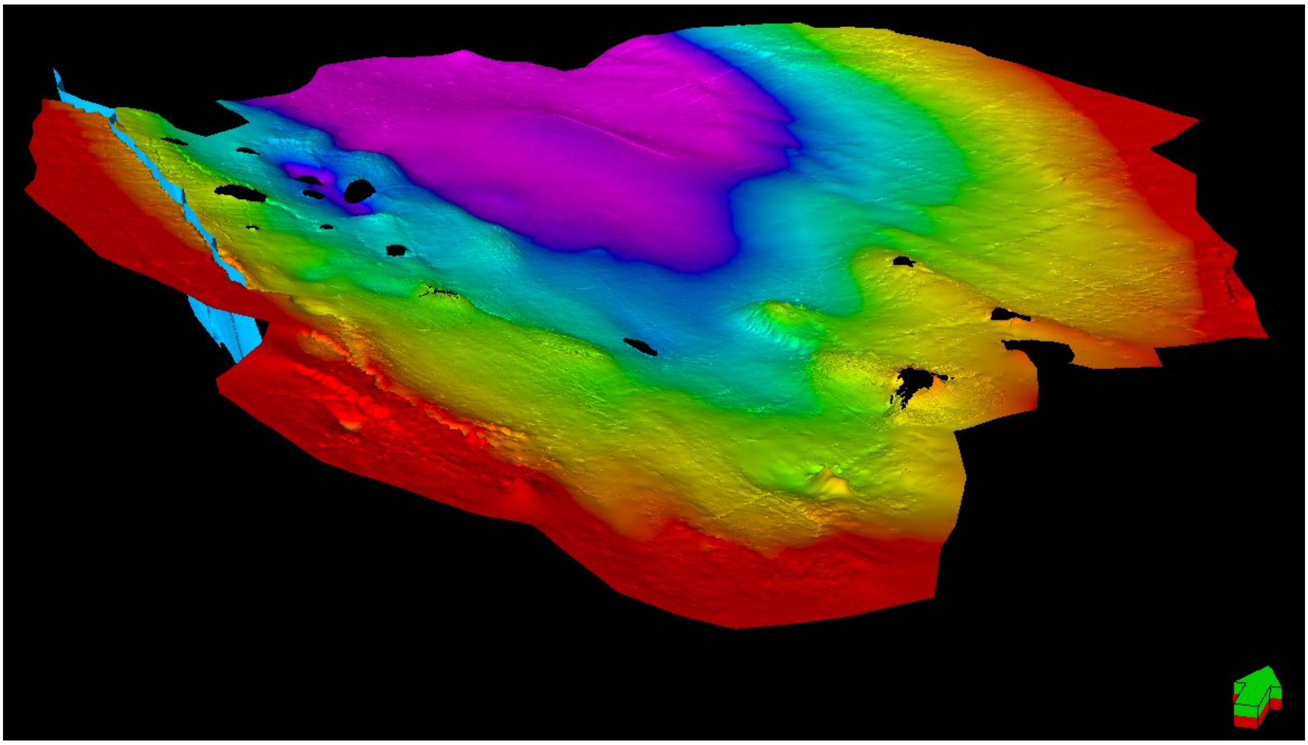

Fig. 1: 3D Image of the Upper Permian in the Petrel Basin showing to location of salt diapirs and salt cored anticlines.

A Possible Structural Control of the Lewis Trough

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The Lewis Trough is a crustal scale synclinal structure situated in the centre of the Dampier Sub-basin. Lower Jurassic growth packages suggest that the Trough developed during Lower Jurassic extension, which was responsible for the formation of the NE trending Dampier sub-basin. With several kilometres of Mesozoic sediments deposited in the Lewis Trough, its evolution impacted sediment distribution patterns across the Northern Carnarvon Basin, including starving sediment supply to the Exmouth Plateau at that time. Poor seismic resolution at Triassic (and older) levels has spawned a number of theories for a mechanism that could produce such a crustal scale feature, notably without a clear, large scale extensional fault adjacent the Trough. The Rankin Fault Zone (RFZ) is parallel to the Lewis Trough but is separated from it by the Madeleine Anticline and Kendrew Trough. It has been suggested as that the Rankin Fault Zone is the structure that controls the formation of the Lewis Trough, however existing models fail to account for the presence of the adjacent shallower Kendrew Trough or Madeleine Anticline.

A series of forward kinematic fault models have been used to identify a possible growth mechanism and fault geometry that could produce the Lewis Trough during regional extension, while honouring adjacent structures. Modelling both east dipping faults (Rankin Fault Zone) and north-west dipping faults (Rosemary Fault System) produces a variety of syn-kinematic sequences depending on the complexity of the underlying fault. The most realistic models suggest that the Rankin Fault Zone is the dominant controlling structure of the Trough, but requires a ramp-flat geometry in order to account for the presence of the Madeleine Anticline and Kendrew Trough.

This study demonstrates that along strike variability in the structural and stratigraphic architecture of the Dampier Sub-basin can be related to the evolution and variations in geometry of the underlying rift border ramp-flat fault systems.

Structural Evolution of a Large Mid-crustal Dome within the Northern Beagle Sub-basin, Offshore Western Australia – Insights from 3D Seismic

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The northern Beagle Sub-basin lies within the Carnarvon Basin, offshore Western Australia. It comprises a thick (~ 5km) Jurassic syn-post rift sedimentary succession. In many respects it has a relatively conventional rift basin architecture, with large normal faults defining thickening growth sequences within an overall NNW trending Jurassic depocentre. There is, however, one large and obvious mid crustal domal structure that impinges upon the overlying basin geometry (Figure 1). This paper explores the origin, timing and tectonic significance of this somewhat enigmatic structure using insights from high quality, deep record, modern 3D seismic data.

Seismic mapping reveals a dome-like structure with a diameter of more than 30km, and with vertical relief of over 5km, elevating the overlying basin sequences above regional levels. The dome has clearly influenced fault architecture in the overlying basin, which is revealed in in exquisite detail in complex map patterns of faulting within the Jurassic intervals. This faulting is also seen to detach within a lower Triassic shale prone section, and is intimately related to an even older Permian sequence, in which large scale carbonate shelf units act as localised mechanical discordances upon which faults appear to nucleate. The spatial distribution of these Permian carbonate shelf sequences also provides some evidence for the relative timing of the overall doming, as do isopach maps within the overlying Triassic and Jurassic section.

Several potential mechanisms have been considered for the emplacement of this feature, including; basement cored compression, reactivated extensional basement faulting, remnant Palaeozoic topographic relief, salt-related diapirism, or plutonic/igneous intrusive activity. Pros and cons for each of these mechanisms are discussed, each of which have important implications for the tectonic and thermal evolution of the Beagle Basin.

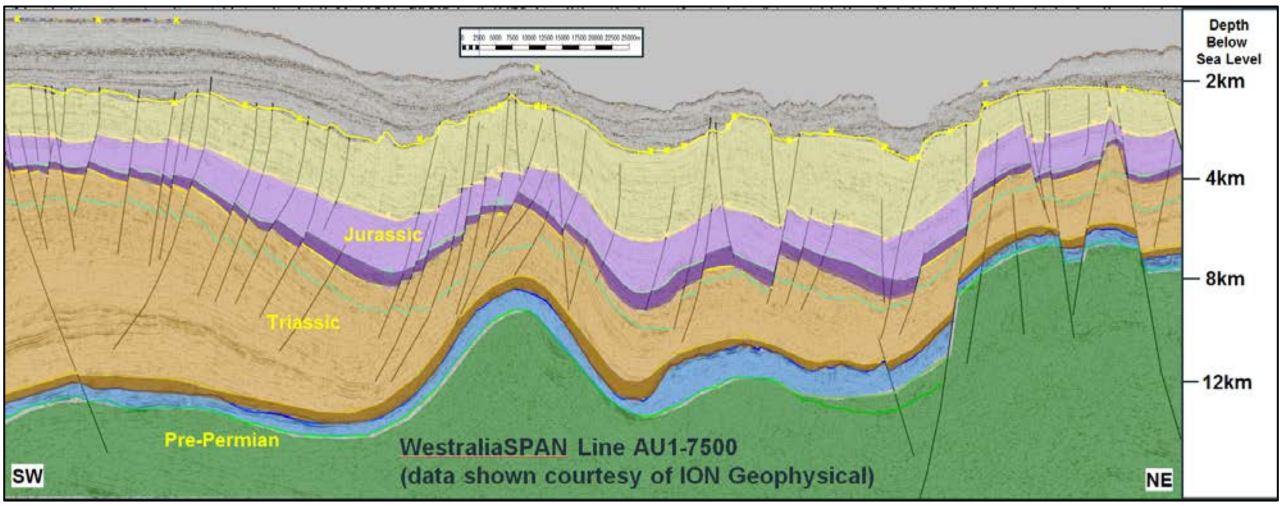

Fig. 1: Regional geoseismic traverse across the Beagle Sub-basin

Re-evaluation of petroleum system in southern Java offshore, Indonesia: new consideration on exploration effort

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The Southern Java Basin is a West-East trending fore arc basin lying on pre-tertiary mélange rock in the Offshore Southern Java, Indonesia. The exploration activities in this basin had been operated since 1970's, however, no petroleum in commercial quantities was found.

Up to the present time, 6 wells had been drilled, more than 3,000 seismic line data and turned out gave disappointing result. Moreover, also only few studies that had been done in this area. C-1 was drilled in 2016 and showed a very good gas reading despite the recent study that concludes there is a poor quality of source rock. From this well also, the lack of maturity and organic content richness of source rock are the main reason why the exploration targets in this area are not interesting in terms of risk and economy. This study will discuss about the possibility of exploration success in this frontier basin.

In term of Petroleum System, Southern Java Basin is divided into Western Java Fore Arc Basin, which was developed as fore arc basin earlier than the eastern part, and Eastern Java Fore Arc Basin. In this study, each component in petroleum system such as source rocks, reservoir rocks, hydrocarbon maturation and migration, trapping mechanisms and seal rocks will be re-evaluated in both areas, particularly on source rock analysis based on the latest biostratigraphy, geochemical and burial history analysis.

This study aims to re-evaluate the petroleum system in Southern Java offshore and provide consideration to oil and gas exploration companies in calculating the petroleum system risk in this area. In summary, based on the data from drilling and seismic acquisitions in Southern Java Basin along with re-evaluation of the wells as mentioned above, the fore arc basin in Southern Java Indonesia are very high risk and frontier area and thus, require big and wild ideas to explore the area.

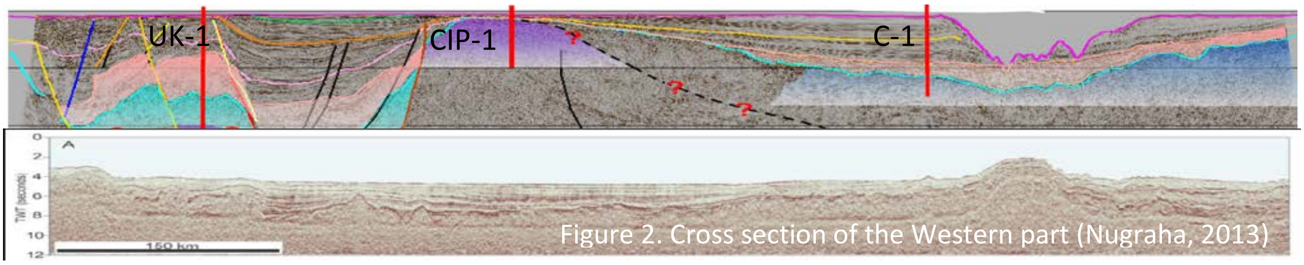

Figure 2. Cross section of the Western part (Nugraha, 2013)

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Structural interpretation from geophysics and its impact on 3D model uncertainty: Yerrida Basin, Capricorn Orogen

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The Distal Footprints of Giant Ore Systems Project is being conducted in the Capricorn Orogen, Western Australia and amalgamates earth science disciplines to provide a toolbox for mineral exploration. There are six themes, each dealing with a unique aspect of mineralising systems: architecture, tectonics and geodynamics; cover; distal footprints; hydrogeochemistry; geochemistry and 3D technologies. This contribution draws from the architecture and 3D technologies themes to determine the structure and 3D architecture of Paleoproterozoic Yerrida Basin and underlying northern Yilgarn Craton. A range of geological and geophysical techniques were used to produce an integrated structural interpretation and forward model that illuminates basin structure. These results were used to construct a 3D model that was tested against geophysical data to support the proposed architecture. These interpretations and models are subject to uncertainties related to errors in input data, prior assumptions necessary for interpretation (though may not be appropriate) and geophysical ambiguity. In order to characterise some of these uncertainties, the geophysical interpretation was evaluated for consistency using the Integrated Exploration Platform (IEP), which compares interpreted structures with anomalies in geophysical and remotely-sensed datasets to produce a quantitive assessment of interpretation confidence. The effects of interpretation confidence on the 3D model, combined with the other uncertainties mentioned before, are explored through Monte Carlo uncertainty estimation facilitated by the CURE (or Common Uncertainty Research Explorer). The magnitude and location of uncertainty is then determined, with the benefit of providing genuine geological contraints for geophysical inversion. The distribution of uncertain regions also provides a guide for collection of additional data and aims to understand the sources of uncertainty in order to reduce their effects. Understanding the nature of uncertainty in these models is important for both scienctific and and mineral exploration exercises. Like any other scientific model, an accurate representation of 3D architecture is incomplete without providing some form of error estimate. An important step towards achieving this aim is provided by this method.

Structural targeting, reconstruction and the role of the 3D seismic cube in exploration within the Plumridge Terrane.

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The Plumridge Terrane comprises variably sheared quartzo-feldspathic and mafic gneisses and granulites. It forms the northernmost 100 km of the Northern Foreland rocks, which extend along the Yilgarn margin (Blenkinsop and Doyle, 2014). It is situated within the Tropicana Zone and is bound to the west by the Gunbarrel fault and basin, and to the east by inverted thrust sequences of the Proterozoic Eastern Biranup Zone. Progressive exploration and interpretation by AngloGold Ashanti Limited geoscientists over the past decade has utilised a geochemical based targeting methodology in which soil/auger sampling and aircore drilling have been followed up with RC and DDH drill testing as confidence in the position of significant anomalies increases. This systematic approach, combined with interpretation of datasets from targeted and broad scale geophysical techniques including magnetics, IP, gravity, AEM and more recently 3D seismic surveys in 2014 and 2015; has effectively defined the +8Moz Tropicana Gold Mine (TGM) and identified numerous small sub-economic discoveries such as Beachcomber, Voodoo Child, Rusty Nail, Madras located predominantly within 30 Km of Tropicana .

An extensive multi-disciplinary dataset has been acquired providing a unique opportunity to advance the structural framework first suggested by Blenkinsop and Doyle (2014) by integrating geological observations from pit mapping and the 3D seismic survey data, which extends along the eastern margin of the Tropicana Gold Mine (TGM) open pits. A revised exploration model has been developed which has been applied at the regional space as an aid to exploration targeting.

At least four stages of deformation are recognised at Tropicana where crucially, late stage, dominantly dextral structures cut the shallowly dipping ore zone and host package. At the deposit scale it is apparent that the interplay of these structures has created blocks of mineralisation that are offset from the main, essentially tabular ore body complicating targeting. A good example of this is the Boston Shaker deposit, which was not discovered until 2009. The mineralised zone is offset ~ 450m dextrally from Tropicana pit along the Boston Shaker shear zone. Had 3D seismic been available it may have assisted in clarifying the Boston Shaker target, and facilitated earlier discovery of the Boston Shaker resource.

Taking these learnings and reconstructing the architecture using multiple datasets at both the belt and deposit scale, has led to a better understanding of the position of the mineralised corridor at the time of gold emplacement by removing the latest stages of deformation. Exploration targeting has advanced and led to the generation of multiple new targets that are the focus of follow-up drilling.

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Deep structures in the Pilbara Craton and their relationship to overlying deformation, mineralization and kimberlite emplacement

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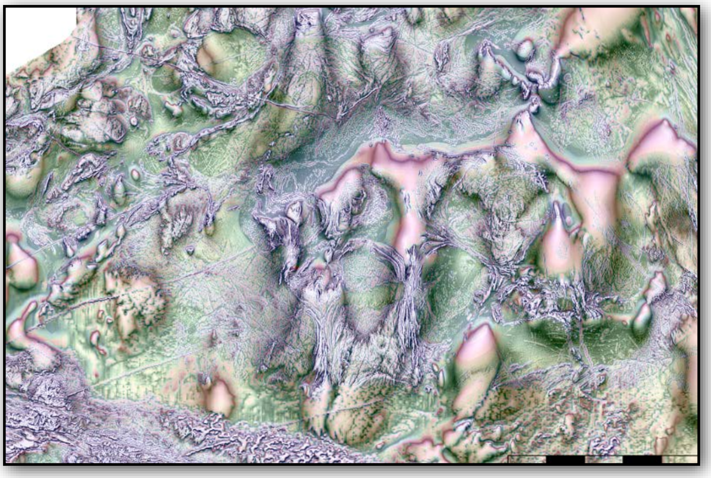
Enhanced pseudogravity images provide an excellent means to distinguish between different tectono-stratigraphic domains or terranes and to highlight deep crustal features. Calculation of pseudogravity involves (i) the vertical integration of reduced to the pole total magnetic intensity data and (ii) the conversion from a dipolar magnetic field to gravity-like polar behaviour using Poisson's relation (the correlation between the magnetic potential and the gravitational potential). In regional structural studies, pseudogravity images provide valuable information, complementary to that provided by standard treatments of aeromagnetic and gravity data, which aids mineral exploration targeting.

Pseudogravity images of Archaean granite-greenstones of the Pilbara Craton, Western Australia support Hf isotope studies (Gardiner et al., 2017) which show that the eastern part of the East Pilbara Terrane (EPT) is a geologically distinct block, separated from the rest of the EPT by the sinistral transpressional Lalla Rookh–Western Shaw structural corridor. Similarly, pseudogravity images of the Yilgarn Craton show marked differences between the Youanmi and Eastern Goldfields terranes that reflects Sm-Nd (εNd) domain boundaries (Mole et al., 2013).

Overlying the edge-enhanced short wavelength aeromagnetic image on pseudogravity portrays the relationships between upper and deep crustal features, allowing one to 'look through' the diapiric granite-gneiss domes of the EPT to see the underlying, basement blocks that in part control their form and deep crustal faults (Fig. 1). In the N Pilbara, conjugate ductile transcurrent shear zones both cross and occur on the margins of basement blocks. Most Au and other mineral occurrences in Pilbara Craton greenstones occur on the margins of the deep N-S elongate blocks that underlie the granite-gneiss domes, commonly at their intersection with NNW to NNE-striking faults. Similarly, iron ore deposits of the Hamersley Basin, which overlies granite-greenstones of the southern Pilbara Craton, occur on the margins of blocks with distinct pseudogravity signatures and/or along deep N-S, NNW-SSE and NNE-SSW faults; this suggests that basement features, highly oblique to regional structural trends in the upper crust, controlled hydrothermal fluid flow associated with hypogene hematite mineralization. Palaeoproterozoic Brockman kimberlite dykes in the Pilbara Craton ca. 50 km NNW of Nullagine occur on a N-S structure that can be traced on pseudogravity images to link with the contact between the Youanmi and Eastern Goldfields terranes in the Yilgarn Craton. Diamondiferous Nabberu kimberlites and ultramafic lamprophyres on the N margin of the Yilgarn Craton also intrude this structure, suggesting Palaeoproterozoic reactivation and northwards propagation of this lithospheric structure from the Yilgarn to cross the Pilbara Craton.



125 km

Fig. 1 Superposition of enhanced short wavelength aeromagnetic and pseudogravity images of the East Pilbara showing the form of basement blocks and faults beneath and on the margins of diapiric granite-gneiss domes wrapped by greenstones. Image ©L. Harris 2017

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'Dyke-like' antimony-gold veins controlled by brittle deformation and dissolution-precipitation reactions: Costerfield, Victoria

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The generation and subsequent transport of fluids in faults and rupture surfaces play a significant role in the formation of antimony-gold deposits at Costerfield. These are a swarm of 'dyke-like' antimony-gold lodes within a brittle transpressional fault system. Individual lodes are dominated by stibnite or stibnite-gold and widths vary from 1 cm to ~200 cm (averaging 30 cm) and lengths can exceed 1 km. Lodes occur as fault-parallel layers or lenses mantled by deformed quartz-rich margins or overgrowths of hydrothermal quartz and carbonate. Inclusions in the stibnite-rich lodes include vuggy, randomly oriented, prismatic crystals, crack-sealed and stretched quartz with sugary mosaics of equant quartz grains, and quartz breccias. Randomly oriented quartz and stibnite textures, common in the centre of the lodes, indicate free growth from a fluid. Throughout the mineralized system, the hydrothermal stibnite has replaced and overgrown the earlier quartz. Deformed lode margins preserve sub-horizontal lineations and evidence of oblique crack-seal re-opening that reflect emplacement associated with late sinistral strike-slip movements in bounding faults. Crystallographic orientation data collected from the marginal quartz, using neutron diffraction and supported by microstructural observations, reveal that lode emplacement also involved dissolution-precipitation creep and pressure solution. Both the marginal quartz and the lodes are overprinted by later microfractures, within which there has been precipitation of stibnite, pyrite, arsenopyrite, sphalerite and minor gold.

The mechanical evolution of the lodes involved short-lived brittle processes in combination with dissolution-precipitation crystallization in active fault zones. These ore bodies provide insights about the dynamics of fluid flow and flow velocities when faults breach over-pressured reservoirs of hydrothermal fluids. During continued displacement, successive batches of fluid and fluidized materials were deposited in the fault system in high permeability channel-ways as 'dyke-like' bodies. The feeding sources and recharge processes were related to processes such as metamorphic devolatilization reactions at depth near the base of the Lower Palaeozoic Melbourne Zone, which lies above the Proterozoic Selwyn Block. From a reinterpretation of seismic reflection data, the deformation in the Melbourne Zone sedimentary wedge is characterised by thrusts isolating relatively undeformed packages of sedimentary units, which were thrust in a piggyback manner up west-dipping faults. In the upper levels of the sedimentary package, out-of-sequence, strike-slip, sub-vertical splays from these second order faults carried the mineralizing fluids to the orebodies. East-west compression during the Tabberabberan Orogeny preceded a northwest-southeast-oriented stress field which reflects the collision of VanDieland against the Gondwanan margin. This produced the sinistral strike-slip faults, which in turn controlled the overall permeability of the hydrothermal system.

Structural controls on the genesis of the Mt Whaleback martite microplaty-hematite deposit, Hamersley Province, Western Australia

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Mount Whaleback, located in the Hamersley Province of Western Australia, is one of the largest hypogene, iron-formation hosted deposits in the world. Understanding the structural controls on ore deposition is key to developing a broader narrative around the genesis of this giant deposit. Iron mineralisation occurs within a fragment of Brockman Iron Formation which is bounded by the Whaleback Fault to the northwest and by dolomitic rocks of the Wittenoom Formation at depth and to the south and east. The orebody has a strikingly sub-horizontal top, appearing to 'fill' the structural and lithological trap formed by the trough-shaped body of iron formation. There are four principal structural events which predate mineralisation at Mt Whaleback: 1) upward propagation of the northeast-trending Whaleback Fault from roots in the Archaean basement, 2) regional-scale, asymmetric Ophthalmian folding, 3) formation of the flat-lying Central Fault and associated splays, and 4) downwarping of the entire stratigraphic package at the western end of the deposit.

The Mount Whaleback deposit is situated immediately to the south of a major jog in the Whaleback Fault. This jog reflects the intersection of 3 structural orientations: NE-trending Whaleback Fault, WNW-trending offset and NNE-trending gravity lineament. These orientations correspond to regional-scale fault systems that transect the Pilbara and have roots in the Archaean craton. The jog in the Whaleback Fault is thus likely to represent a major basement-tapping structural conduit.

Two regional-scale synclines mark the northern and southern margins of the orebody. The hinge lines deviate from the typical west-northwesterly Ophthalmian trend to wrap into the Whaleback Fault zone with an east-west orientation. The Whaleback Fault must have propagated up through the Proterozoic stratigraphy by the start of the Ophthalmian Orogeny.

The Central Fault cuts the Ophthalmian folds at an oblique angle but is also gently warped where it intersects the flat-lying fold limb. Together with associated splays it has a combined throw of ~1000m top-block-east and propably formed in response to strain build-up around the Whaleback fault-jog as a result of north-directed compression during the latter stages of the Ophthalmian Orogeny. The widespread presence of micro-platy hematite associated with this fault group indicates that these faults were instrumental in providing a local plumbing system for the ore fluids.

The Central Fault has itself undergone up to 400m of down-warping at the western end of the deposit, adjacent to the jog in the Whaleback Fault, some of which has been taken up on the Conjugate Fault set. The depression is triangular in nature, with sides oriented NE, WNW and NNE, parallel to the structures which intersect in the vicinity of the Whaleback fault-jog. The cause of this downwarping is unclear but one possibility is that it reflects hydrothermal karstic dissolution of the Wittenoom Formation in the underlying structural conduit and subsequent collapse. This down-warping episode not only produced a bowl-like depression in the Brockman Iron Formation but may have provided the transient dilational conditions necessary to allow the ore fluid to ascend through the conduit and permeate the Brockman Iron Formation.

The influence of Neoarchean rift architecture on the location and style of manganese deposits in the Oakover Basin, East Pilbara

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Manganese mineralisation in the Oakover Basin, East Pilbara, is associated with Mesoproterozoic extension, basin formation and deposition of the Manganese Group. The underlying basement architecture of the Oakover Basin (a local half-graben geometry), inherited from a Neoarchean rifting event, plays an important role on the distribution, style and timing of manganese deposits. Fault-hosted manganese deposits are dominant along the 'active' faulted eastern margin, whereas flat-lying sedimentary deposits are dominant along the western 'passive' margin and reflect fundamental differences in the ore-forming processes and structural setting.

Hydrothermal manganese deposits are typically located on steep 2nd and 3rd order structures that extend off major growth faults that define the basins. Mineralized structures display a dominant northeast trend reflecting the direction of maximum dilation during northwest-southeast directed extension. Sedimentary manganese deposits are not uniformly distributed along the western edge of the basin; instead they are concentrated into discrete areas (e.g. Mt Cooke–Utah–Mt Rove, Bee Hill, Skull Springs and the Ripon Hills districts), suggesting a degree of structural control on their distribution.

The large number of significant manganese deposits in the Oakover Basin, previously thought to reflect a spatial association with Carawine Dolomite, more likely reflects the restricted nature of the Mesoproterozoic basin and development of a large reservoir of Mn^{2+} and Fe^{2+} in an anoxic zone of a stratified basin. Low O_2 conditions in the basin developed due to the presence of a paleotopographic high in the southern part of the basin that formed a barrier to open ocean circulation. The western margin sedimentary deposits formed later than the fault-hosted hydrothermal deposits along the eastern margin, once a significant reservoir of Mn^{2+} and Fe^{2+} had developed in the basin, and when there was sufficient subsidence to allow migration of the redox front onto the shallow shelf, with manganese precipitation on and within the seafloor sediments.

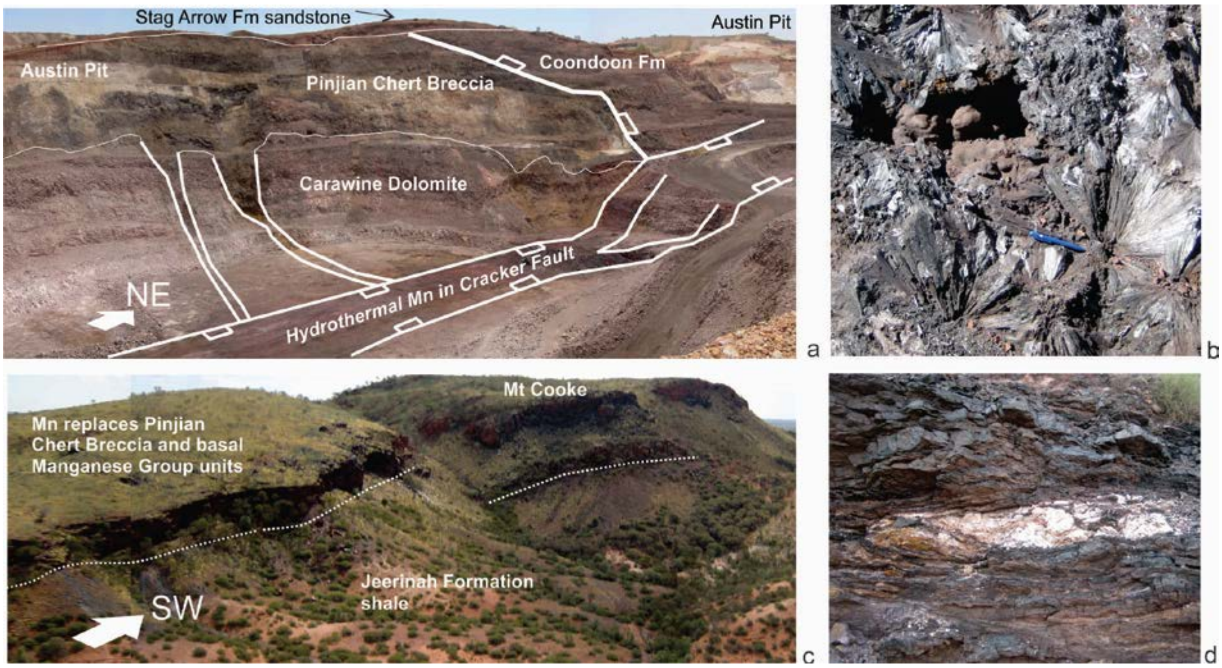

Fig. 1: a) Hydrothermal fault-hosted Mn deposits in Austin Pit, Woodie Woodie; b) Large radiating pyrolusite crystals in fault zone, Austin Pit; c) Stratabound Mn at Mt Cooke, southwest Oakover Basin; d) Sedimentary Mn at C Deposit, Ripon Hills, Northwest Oakover Basin.

The tectonic implications of the carbonaceous metapelite-schist boundary at Mount Elliott in the IOCG corridor of the Mt Isa Inlier

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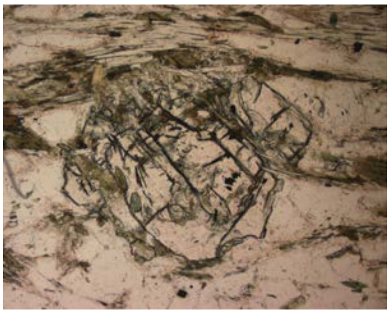
The Mt Elliott area is the location of one of the richest mineralisation zones of the Staveley-Kuridala Iron Oxide Copper Gold (IOCG) corridor in the Eastern Fold Belt of the Mount Isa Inlier, with an estimated copper resource exceeding 0.3Gt. Local IOCG mineralisation is characterised by a variety of different styles and contrasting overprinting of affected lithological units. The aim of the current study is to develop an understanding of the tectonic architecture of the IOCG corridor, which comprises adjacent meridional belts of the contrasting tectonic styles. This study examines the nature of the contact between the western belt of carbonaceous metapelites and underlying eastern belt of strongly deformed metamorposed arenites and pelites. The contrast is significant as, the carbonaceous metapelites (CMPs) appear to be relatively low-grade, and not subjected to protracted periods of high temperature. In contrast, the underlying more highly metamorphosed schists are phyllonitic, albeit subsequently heated to the point that grain boundary migration and recrystallisation of white mica led to the development of decussate textures, and the development of statically overgrown metamorphic minerals including typical medium-pressure Barrovian assemblages such as garnet and staurolite. It is tempting to draw an analogue with the occurrence of Barrovian assemblages in the Cenozoic Alpine-Himalayan orogens, where such a scenario would attest to an accretion episode, or crustal thickening during collision of continental blocks, followed by rapid exhumation on the footwall of regionally-developed extensional ductile shear zones.



Detailed structural mapping and petrological analysis, including Electron Microscopy (SEM and QEMSCAN), allowed recognition of preserved relicts of staurolite, garnet and sillimanite (see adjacent) in the eastern metamorphics. Preliminary pressure estimates suggest ~0.5–0.7 GPa, *i.e.*, in the range of Barrovian-type metamorphism. In parts, intensive hydrothermal alteration has partially or completely destroyed the original prograde mineral association, however. Of note, the adjacent CMPs are locally heated to the point that static growth of scapolite takes place, but otherwise high-grade metamorphic assemblages have not been observed. The footwall metamorphic rocks have been strongly deformed, presumably in a regionally developed shear zone, with the development of phyllonitic shear bands outlasting metamorphism. Finally, the metamorphic rocks have been subject to metasomatism, related to one or more of the phases of IOCG mineralisation.

The tectonic evolution of the region is further complicated by later regional shortening episodes, and ongoing research will seek to put this work in a broader structural context: including considering the tight folding that has resulted in almost all structures and stratigraphy being steeply dipping across the area. Later thrusting has further dissected the earlier fold/thrust architecture, whose remnants are now fragmentary within the IOCG corridor. Nevertheless, microstructural studies of the metapelites in conjunction with field observations, allowed Tectonic Sequence Diagrams (TSDs) to be produced, and microstructurally-focussed targetted $^{40}Ar/^{39}Ar$ geochronology that potentially dates decussate recrystallisation followed by rapid cooling in the schist package at ~1490 Ma.

Structural Geology and Epithermal Gold Mineralization in Hishikari (Southern Kyushu, Japan): A Paleostress Analysis Approach using GArcmB

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The world-class Hishikari gold deposit has 60% of its reserves hosted by the Cretaceous Shimanto Supergroup, previously thought to be barren. Also, mineralized veins have a coherent trend in the host Hokusatsu gold district of Southern Kyushu. These two facts strongly suggest a structural control of the mineralization in Hishikari. Another element supporting a probable structural control of Hishikari mineralization is the presence of ENE-WSW to NW-SE-trending normal faults with horizontal displacement components in the deposit (Abe et al., 1986).

Horizontal strain rate calculation suggests that regional extensional movements in Southern Kyushu are responsible for the Hishikari mineralization (Uto et al., 2001). Moreover, structural differences (strike, dip, and width) between early and late veins (Sekine et al., 2002) might suggest a temporal variation of the stress conditions in Hishikari deposit during mineralization. Also, the orientations of the veins show spatial variations between Honko-Sanjin (N50°E - 70°NW to 90) sub-deposits and Yamada sub-deposit (N50°E - 70°NW to 90 and N30°E - 80°NW to 90). Thus, spatio-temporal variations of the paleostress conditions under which Hishikari deposit formed should be expected.

However, the scarcity of tectonic structures as well as the generally coherent trend of veins makes it difficult to separate the potential different paleostress states and determine their characteristics. To overcome this difficulty, a stress inversion method can be utilized. Yamaji et al. (2010) demonstrated this technique to determine paleostress conditions of Plio-Pleistocene epithermal gold and silver-mineralized veins of Hashima located in the same gold district in Southern Kyushu as the Hishikari deposit. In this research, the software GArcmB (Yamaji, 2016) has been used for the determination of the principal stress axes orientations, the stress ratios and the driving pressures of the stress states during mineralization in Hishikari.

Two stress states have been identified. Paleostress state A, subject to time-dependent and space-dependent rotations of its intermediate and maximum stress axes, is the oldest. It is related to regional tectonics and controls the main mineralization phase. Its time-dependent variations might be due to fault slip events whereas space-dependent variations could result from topographic loading of volcanic rocks deposited on the surface during mineralization. The youngest paleostress state B may result from local lithostatic loading due to the deposition of mudstones in a thermal lake above the Yamada sub-deposit. Mineralization has occurred under high fluid pressure and high differential stress conditions, even though these two parameters have probably decreased between early and late mineralization stages.

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Controls on the distribution and styles of orogenic Au mineralisation, New Holland Genesis deposit, Agnew goldfield, Western Australia

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The New Holland Genesis (NHG) deposit is a late Archaean, orogenic lode gold system hosted within a greenschist facies metasedimentary sequence in the Agnew-Lawlers region of the Eastern Goldfields Province of the Yilgarn craton. Mineralisation at NHG is localised largely within a 50 - 90m thick, steeply-dipping and competent metasandstone sequence (New Holland Sandstone) that is located within a thicker, less competent, pelite-dominated sequence. The lode systems at NHG illustrate fault behaviour in high fluid flux regimes and highlight the role of competent mechanical stratigraphy in perturbing local stress states, localising failure and controlling fluid pathways in overpressured hydrothermal systems.

Two generations of fault-related gold lodes are present at NHG. Stage 1 lodes occur within WSW-dipping reverse faults and related extension veins. Stage 2 lodes overprint Stage 1 structures and are predominantly ENE-dipping, mixed brittle-viscous, reverse shear zones dominated by sigmoidal extension vein arrays. Early development of en echelon vein arrays in Stage 2 lodes was overprinted by viscous creep. Brittle reactivation and formation of fault-fill veins has occurred in the cores of some Stage 2 lodes. Stage 1 and Stage 2 lodes formed in the same stress field.

In the southern and upper parts of the NHG deposit, both Stage 1 faults and Stage 2 shear zones are restricted to the New Holland Sandstone. Stage 1 fault-fill lodes are blade-like structures with strike lengths of 100 - 800m, and down-dip continuity less than 70m. Vertical spacings are between 50m and 90m and maximum net slips are up to several 10s of metres. In contrast, Stage 2 shear zones in the same area have strike lengths of 50 - 400m, down-dip extents of 10 - 50m, and maximum net slips up to several metres. The vertical spacing between Stage 2 lodes is commonly less than 10m. Although Stage 1 fault lodes are well-developed in the deeper, central to northern parts of the lode system, Stage 2 lodes are absent. The largest Stage 1 lode in this area has a strike extent of 1800m and has propagated 10s of metres outside the New Holland Sandstone. Wing vein arrays are well-developed around parts of the tip line of this structure. Extension veins and dilational breccias are especially abundant within dilatant jogs.

Differences in structural styles between Stage 1 and Stage 2 lodes are related to stress relaxation during injection-driven Stage 1 faulting at near-lithostatic fluid pressures. This resulted in ambient differential stresses dropping below levels required to sustain brittle shear failure. Progressive hydrothermal alteration around Stage 2 vein arrays was associated with reaction weakening, suppression of vein formation and localised viscous shear strain along the vein arrays. The change in slip vergence between Stage 1 and Stage 2 may relate to changing torque on the competent New Holland Sandstone during progressive shear and vertical stretching. The marked difference in vertical spacing of Stage 1 and Stage 2 lodes correlates with differences in lode dimensions and net slip, and is interpreted to reflect stress shadow effects associated with stress transfer during slip events.

The Nature of Eye-Shaped Features in the Fraser Zone, Albany Fraser Orogen, Western Australia

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Since the discovery of the Nova-Bollinger magmatic Ni-Cu deposit in the Fraser Zone of the Albany Fraser Orogen in 2012, the Albany-Fraser Orogen has been the focus of intense exploration and research by government, academia and industry workers. The Fraser Zone is an elongated basin of 1.4-1.3Ga metasedimentary and volcanic rocks, including marbles, iron formation, conglomerate and graphitic pelitic gneiss correlated with the Snowies Dam Formation. These rocks were tectonothermally metamorphosed to high P-T granulite facies at 1.3Ga. Elliptical shaped features are developed periodically along the length of the basin with interpretations ranging from domes, basins, and mega-boudins. Work at Octagonal and Nova will show these two features are doubly plunging synforms cored by mafic-ultramafic intrusive complexes.

The Nova deposit (14.3Mt @ 2.3%Ni, 0.9%Cu) is hosted within an elliptical structural feature termed the 'Nova Eye', coinciding with a doubly plunging synformal fold inclined to the SE. The Nova intrusive complex forms the core of the basin with ore-bearing mafic-ultramafic intrusions emplaced within a marble-iron formation-conglomerate bearing sequence at the base of the complex. The northern margin of the Nova Eye is a major structural contact between mafic granulite and charnockitic granites in the North and deformed metasediments of the Snowies Dam Formation and Nova intrusive rocks to the South. The southern margin of the Nova Eye is poorly understood due to a lack of drilling.

The Octagonal Eye is another elliptical shaped feature evident in magnetic imagery 150km NNE of Nova. Drilling has shown an identical package of metasediments correspond with the magnetic expression of the Eye. The Octagonal intrusive complex also consists of gabbronorite and norite, with lesser pyroxenite, troctolite and peridotite. The intrusive complex is emplaced into a conglomerate-marble-iron formation horizon, identical to Nova. Magmatic Ni-Cu sulphides are associated with small olivine pyroxenite dykes intruded at and near the contact. The Octagonal Eye, is a doubly plunging synformal F_2 fold which is overturned towards the NW. Sulphide mineralisation is hosted on the SE limb where the geology is upside down. The gneissic foliation (S_1), is folded by gentle NE-plunging, asymmetric F_2 folds which are parasitic to the overturned limb of the larger F_2 synform. An axial planar foliation S_2 is developed in the F_2 folds. Horizontal granite dykes cut the short-limb of these F_2 folds.

The folded granulitic rocks are overprinted by retrograde mylonitic shear zones and brittle-ductile faults assumed to correlate with Stage II of the Albany-Fraser Orogen. NNE-SSW striking mylonitic shear zones with thrust kinematics are hosted within granite dykes cutting the intrusive complex. Brittle-ductile faults strike NW-SE with sinistral offsets of pegmatoid veins and are characterised by intense epidote-chlorite-carbonate alteration. Clearly retrograde deformation events are developed, despite their absence in regional geochronological data in the Fraser Zone.

The Nova and Octagonal Eye features are both doubly plunging synformal structural basins cored by mafic-ultramafic intrusive complexes, they do not appear to be megaboudins. The presence of marble and conglomerate marker horizons seems important for focussing of the intrusive complexes. Understanding fold interference patterns and stratigraphic position within the Albany-Fraser Orogen will assist explorers to the next discovery.

Geodynamic controls on gold mineralization in the southeastern Paleoproterozoic (2.26-2.05 Ga) Birimian Orogen, Ghana

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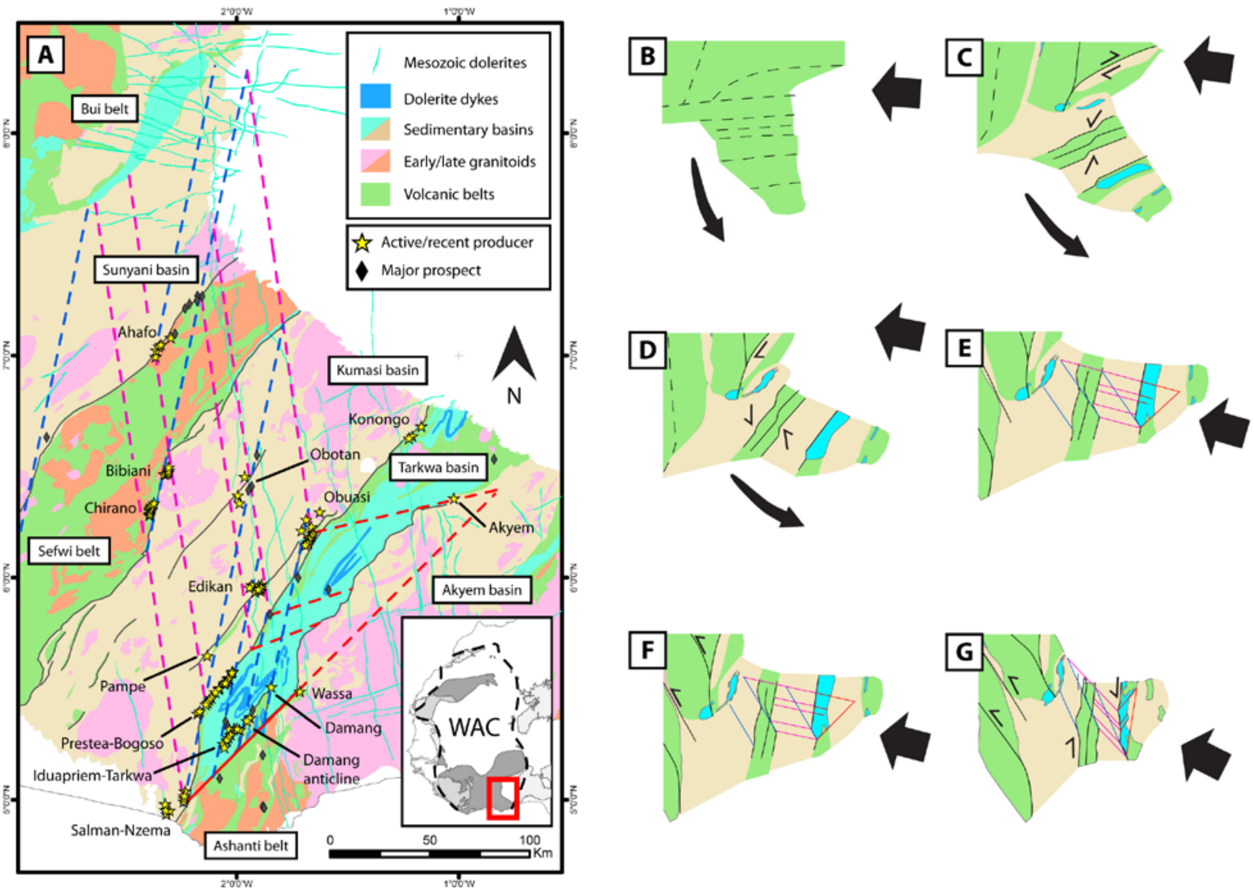
The southeastern Birimian Orogen of the West African Craton is host to a number of significant gold deposits, including the giant Obuasi (Fig. 1a). Although several studies have been conducted on individual deposits, the regional-scale controls on their distribution is less well understood. The deposits typically occur along shear zones marking the contacts between alternating greenschist-amphibolite facies volcanic belts and greenschist-facies volcano-sedimentary basins. However, they are not evenly distributed, instead occurring separately or in discrete clusters at the intersection of lithological boundaries and structures, seemingly controlled by cryptic trends and lineaments that diverge from the regional NE-SW structural grain (e.g. Allibone et al., 2004; Chudasama et al., 2016). It is argued here that the distribution of major deposits form a framework defined by three sets of trends, oriented NNE-SSW, NNW-SSE and NE-SW to ENE-WSW (fig. 1b-c). These trends also outline major structures, including faults, belt-basin boundaries and batholith margins. A model is presented in which the trends reflect structures established during a regional transtensional event between ca. 2160-2130 Ma, which led to the opening of the basins and uplift of the volcanic belts as horsts (fig. 1b-c). NNE-SSW trends are interpreted to represent sinistral shear zones developed during regional transtension whereas NNW-SSE and NE-SW to ENE-WSW trends could represent transfer or boundary faults related to the opening of the basins. These structures were subsequently reactivated and overprinted during NW-SE compression and late sinistral and dextral shearing between ca. 2120-2070 Ma, at which point the final architecture of the framework was established (fig. 1e-f).



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Investigating the geologic processes which control the formation of unconformity-related uranium deposits using numerical simulations on a supercomputer

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Uranium deposits of the Athabasca Basin, Canada and Alligator Rivers region, Australia are located in close proximity to sub-horizontal unconformities between multiply metamorphosed and deformed Early-Proterozoic and Archaean rocks (commonly referred to as the basement) and overlying relatively undeformed Mid-Late Proterozoic sedimentary rocks (predominantly sandstones). The majority of the deposits are associated with faults within the basement; however, within the two mineral fields the location of uranium mineralization with respect to the unconformity is quite variable. Deposits in the Athabasca Basin occur at and above the unconformity within the sandstone (e.g. Cigar Lake), at and below the unconformity (e.g. McArthur River) and below the unconformity (e.g. Rabbit Lake). Conversely, all deposits in the Alligator Rivers region discovered to date occur (sometimes deep) below the unconformity (e.g. Ranger 1). Conceptual models for the formation of these deposits generally require oxidised fluid from the sandstone to move down into the basement (for mineralisation below the unconformity), or reduced fluid from the basement to move up into the sandstone (for mineralisation above the unconformity). Such fluid movement may be driven by topography, deformation or thermal buoyancy. This study focuses on deformation-driven flow, using numerical simulations to explore controls on fluid flow patterns in a model representing a weak, permeable fault in strong, low-permeability basement rocks, overlain by more permeable sandstone. The model is subjected to horizontal shortening resulting in elastic-plastic deformation, which drives fluid flow. We explore the effect on fluid flow directions by varying fault dip, shortening direction, strain rate, basement rock strength, and permeability. Over 300 finite element simulations were performed using MOOSE, a parallelised implicit simulation environment for solving multiphysics problems. The results indicate that shallow fault dip, high strain rate and shortening perpendicular to the fault favour downward flow from the sandstone into the basement, whereas steep fault dip, low strain rate and shortening at a low angle to the fault favour upward flow from the basement into the sandstone. These results may be used in conjunction with field observations to predict likely locations of unconformity-related uranium mineralisation in particular field settings.

Poster Session 2

Evolution of structures in extensional tectonic setting in southern Sindh Monocline, Indus Basin, Pakistan

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There are number of structures and structural styles found in extensional tectonic settings of the world but the evolution of these structures is still needful and a big challenge as well. Evolution of structures in extensional settings have been studied by Yuan et al., (2016) and many other reserachers on different extensional basins of the world. Sindh Monocline lies on the western corner of Indian Plate and the tectonic history of Indian plate has been well described by Chatterjee et al., (2013) while tectonic history of Sindh Monocline has been studied by Zaigham, and Mallick, (2000). The aim of this study is the evolution of structures in the subsurface of Southern Sindh Monocline, Pakistan using the seismic data interpretation and faltenning of horizons approach. Jamaluddin et al., (2015) and others have also testified such approach. Southern Sindh Monocline is charaterized and experienced by different tectonic episodes of Indian plate while rifting from Gondwanaland, rifting from other plates at different geological times and to its collision with the Asia. Basic structures with in study area are classified into nine types while the structural styles have been classified into six types as horst and grabens, dominos, crotch, synthetic and antithetic, negative and flashlight structural style. The structures with in the study area revealed evidence for three major structural episodes which can be characterized as Episode 1: Structures associated with rifting of Indian plate from Gondwanaland during Late Jurassic to Early Cretaceous, Episode 2: Modification and reactivation of previous structures while Madagascar rifted from Indian Plate during the Middle Cretaceous and during Episode 3: Inversion and reactivation of structures occurred when Indian Plate collided with Asia during Early Eocene (Fig. 1).

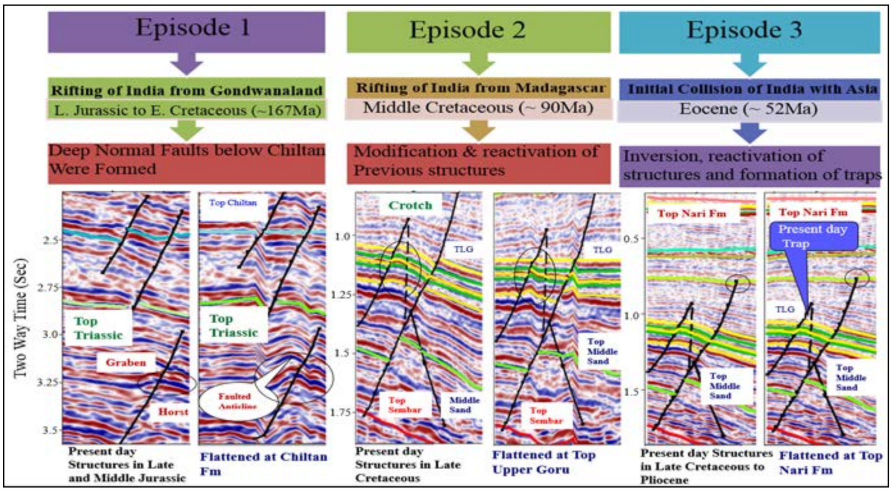

Fig. 1: Evolution of Structures in Extensional Tectonic Setting in Southern Sindh Monocline, Indus Basin, Pakistan

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Emplacement mechanisms for small mafic-ultramafic intrusions hosting Ni-Cu sulfide ores: evidence from the Savannah (Sally Malay) deposit.

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Magmatic Ni-Cu sulfide ores are commonly hosted by small mafic-ultramafic intrusions that have a range of characteristic morphologies, ranging from flared dykes through funnel-shaped bodies to tubular or ski-shaped bodies termed chonoliths (Barnes et al., 2016). The Savannah (formerly known as Sally Malay) deposit in the Halls Creek Orogenic Belt in the East Kimberley region is an example of a particular geometry where sulfide-matrix breccia ores are developed along the lower edge of a blade-shaped dyke. This deposit has evidently been rotated through about 90 degrees by post-emplacement deformation, but lies within a few hundred metres of a second ore-bearing intrusion, Savannah North, that has a probable funnel-type geometry and has undergone little or no post emplacement rotation. High-resolution TIMS dating indicates that the Savannah North intrusion is 2 million years younger than the Savannah Intrusion. There is no obvious fault or shear zone developed between the two intrusions within the well exposed metasedimentary country rocks, implying that the rotation of Savannah took place within the 2 ma time window between the emplacement of the two intrusions.

Both intrusions, along with a number of other small mafic-ultramafic bodies of similar affinity and age, were emplaced during a period of active deformation at the earliest stages of the continent-arc collision that created the Halls Creek orogeny. This conforms with observations made elsewhere, including in the Norilsk region of the Siberian LIP , that intrusion of ore-bearing intrusions takes place at times where significant reorientations take place in regional stress fields. Geochemical characteristics of the Savannah area intrusions suggest an island arc tholeiite parentage, possibly reflecting asthenospheric upwelling into a back arc setting during slab detachment.

The dyke-like geometry of the Savannah intrusion is an end-member in a spectrum of morphologies from bladed dykes through to tubular chonoliths. We suggest that this progression is a consequence of predominantly lateral emplacement of mafic dykes and sills, with the final geometry being controlled by local structural intersections and the presence of erodable country rock units. The presence of sulfide-matrix ore breccias at the basal edge of the dyke, and the injection of sulfide along extensive fractures into the footwall, can be interpreted as gravity-driven accumulation of sulfide into the damage zone that originally forms ahead of the propagating dyke front.

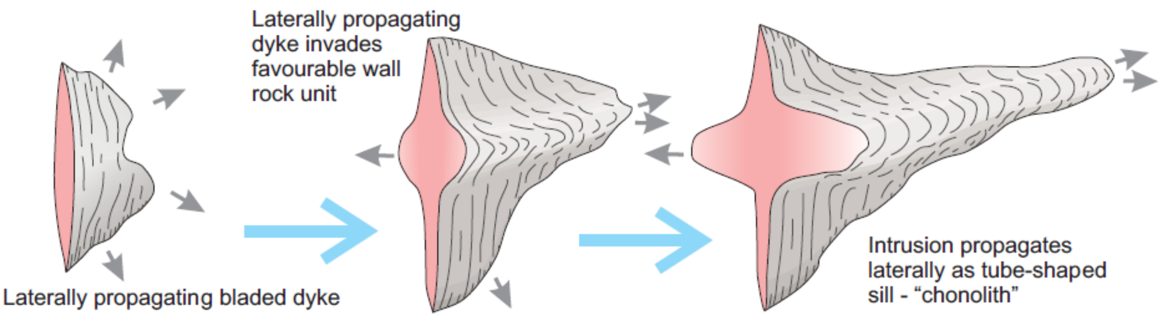

Fig. 1: Transitional dyke-chonolith intrusions start out as laterally propagating dikes, which broaden into chonoliths where they encounter easily melted and eroded wall rocks. The Savannah ore deposit is an example of sulfide accumulation at the propagating lower edge of a bladed dyke.

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Integrated geophysical and structural mapping techniques in lithologically homogenous terranes

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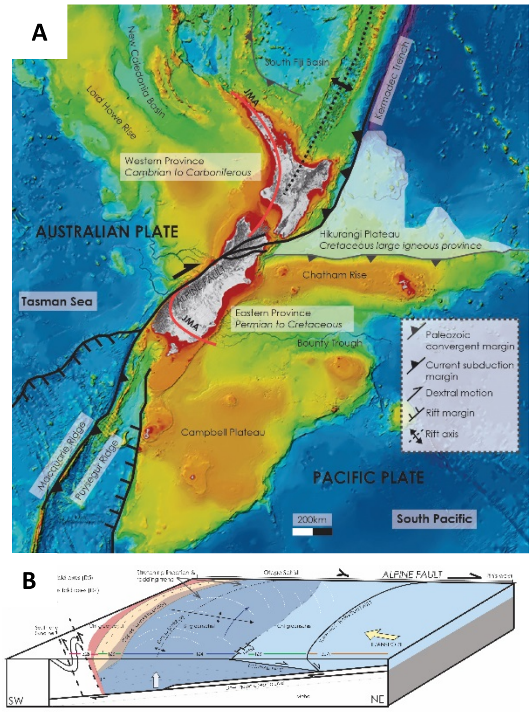
Acquisition of geophysical data across Otago, New Zealand, presents a unique opportunity to explore in detail the subsurface geometries of this poly-deformed Mesozoic accretionary belt. Interpreting geology from geospatial data requires critical assessment and integration with detailed structural field mapping and other geochemical and petrophysical analyses. This method aims to identify and map lithological distributions, patterns and anisotropies resulting from tectonic juxtaposition and the development of structural fabrics at regional scales using traditional principles of structural geology. The Otago Schist preserves a complex history of deformation and metamorphism since the Paleozoic. This study explores a detailed interpretation of geometries within the Otago Schist using structural mapping and regional geophysical data.



A: Regional map showing emergent crust (grey) and location of study area (black box
B: Schematic 2.5D section through study area

Comprised of the Torlesse and Caples Terranes, the field area displays little of the lithologic diversity found in other locations in New Zealand. Minor mafic horizons (basalt-chert-limestone, <5% volumetrically) provide the only lithologically distinct unit within a succession of lightly metamorphosed, indurated mudstone-sandstone units that comprise the approximately 150 km-wide schist belt. Subdivision of the schist into continuous and ‘mappable’ units is based on metamorphic facies and textural observations. This is based on early work focussing on high-grade metamorphic mineral distributions, with division of sub-greenschist facies rocks achieved using textural observations such as degree of schist foliation and segregation. Recent work has defined boundaries of low-grade prehnite-pumpellyite and chlorite zones that flank the higher-grade garnet-biotite-albite zone core of the schist. With scattered occurrence of high grade metamorphic minerals, mapping that relies on changes in mineralogy, lithological distribution and facies is complemented with detailed structural studies. The extent of the schist belt encourages that structural mapping of localities be completed alongside interpretation of regional geophysical data.

This study uses detailed structural mapping at key localities throughout the Otago Schist, and assessment of geospatial data to inform our understanding of geometries at a regional scale. Magnetic data reveals anomalous features in the schist that are not coincident with any obvious surface feature, and are likely reflective of deeper structures. Electromagnetic (EM) data highlights several near-surface anomalies and discontinuities not previously mapped in Otago using existing methods. This study demonstrates that integrated geophysical and traditional structural geological techniques will prove to be an effective tool for mapping in poly-deformed, apparently lithologically monotonous terranes such as Otago.

Fold-interference patterns in the Bowen Basin, northeastern Australia

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Deformation patterns of Paleozoic and Mesozoic strata in eastern Australia are evidence of a structural and tectonic history that included multiple periods of deformation with variable strain intensities and orientations. Detailed analysis of structural data from the Bowen Basin in northeastern Australia reveals previously undescribed, north–south elongate, Type-1 fold-interference patterns. The Bowen Basin structures have similar orientations to previously described interference patterns of equivalent scale in upper Paleozoic strata of the New England Orogen and Sydney Basin of eastern Australia. The east Australian folds with north–south-trending axes most likely formed during late stages of the Permian–Triassic Hunter–Bowen Orogeny, and they were subsequently refolded around east–west axes during post 30 Ma collision of the Indo-Australian plate with the Eurasian and Pacific plates. The younger, east–west-trending folds have orientations that are well aligned with the present-day horizontal stress field of much of eastern Australia, raising the possibility that they are active structures.

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Generation of Folds Through Karsting in the Hamersley Basin, WA

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Unusual fold and fault geometries have been observed in the Hamersley Basin that seem to defy basic fundamentals of structural geology or do not fit within the region's structural framework. One explanation for how these structures formed is karsting. Dissolution of carbonates in the Wittenoom Formation appears to have played a significant role in shaping the geology of the Hamersley Basin, including the generation of post-tectonic structures and modification of Proterozoic bedrock structures.

Folded thrust fault planes observed around BHP's Mining Area C operations display peculiar undulating geometries. Thrust faulting is interpreted to have developed during the Ophthalmian Orogeny, typically in areas of the tightest, overturned, asymmetric folding. Faulting often resulted in Marra Mamba Iron Formation being thrust over carbonates of the Wittenoom Formation, resulting in massive crystalline dolomite in the footwall and BIF-chert-shale in the hangingwall. Where carbonates are preserved in the footwall the fault planes exhibit a typical geometry predicted for thrust faults. However, where significant volumes of carbonate have been removed through dissolution, the fault planes have undergone modification to accommodate volume loss in the footwall, leading to a range of unusual folded fault geometries. Dissolution is believed to be due to the through flow of supergene fluids, although Perring, 2016 has shown down warping of faults and folds at the Mt Whaleback mine also likely occurred as a result of hypogene fluid flow dissolving the underlying carbonates.

At BHP's Marillana deposit several narrow, elongate synclines strike approximately perpendicular to the main tectonic fold trend. Mapping and drilling beneath the base of weathering have identified carbonate turbidites sourced from a carbonate reef within the Fortescue Valley. The proximal nature of their deposition at Marillana has resulted in the turbidites exhibiting lobate geometries that extend over several kilometres. In some areas of the deposit supergene weathering has dissolved the carbonate turbidites causing the overlying rocks to slump into the resultant cavity, forming sporadic elongate synclines. Additional dissolution of carbonates is interpreted to have occurred in the underlying Wittenoom Formation and hypogene-siderite altered rocks associated with NNE-trending structures. Fold interference between the karst-generated synclines and tectonic folds has resulted in a complex dome-and-basin geometry that presents a challenge during geological modelling.

Phanerozoic sediments have formed during several distinct periods within the Hamersley Basin. The Red Ochre Detritals (ROD), or Cenozoic Detritals 1 (CzD1), were originally deposited as alluvial clays, silts, sands and conglomerates along strike-parallel river valleys. However, bedding within these sediments regularly exhibits steep dips (beyond the angle of repose) and folding that mimics the contours of the underlying bedrock. Gradual dissolution of the carbonates underlying the ROD sediments is interpreted to have formed folds through karsting rather than tectonic processes.

Identification of karst-generated folds in the Hamersley Basin has furthered our understanding of the region's geological history and has been critical in resolving structural complexity at the deposit scale. Accurate definition of these structures has implications for exploration and mine geology, geological modelling and resource estimation, and especially hydrological and geotechnical design.

Low angle normal Faults – important fluid conduits for the formation of high grade hematite deposits in the south-eastern Hamersley Basin, WA

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Low angle normal faults form a unique subset of the faulting in the southern Ophthalmian Orogeny. The dip of these faults typically ranges from 0-30° and in extreme cases can display reversal of dip azimuth. In addition to their abnormal geometry they are regularly associated with high grade hematite mineralisation, making them some of the most enigmatic structures of the region.

At BHP's Mt Whaleback mine two low angle normal faults, the Central Fault and East Footwall Fault, juxtapose Brockman Iron Formation in the hangingwall over Wittenoom Formation in the footwall with a combined displacement of ~1000m. These are interpreted to have formed as lateral escape structures adjacent to a major fault jog during transpressive movement along the NE-trending Whaleback Fault. Both faults appear to have formed major fluid conduits for hypogene fluids responsible for upgrading the banded iron formation to high grade hematite.

Further north, within the Mt Newman Anticline, Orebody 26 represents the remnants of a high grade hematite orebody hosted in the Brockman Iron Formation. Similar to Mt Whaleback, the deposit is floored by a low angle normal fault that juxtaposes Brockman Iron Formation against Wittenoom Formation. This fault also appears to have developed to accommodate transpressive movement adjacent to a major jog in a NE-trending fault (in this instance, the Knotts Creek Fault).

South of the Whaleback mine, high grade hematite occurs within the southern limb of the Western Ridge Syncline. In the eastern end of the fold limb a low angle normal fault, Finn Fault, transects both the Brockman and Marra Mamba Iron Formations. Within the Brockman Iron Formation high grade hematite, variably overprinted by supergene enrichment, occurs proximal to the fault. In the Marra Mamba Iron Formation to the east, hypogene mineralisation occurs as magnetite-siderite-pyrite and is associated with significant thinning of the stratigraphy. This fault is interpreted to have formed as a listric normal fault, with only the lower sub-horizontal portion preserved, and is connected at depth to the Whaleback Fault through a series of sub-vertical normal faults.

The genesis of these structures has long been debated, with interpretations including; 1) relaxation of thrust faults, 2) tilting of early steep normal faults, 3) parallel extensional shears, 4) remnants of basal listric faults, and 5) lateral escape structures adjacent to major fault jogs. All of these interpretations involve the faults forming during or soon after the Ophthalmian Orogeny but prior to formation of hypogene mineralisation. During the ascent of hypogene fluids along major fault corridors, the low angle normal faults appear to have formed ideal distributary conduits, allowing fluids to migrate laterally and interact with large volumes of banded iron formation, particularly where these faults intersect the steep limb of a regional asymmetric fold (bedding-parallel permeability being very much greater than bedding-orthogonal permeability in these sequences). Thus, targeting structural positions likely to include low angle normal faults should increase the chance of intersecting high grade hematite mineralisation at depth.

Preliminary insights from the Coompana Drilling Project

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The Coompana Province is situated at the nexus between the West, South and Northern Australian Cratons (Fig. 1), and is one of the least understood geological provinces remaining on the Australian Continent. The region may record the final amalgamation of the proto-Australian Continent during the Mesoproterozoic, but is completely covered by Neoproterozoic to Cenozoic sediments, with no known basement exposures. Limited previous exploration in the province resulted in 11 drill holes that intersect basement, only 3 of which are diamond holes.

Five new diamond drill holes recently drilled by the Geological Survey of Western Australia has begun to shed light on the evolution of the region, indicating a complex multi-phase history beginning with interpreted oceanic crust formation at ~1950Ma and subsequent magmatic events, associated with subduction, and the reworking of that oceanic crust through the Mesoproterozoic. The SA Coompana Province also hosts the enigmatic Coompana Magnetic Anomaly, a ~50 km wide deep seated remanently magnetised anomaly possibly associated with a number of smaller satellite intrusions.

The Geological Survey of South Australia, together with our collaborative partener Geoscience Australia, has undertaken a multi-million dollar program of new pre-competitive geoscience data acquisition across the SA Coompana Province. This includes: part of the 13GA-EG1 Eucla-Gawler seismic line, newly aquired 400 m and 200 m spaced airborne magnetic and radiometric data, 1 and 0.5 km spaced gravity data and long-period magnetotelluric data as part of the AusLAMP acquisition. This geophysical data acquisition has culminated in the $3M Coompana Drilling Project, a stratigraphic drilling program to retrieve new core samples from the various geophysical domains identified from the new geophysics (Fig. 1).

Here we present some preliminary results from the Coompana Drilling Project. Drilling has revealed a predominantly igneous evolution, potentially continuing to as recent as the Neoproterozoic. Bores have intersected various lithologies ranging from early, deformed and migmatitic orthogneisses from the low magnetic intensity, low density domains; undeformed porphyritic granites corresponding to the highly magnetic NE trending band of plutons; and fresh, undeformed gabbronorites corresponding to the remanently magnetised and high density late-stage intrusions. The results from this drilling continue to shed light on the complex evolution of the Coompana Province and links with neighbouring provinces.

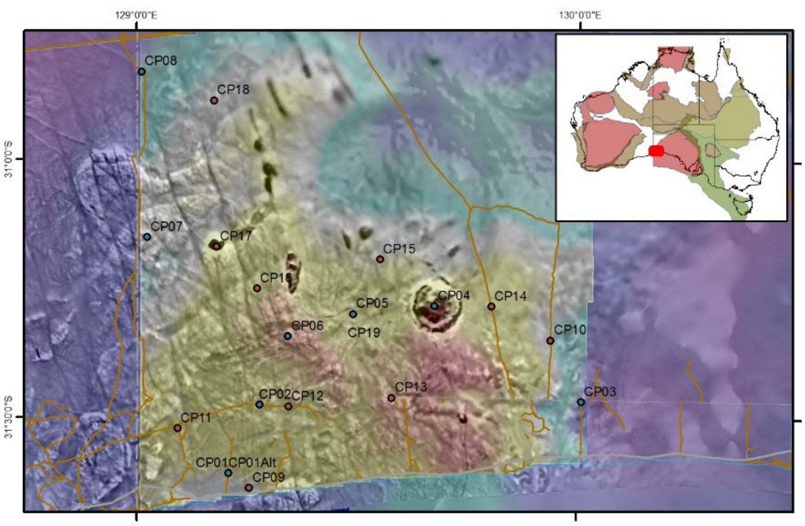

Fig. 1: Location of the proposed Coompana Drilling Project boreholes. Image 1VD magnetics over gravity. Inset: Location of the Coompana area of interest over Australian Archaean–Palaeozoic tectonic provinces.

Lower cretaceous deformation in the Exmouth sub-basin

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Cretaceous deformation in the Exmouth sub-basin is enigmatic. Basin architecture is a result of latest Triassic to Middle Jurassic extension, with fault geometries being influenced by underlying Carboniferous-Permian age structures. Relative tectonic quiescence from the Oxfordian to the Berriesian was accompanied by a large influx of sediment associated with uplift to the south, culminating in the progradation of the Barrow Delta. However, these Upper Jurassic to Lower Cretaceous sequences were themselves subject to significant uplift and erosion during the Valanginian, accompanied by a very short lived phase of extensional faulting which reactivated some Lower-Middle Jurassic faults as well as forming new faults with a different orientation.

Mapping of sequences beneath the Valanginian unconformity reveals the distribution and scale and of the uplift. Localised uplift may be associated with igneous intrusions and volcanic centres, but there is also basin scale uplift and erosion. The relationship between the extensional faulting and the uplift, the temporal association of this deformation with the final separation of Greater India from Australia and the fact that this deformation is restricted to the Exmouth sub-basin suggests a complex relationship to regional tectonics. However, the uplift of Upper Jurassic source rocks has implications for the timing of hydrocarbon generation, while fault reactivation has the potential to affect seal quality.

Regional scale mapping of the Carnarvon and Roebuck Basins

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The rifted continental margins of northern and western Australia document the break up of Gondwana and subsequent tectonic events associated with the northwards drift of the Australasian plate and its interaction with Eurasia. They also host significant hydrocarbon reserves which has resulted in the collection of extensive seismic data across the region. Policies that promote public access to this data means that the evolution of the margin can be studied in much greater details than on comparable margins in other parts of the world.

Despite this widespread availability of data, most publications focus out of necessity on specific areas of exploration or production interest, or are confined to the individual “basins” into which the margin is sometimes divided. However, the evolution of the margin can often be better understood by looking at processes that operate across these sometimes arbitrary boundaries, and the way in which they vary in timing, style and orientation within and between basins.

The most recent syntheses of data along the entire margin date back to the early 2000’s since when significant additional data has been acquired. By compiling interpretation from individual projects completed by several cohorts of honours, masters and PhD students, regional scale maps that combine the detailed information contained within 3D seismic surveys, regional patterns of basin evolution are emerging that shed light on the tectonic processes that have affected the margin.

Specifically, the extent to which Permian and older rift events have influenced Mesozoic structure is becoming increasingly apparent. The onset of Mesozoic extension varies across the basin, but is generally a result of East-West oriented extension during the Lower & Middle Jurassic (in contrast to NW-SE oriented extension in the Browse Basin associated with formation of the Argo Abyssal Plain). Upper Jurassic and Lower Cretaceous extension is associated with a change in stress regime, is also variable in timing and intensity and is surprisingly localised given its supposed relationship to the separation of Greater India from Australia. Post break-up compressional deformation occurs at different times in different places from the Late Cretaceous to the present day.

Although the maps presented here are a work in progress, they illustrate greater complexity in the evolution of the margin than perhaps previously recognised, the way in which individual extension events have influenced (or been influenced by) sediment distribution and uplift, and provide constraints for plate tectonic and geodynamic models of the margin.

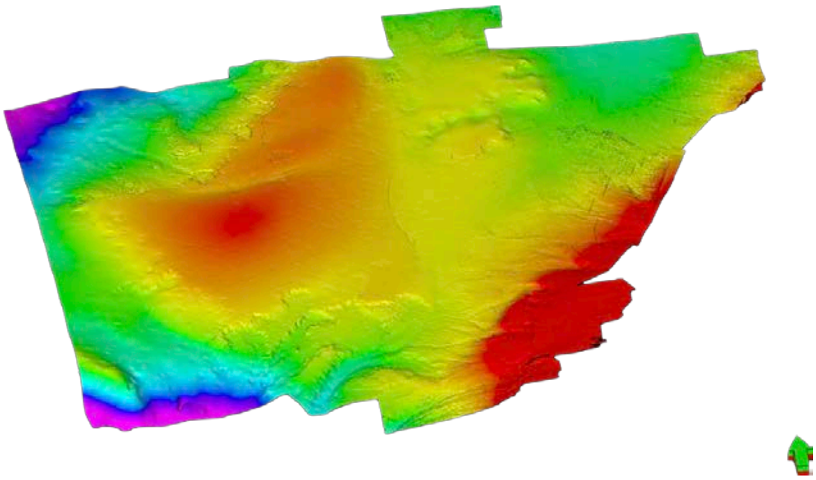

Fig. 1: Seabed map of the Exmouth Plateau showing recent compressional deformation (Exmouth Arch) and associated slumps

Structural domains, regional deformation, and the role of deep structures on mineralization in the Opinaca-La Grande subprovinces of the Superior Craton, Eeyou-Eetschee, James Bay, Québec

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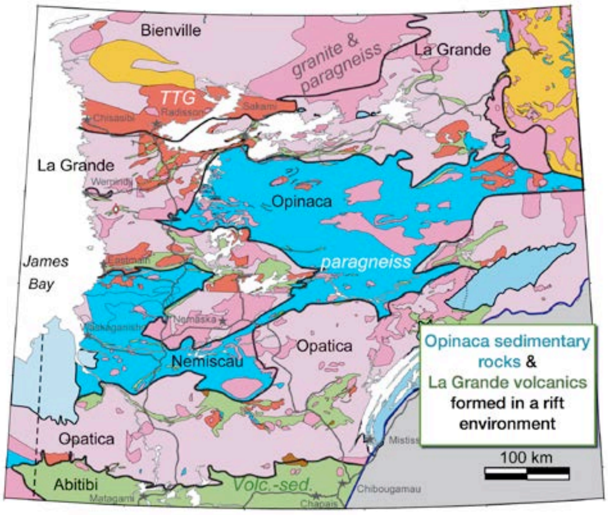
Archaean deformation and the localisation and nature of boundaries between the La Grande volcano-plutonic subprovince and the Opinaca metasedimentary subprovince of the NE Superior Craton in the Eeyou-Eetschee region, James Bay, Québec, Canada (Fig. 1), were characterised through the interpretation of enhanced high resolution aeromagnetic data integrated with field studies. Opinaca sedimentary rocks & La Grande volcanics, interpreted as having formed in a rift environment, were deformed at ca. 2722 Ma.



Distinct structural domains were defined based on the character of short wavelength tilt angle aeromagnetic images. Regional ductile dextral transpression is interpreted based on (i) the displacement of the regional E-W foliation and fold axial traces by WNW-ESE dextral and WSW-ENE sinistral ductile shear zones and the asymmetry of foliations around intrusions (akin to both σ and δ porphyroblasts in a mylonite) portrayed by enhanced short wavelength aeromagnetics (e.g. Fig. 2) and (ii) the E-W dextral offset of deep crustal units in enhanced pseudogravity ('magnetic potential') images.

Mineral deposits, including the Roberto (Éléonore) Au deposit (one of the most significant discoveries of the past 10 years in Canada) are spatially associated with (diapiric?) pluton margins and diffuse N-S (i.e. orthogonal to regional structural trends), deep crustal discontinuities revealed by enhanced pseudogravity images, especially where they intersect other regional structures. The intersections also correlate to series of local ultramafic intrusions, highlighting the trans-crustal nature of the structures and their facility as fluid conduits. This discontinuity aligns with a N-S lithospheric-scale rift in the SCLM beneath the Minto Subprovince further northwards, imaged in 3D from seismic tomographic data.

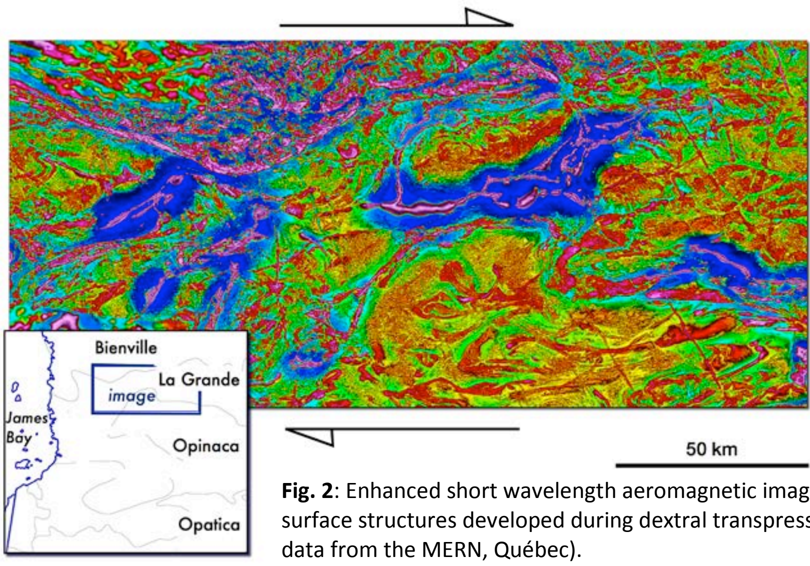


Fig. 2: Enhanced short wavelength aeromagnetic image showing near-surface structures developed during dextral transpression (original data from the MERN, Québec).

Structural controls on Au and Ni mineralisation in the Halls Creek Orogen; insights from numerical geodynamic modelling and geophysical interpretation

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It is widely accepted that structure is one of the dominant controls on the localization of mineralisation. Deep-crustal or lithospheric-scale structures are understood to influence the development of a wide range of mineral deposits, thus identification of controlling structures is critical for mineral systems prospectivity analysis. In addition, damage zones and geological complexities that act as physical throttles for fluid movement are important for prospectivity analysis at camp and deposit scales. In this study, an integration of geophysical, geological data and geodynamic numerical modelling applied to identify major geological features or structures that may be important for controlling the localisation of gold and nickel mineralisation in the Halls Creek Orogen, east Kimberley. The Halls Creek Orogen includes the 1910-1805 Ma Lamboo Province that developed between the Kimberley and North Australian Cratons. In the east, the Lamboo Province comprises three parallel, north-northeast trending zones (the Western, Central, and Eastern zones) that have been 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 then juxtaposed during the 1870-1850 Ma Hooper and 1835-1805 Ma Halls Creek orogenies. The meta-sedimentary rocks of the Halls Creek Group in the Eastern Zone are known to contain Au that probably formed during the later stage of deformation events in the Halls Creek Orogen. Significant Ni-Cu-PGE mineralisation is mainly restricted to c.1856-1830 Ma layered mafic-ultramafic intrusions in the Central Zone of the Lamboo Province.

Multi-scale structural controls are interpreted using combined gravity and magnetic data. There is a strong association between 1st order crustal-scale shear zones and faults and mineral deposits. The major crustal-scale fault systems represent terrane sutures in the Halls Creek Orogen are thought to act as fluid conduits supplying metal-rich fluids or magma to the upper crust, particularly where they are cut by orogen-normal structures. The concept that deep lithospheric-scale structures acted as conduits was tested using a 2D thermos-mechanical-petrological geodynamic numerical modelling code, I2VIS. The geodynamic models determine the second invariant of strain rate ($\dot{\varepsilon}_{II}$), which is used as a proxy for deformation, and allowed investigation of the processes leading to the development of major faults or shear zones. The role these structures had as lithospheric-scale conduits and pathways for the movement of magmatic and hydrothermal fluids into the upper crust can then be nuerically evaluated. The relationship between Au and the large-scale structures appears to be important, althogh second- and third-order faults are co-located with the deposits. These lower-order structures are interpreted to act as structural traps. Anticlinal hinge zones, dilational jogs, reactive rocks such as dolerite, high spatial density of faults and folds are also the main consistent controlling features for gold deposits. In the Halls Creek Orogen, magmatic nickel sulphide deposits occur between long-lived, trans-lithospheric fault systems at the margin of Kimberley Craton. They are mainly hosted in the margins of mafic-ultramafic intrusions associated with regional positive gravity anomaly, which may be derived from large fluxes of magma into deep crust.

Integration of structural and geophysical data in estimating uncertainties in 3D geological models

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The spatial relationship between different rock types and relevant structural features is an important aspect in the characterization of ore-forming systems. Our knowledge about this geological architecture is often captured in 3-D structural geological models. Multiple methods exist to generate these models, but one important problem remains: structural models often contain significant uncertainties. In recent years, several approaches have been developed to consider uncertainties in geological parameters that are used to create these models through the use of stochastic simulation methods. However, a disadvantage of these methods is that there is no guarantee that each simulated model is geologically reasonable – and that it forms a valid representation in the light of additional data, for example geophysical measurements. Here we use the integration of structural geological and geophysical data into a framework that explicitly considers model uncertainties.

We present a method to consider the entire geological modelling process as an inference problem and apply this concept to combine both, the consideration of uncertainties in structural models, as well as the integration of further data and information, through an implementation in a probabilistic Bayesian modelling framework. The possibility to consider uncertainties through the generation of multiple realisations directly raises two important questions: (i) how can we determine if all generated realisations present geologically reasonable model assumptions, and (ii) how can information that is not primarily used in the model construction step itself, and specifically geophysical measurements, be used to further reduce uncertainties?

We combine existing implicit structural modelling methods with probabilistic programming where we generate multiple models using a probability estimation of the structural measurements used to define the initial model. A sufficient exploration of the parameter space is conducted to estimate meaningful statistics of the posterior distribution. Representations of the full 3-D geological model are then derived on the basis of these posterior parameter distributions. Each model produced is contained within a 3D entropy plot which shows the probabilistic distribution of rock types for that set of input parameters.

Models are then discriminated on using additional information: in this case a comparison with the observed Bouguer Anomaly. Models with a RMS error of greater than certain value are excluded from the acceptable model. The final discrimination criteria is based on a conceptual model to ensure that the important features are retained such as the expected structural setting, stratigraphic relationships, fault relationships, fault behaviour, etc.

In an application of these concepts to a gold-bearing greenstone belt in Western Australia, we show that we are able to significantly reduce uncertainties in the final model by additional data integration.

Reconstructing the Tectonic Evolution of the Houtman Sub-basin, Western Australia

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The Houtman Sub-basin is an under-explored region of the northern Perth Basin, offshore Western Australia. Interpretation of Geoscience Australia's recently acquired GA349 seismic survey reveals that the northern sub-basin contains a Permian–Early Cretaceous succession up to 16 km thick, dominated by two main phases of extension in the Permian and late Jurassic–Early Cretaceous. The most prominent feature of the basin architecture is a series of large Permian half graben which extend along the inboard part of the basin and are overlain by a westward-thickening Triassic–Jurassic succession with closely spaced faulting in the outboard region. To aid understanding of the basin's petroleum prospectivity, this study uses 2D structural restorations to investigate the major phases of basin evolution, the amount of crustal extension (ß) associated with each rifting event and the magnitude of uplift and erosion associated with the Valanginian unconformity.

Newly interpreted seismic sequences were used to construct a 2D geological model on a dip line through the northern Houtman Sub-basin, which formed the basis of the structural restorations. A combination of decompaction and reconstruction using a simple shear kinematic model enabled regional restoration of the basin through time. Constraints on estimates of erosion at the Valangininian unconformity were provided by area balancing. 1D subsidence curves extracted along the section were compared with crustal thickness changes in the restored 2D profile to investigate the variation in extension factor along the transect.

Results indicate a complex basin history with multiple phases of rifting, culminating in the separation of Australia and Greater India. Initial Early- to mid-Permian rifting was focused along the inboard part of the basin, resulting in the formation of large half-graben and deposition of up to 10 km of synrift sediments. This was followed by widespread Triassic–Early Jurassic thermal subsidence. The second major phase of rifting occurred in the late Jurassic–Cretaceous and saw the focus of deformation shift to the outboard region of the basin. The total ß factor for both phases of extension is >6 over the outboard part of the basin, indicating hyperextension of the crust, with a maximum ß factor of 3 associated with Permian graben formation. The results of this work have important implications for petroleum potential in the basin. Crustal thinning and maximum burial depth are two key factors influencing the basin's burial and temperature history, and hence are required for predicting source rock maturity and generation history.

Megapixel Imaging of Brecciation and Grain Boundary Processes Controlling Gold Mineralisation

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Chemical alteration resulting from fluid flow manifestly changes rocks properties such as flow strength, permeability and density. The chemical halos around fluid flow paths are routinely used in structural and economic geology to infer fluid chemistry, conditions and fluid-rock ratios. Whilst chemical halos ranging in scale from microns to kilometers can be mapped out using a variety of techniques, efficient analysis of chemical changes at the cm to core-scale can be challenging to quantify. A recent innovations in X-ray detector technology, the Maia Detector Array, allows megapixel chemical maps of thin sections and small, cm-scale rock samples to be collected with 2 µm resolution in a few hours and the data can be quantified to give spatial variations in elemental concentrations. A new instrument, Maia Mapper, designed and built by CSIRO couples these detectors with an ultra bright X-ray source to allow mapping of samples upto 50 cm long at 30 µm resolution opening up a new scale of chemical analysis for mineral deposits, structurally controlled fluid flow pathways and metamorphism.

In this presentation we showcase results from thin section scale mapping of 'vein hosted' gold from Sunrise Dam Gold Deposit and Jundee Gold Deposit, both in the goldfields of Western Australia. Chemical mapping at 2 µm resolution shows that the gold in this part of Sunrise Dam is associated with thin seams of Fe-alteration in the host carbonates. Overprinting relationship show that the euhedral dolomite grains that host the mineralisation were formed by an evolving fluid prior to gold emplacement by brecciation and reactions at the grain boundary scale. The chemical map provides a template for understanding these rocks further using electron backscatter diffraction mapping and other higher resolution chemical techniques. The second sample (Fig. 1), mapped using the new Maia Mapper instrument highlights Ca alteration in the host dolerites, several populations of pyrite as identified using As zoning and the local, 10 cm scale mobility of Cr. Such features will allow understanding of the extent and importance of chemical halos around deposits to aid exploration and improve recovery during processing or Australia's world class mineral endowment.

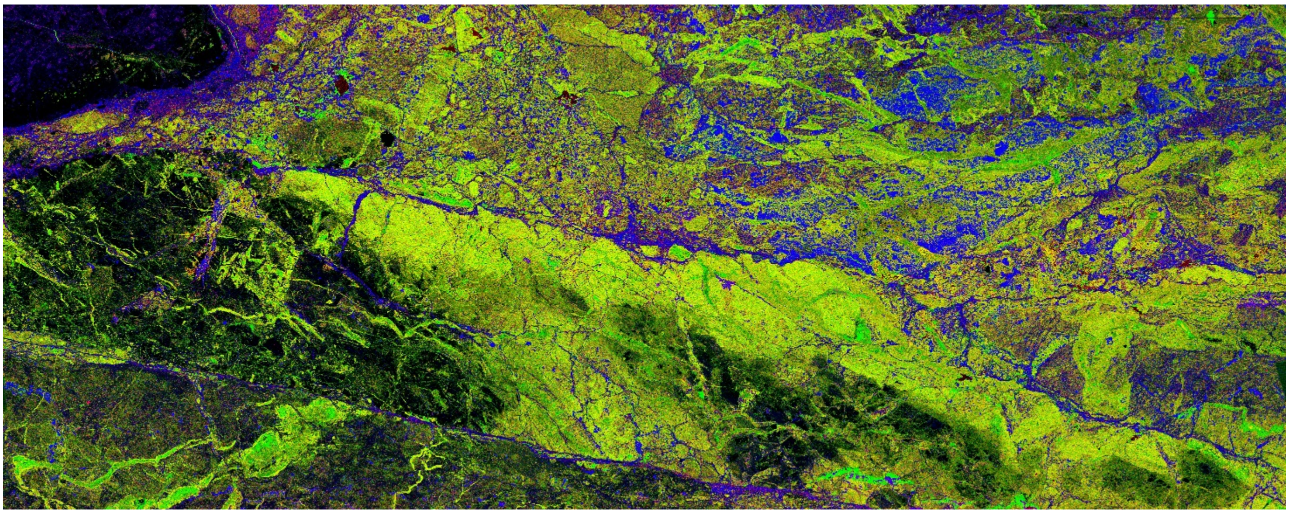

Fig. 1: Chemical composite map showing variations in Mn (red), Ca (green), Fe (blue) in a gold-rich sample 40 cm across, mapped at 30 µm spatial resolution.

Structural Emplacement of the Greenbushes Rare-metal Pegmatite

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The Greenbushes Pegmatite is a large Sn-Ta-Li-bearing rare-metal pegmatite that was emplaced within the Donnybrook-Bridgetown Shear Zone in the Archean Yilgarn Craton, Western Australia. Two deformation events, D_1 and D_2, have been identified within the Spodumene Pit at the Greenbushes minesite.

D_1 combines three fabric elements, S_{1A}, S_{1B} and S_{1C}, that range from low-strain semi-brittle fabrics within linear shear zone segments to mylonitic within curvlilinear segments. The change in orientation of Li-amphibole – holmquistite – mineral lineations around a right-stepping shear zone combined with indication of sinistral-slip shear sense confirms non-coaxial strain and represents Li-metasomatism focussed within dilatational jogs. The distribution of aligned holmquistite was continuous between pegmatite margins and the host amphibolite. Pegmatite-hosted tin and rare metals were concentrated within extensional sites relative to linear shear zone segments.

D_2 is associated with silicification and chloritisation of the pegmatite and host rocks. Synchronous fabrics, S_{2A} and S_{2B}, controlled the migration and localization of the hydrothermal fluid during retrograde greenschist facies metamorphism. Zones of S_2 coincide with lithium-enrichment within the Spodumene Pit and represent recrystallization of the primary Li-feldspar, spodumene.

The variation between mylonitic and semi-brittle fabrics is a function of strain intensity that decreases with distance away from dilatational jogs and may be explained through fluctuations in pore fluid pressure. Sub-hydrostatic fluid pressure within the dilatational jog created high-strain conditions and induced the formation of mylonite within an otherwise semi-brittle shear zone at near-lithostatic fluid pressures. Primary mineralization of the pegmatite involved fluid mixing between a pegmatitic melt and host rock hydrothermal fluids that enabled the precipitation of rare-metals. Metasomatic holmquistite growth was synchronous with primary mineralization and a sub-vertical crystal alignment measured in regional field mapping in combination with Li-anomalism in soil geochemistry may jointly be used as a prospectivity indicator in pegmatite-hosted rare-metal exploration.

Controls on Mesozoic rift-related uplift syn-extensional sedimentation in the central Exmouth Plateau

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The Exmouth Plateau forms the outboard component of the Northern Carnarvon Basin and has experienced multiple phases of rift-related extension. The history of fault activity, and associated impacts on the distribution of sediments, are revealed through the interpretation of high-quality 3D seismic data. The rifting is associated with regional-scale uplift, including the uplift and erosion of individual rotated fault blocks. The uplift and rotation of fault blocks in the central region of the plateau have disrupted the distribution of sediments, resulting in the formation of sediment starved half grabens and the onlap of sediments onto upthrown and tilted fault blocks. Uplifted and tilted fault blocks form potential hydrocarbon traps in pre-rift Triassic sediments. Detailed analysis of syn-extensional sediment packages reveals the timing of fault activity, sediment distribution pattern and the potential for additional hydrocarbon plays in syn-rift sediments.

Following the initiation of rifting in the latest Triassic, erosion of the pre-rift Triassic aged sediment occurred and continued into the Jurassic. At the onset of the Jurassic fault block uplift had largely come to an end, with only larger faults remaining active. By the Late Jurassic, regional uplift shifted to the south, in conjunction with the increase of movement on north-south trending faults. The development in fault activity continued into the earliest Cretaceous, encompassing all major faults. During the Early Cretaceous, the Barrow Delta prograded out onto the central region of the Exmouth Plateau. This change in depositional regime is associated with a change in the source and supply of sediments to the area. This deposition filled in the starved half grabens as displacement along major faults began to slow. Towards the middle of the Cretaceous movement along faults had decreased significantly and by the end of the Cretaceous fault activity was primarily limited to a network of polygonal faults. The new insights attained from this study reveal the extent to which rift-related topography formed early in the rift history, implying a change in stress regime between the Lower and Upper Jurassic.

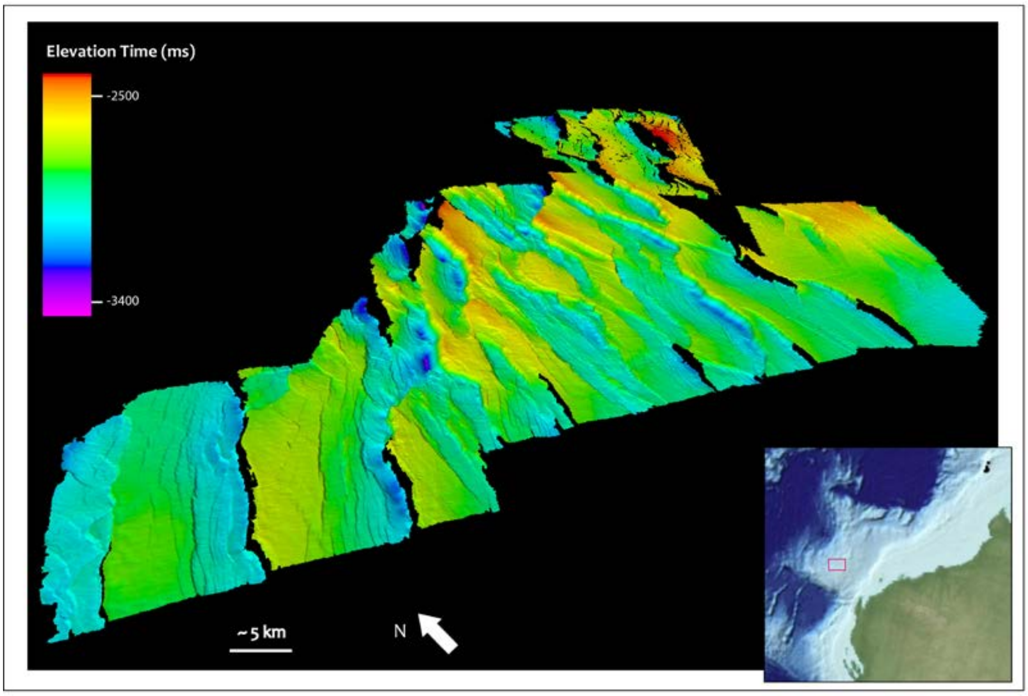

Fig. 1: 3D perspective view of rotated fault blocks mapped at the top of the pre-rift Norian Mungaroo Formation. Surface mapped across the Thebe, Bonaventure and Scarborough seismic surveys.

The geometry of hydrothermal veins in the 3.5 Ga Dresser Formation, North Pole Dome, Western Australia

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The 3.5 Ga Dresser Formation in the Pilbara Craton of Western Australia is famous for hosting Earth's oldest convincing evidence of life exposed in the North Pole Dome. The Dresser Formation is preserved as a ring of hills, up to 14 km in diameter, and dips shallowly away from the younger, c. 3.46 Ga North Pole Monzogranite that was emplaced in the core of the dome as a sub-volcanic laccolith during eruption of the overlying, c. 3.45 Ga, Panorama Formation.

Previously considered to represent a quiet, shallow-water marine environment, more recent studies have suggested the Dresser Formation was deposited in an active volcanic caldera floored by an extensive network of syn-depositional hydrothermal veins (Van Kranendonk et al., 2004, 2006, 2008). Although these veins have been recognized as filling fractures and syn-depositional growth faults (Nijman, 1999), no kinematic reconstruction of the offsets has previously been attempted to try to constrain the regional tectonics and associated deformation. Was there a regional stress field, or can the veins be related to processes directly related to magma supply and discharge within an evolving caldera system? Is there more than one vein set and, if so, how do these relate to the developing caldera?

This project investigates the vein network, through detailed field mapping and structural analysis, in order to constrain the geometry and the history of veining and fault-related offsets.

Hydrothermal veins were mapped spatially and measured for their strike and dip orientation, as well as for cross-cutting relationships between veins, and offsets, to define the age relationship between them.

Measured veins were plotted using the GEOrient computer program. The principal orientations of the vein sets in the current (deformed) state were analyzed. The measured data was then back-rotated to horizontal by un-tilting the bedding, representing the orientation of the veins before regional tilting.

Rose diagrams of back rotated veins showed:

1) Veins were all vertical prior to regional tilting;
2) Conjugate vein networks are concentrated in the middle and northern parts of the area;
3) Veins in the northern and southern parts of the area generally have one main direction;
4) There are two main vein systems (radial and listric fault related veins) in the whole study area.

The results are consistent with fracturing under a stress regime with a vertical $\sigma1$. The geometry of boxwork core zones flanked laterally by unidirectional veins is consistent with sandbox models (Acocella, 2007) of overburden fracturing during emplacement and discharge of magma chambers in a volcanic caldera environment. The two sets of conjugate veins represent separate areas of maximum uplift and subsequent subsidence, possibly separate, but linked calderas. Areas of single vein orientations reflect marginal areas, dominated by ring faults. This is the first quantified support for the caldera model for the Dresser Formation.

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Structural history of the southern Perth Basin

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The southern Perth Basin represents the southernmost arm of the Gondwanan interior rift in Western Australia, and now forms part of the passive margin of Australia. It is an informal name taken here to be that part of the Perth Basin south of the latitude of Perth city, and includes offshore. To the west it is bounded by the Dunsborough Fault and to the east by the Darling Fault, but in the Permian sedimentation extended east of the Darling Fault and onto the Yilgarn Craton. Sedimentation in the southern Perth Basin was continuous with no major hiatuses from at least the Early Permian until Gondwana breakup in the Early Cretaceous, but seismic imaging of the deepest troughs suggests the basin may have initiated earlier. Interpretation of basin architecture from recent industry seismic surveys and reprocessed legacy seismic data by the Geological Survey of WA has revealed thickening of some sedimentary successions towards the major faults.

At least three phases of extension are recognised (listed in chronological order): pre-Permian or earliest Permian extension, Late Triassic to Early Jurassic extension, and Late Jurassic to Early Cretaceous rifting. The earliest extension phase may have lasted until the end of Early Permian. The N-striking Darling and Badaminna Faults and the N- to NNW-striking Busselton and Dunsborough Faults accommodated most of the brittle strain during these phases.

The Darling Fault is the most significant fault in the southern Perth Basin and accumulated ~ 12 km of throw since its inception. Although today the fault is a long continuous structure, different sections of the fault initiated and experienced movement during different phases. During the earliest extension phase the northern half of the fault was initiated, allowing deposition of an up to ~ 3.5 km-thick pre-Permian or lowermost Permian sedimentary wedge. Later extension saw the propagation of the fault southwards. Late Triassic to Early Jurassic extension resulted in another thick (up to 4.5 km) sedimentary wedge deposited along the entire length of the Darling Fault.

Late Jurassic to Early Cretaceous rifting saw intense basin-wide normal faulting and rapid subsidence, and led to continental breakup between the Australian-Antarctic continent and Greater India at ~ 136 Ma (Gibbons et al., 2012). Based on Cretaceous seafloor magnetic isochrons, extension is inferred to have been NW-SE, which set up an oblique rifting regime. The Harvey Ridge – an enigmatic structural high adjacent to the Darling Fault – is proposed here to have formed during this final oblique rifting phase. Mapped sedimentary thickness of the Upper Jurassic to lowermost Cretaceous section combined with thermal maturity data suggests the Darling Fault south of the Harvey Ridge was active during this time but the fault adjacent the ridge and northwards became inactive or less active, with its throw transferred onto the Badaminna Fault. As rifting progressed, oblique dextral slip on the Darling and Badaminna Faults caused compression and uplift at the transfer zone to form the Harvey Ridge.

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Saturday 11th November

Strain Localisation & Fluids, Quantitative Approaches to Structural Geology

Cumulative co-seismic fault damage and feedbacks on earthquake rupture

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The importance of the damage zone in the faulting and earthquake process is widely recognized, but our understanding of how damage zones are created, what their properties are, and how they feed back into the seismic cycle, is remarkably poorly known. Firstly, damaged rocks have reduced elastic moduli, cohesion and yield strength, which can cause attenuation and potentially non-linear wave propagation effects during ruptures. Secondly, damaged fault rocks are generally more permeable than intact rocks, and hence play a key role in the migration of fluids in and around fault zones over the seismic cycle. Finally, the dynamic generation of damage as the earthquake propagates can itself influence the dynamics of rupture propagation, by increasing the amount of energy dissipation, decreasing the rupture velocity, modifying the size of the earthquake, changing the efficiency of weakening mechanisms such as thermal pressurisation of pore fluids, and even generating seismic waves itself . All of these effects imply that a feedback exists between the damage imparted immediately after rupture propagation, at the early stages of fault slip, and the effects of that damage on subsequent ruptures dynamics. As such, investigating the relative contributions of individual ruptures to cumulative off-fault damage is critical to fully understand the earthquake energy budget.

The occurence of pulverized rocks, a type of intensely damaged fault rock which has undergone minimal shear strain, has been linked to damage induced by transient high strain-rate stress perturbations during earthquake rupture. Damage induced by such transient stresses, whether compressional or tensional, likely constitute heterogeneous modulations of the remote stresses that will impart significant changes on the strength, elastic and fluid flow properties of a fault zone immediately after rupture propagation, at the early stage of fault slip. In this contribution, we will demonstrate laboratory and field examples of two dynamic mechanisms that have been proposed for the generation of pulverized rocks; (i) compressive loading by high-frequency stress pulses due to the radiation of seismic waves and (ii) explosive dilation in tension in rocks containing pressurized pore fluids. Our combined field, experimental and theoretical studies suggest that the passage of a rupture can lead to significant permanent variations in fault damage structure leading to changes in strength, stiffness and off-fault permeability, directly effecting fault weakening processes such as thermal pressurization, and hindering further rupture propagation.

Melt welding and its role in fault reactivation and localisation of fracture damage in seismically-active faults

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Low displacement fracture damage plays an important role in the mechanical evolution of faults. The development of fault damage can influence slip behaviour through changing near-field stress orientations, altering fluid pathways and by modifying fault structure. Recent experiments have also shown that frictional melting occurs over slip distances less than 100μm at slip velocities greater than ~10cm.s^{-1}, raising the possibility that frictional melting occurs, at least to some extent, during most, if not all seismic ruptures (Hayward et al., 2016). Although the generation of frictional melt may have a lubricating effect during fault slip, as the rupture ends, the melt cools and solidifies, resulting in near-instantaneous cohesive strength recovery (Mitchell et al., 2016; Proctor and Lockner, 2016). The relationship between melt welded asperities and the generation of fault damage has, until now, been essentially unexplored.

In this study we use triaxial experiments to explore the development of fault zone fracture damage, frictional lock-up and the generation of new faults using samples with pre-ground faults oriented in 5° increments between 25° and 65° relative to the shortening direction (bulk maximum principal stress). Quartz sandstone cores were shortened using a constant load point velocity of 3.6μm.s^{-1} at confining pressures of 50MPa and 100MPa. With increasing reactivation angle, faults support higher peak normal stresses (104 - 845MPa) and their behaviour transitions from stable sliding to stick-slip behaviour. Microstructural analysis shows frictional melting of surfaces where stick-slip is initiated, forming micron-thick layers that locally weld asperity contacts. The extent of melt welding is correlated with normal stress. Microcomputed X-ray tomography provides a 3-dimensional constraint on the spatial extent of melt welding, with fusion of up to 50% of fault surfaces at high normal stress.

The distribution of melt welding plays a critical role in localising the distribution and style of fracture damage during successive slip events. Damage is thought to occur both quasi-statically and dynamically. Welded sections locally lock the fault perturbing the surrounding stress states. Fractures form preferentially in dilatant regions, by-passing the melt-welded zones. Adhesion of welded regions to the opposite fault surface changes fault topography, forming geometric asperities on the interface. Cataclastic deformation of asperities contributes to the formation of gouge. During slip on unfavourably oriented faults ($\theta_r \geq 55°$) melt welding is so widespread that subsequent re-loading results in the formation of a new optimally-oriented fault. From these experiments we conclude that pseudotachylyte is strong under brittle conditions, even leading to fault lock-up and death. However, given the heterogeneous distribution of pseudotachylyte on fault surfaces, in many situations fault lock-up is unlikely. Rather, pseudotachylyte layers may play a significant, and previously unrecognised role in the development of off-fault fracture damage.

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Who's your daddy? The influence of inheritance on fracture patterns

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Understanding the multi-scale geometry and crosscutting relationships of fractures in rift basins is key to deriving their structural history. Brittle deformation is controlled by far-field stresses but also influenced by the geometry of pre-existing fabrics, faults, and discontinuities, either in the host rock itself or in older, underlying rocks. In particular, pre-existing structure in basement can lead to inheritance which encompasses fault reactivation or the poorly understood phenomenon of geometric similarity between cover structures and basement anisotropy (fabrics, fold hinges, etc.).

Here, we study the relationship between structures in the basement and cover of the onshore Gippsland Basin, southeastern Australia. The study area is ideal due to the presence of outcropping basement rocks and overlying Mesozoic sediments exposed along the Bass Coast of Victoria. We combine potential field (magnetic and gravity) data, satellite imagery, near-shore bathymetry, and aerial orthophotos from unmanned aerial vehicle (UAV) surveys. The array of data and field observations allow us to map fractures (i.e., faults, joints, and dikes), with near-continuous, high-resolution data coverage along approximately 100 km of coastline. We link fracture sets with deformation events within the basin's history, from the initial two-stage Cretaceous rifting to the recurring periods of Cenozoic inversion.

Results from this study show that NE-SW regional (tens of km scale) faults, which are early rift-related faults, are aligned with faults and fabrics in the underlying basement. In contrast, fractures at meter to 100 meter scale exhibit no apparent relationship to basement fabrics and structures, although they are compartmentalized into domains bound by regional faults or other rheological boundaries. Therefore, the smaller fault geometries do not reflect the regional fault geometries. We suggest this is an outcome of the scale dependency of inheritance, where larger faults are controlled by underlying geometries, but smaller faults (being unaffected by anisotropic boundary conditions) reflect the far-field stress more faithfully. Our results are supported by an apparent contradiction reported in the literature between a N-S extension inferred for the Gippsland Basin from seismic studies along the Australian southern margin and a NW-SE extension inferred from onshore mapping in southern Victoria. We suggest extension was N-S and but the development of NE-SW rift-related faults are the result of basement-controlled inheritance. This highlights the potential pitfall of inferring extension direction based on fault orientations that are influenced by basement anisotropy and therefore do not reflect the far-field stress.

Incipient faulting in an unstable volcano: Implications for edifice failure

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The volcanic island of La Palma (Canary Islands, Spain) is well known for flank collapse events, which potentially trigger large tsunamis. The most recent large collapse removed a significant portion of the Cumbre Nueva edifice at ca. 550 ka, and erosion of this collapse scar has exposed up to 2 km of stratigraphy within Caldera de Taburiente, including thousands of dykes in an approximately radial swarm. Here we explore the role of dykes in volcano edifice instability and eventual failure.

Using 21 UAV-based 3D virtual outcrop reconstructions to gain access to inaccessible exposures, we map the dyke networks in unprecedented detail over multiple areas of up to 1 km^2. These highlight frequent interactions between the dykes and the stratigraphy of interlayered basalts, pyroclastics and volcanic breccias, with dykes commonly terminating or developing complex geometries at contacts. Many dykes also form anastomosing dyke networks as individual dykes join together to form multiple-dykes. Significantly, we identify multiple ~1–5 m long faults that offset the dykes by 20–50 cm but do not propogate into the surrounding pyroclastics (Fig. 1). These faults initiate on irregularities in dyke geometry and terminate on the opposing dyke contact. Their offsets and geometries are consistent with gravitational loading.

Hence, we suggest that dyke networks can form load-bearing frameworks in volcanic edifices. Such networks will initially support edifice load, allowing steeper slopes and larger edifice growth over time. However as the strength of the dykes is exceeded, progressive faulting will result in a strain-weakening effect, possibly allowing the edifice to reach a super-critical state prior to runaway failure. Although difficult to directly link to the 550 ka Cumbre Nueva collapse, it is clear that dyke networks influence edifice strength, and that much needs to be done to understand their role in catastrophic failures.

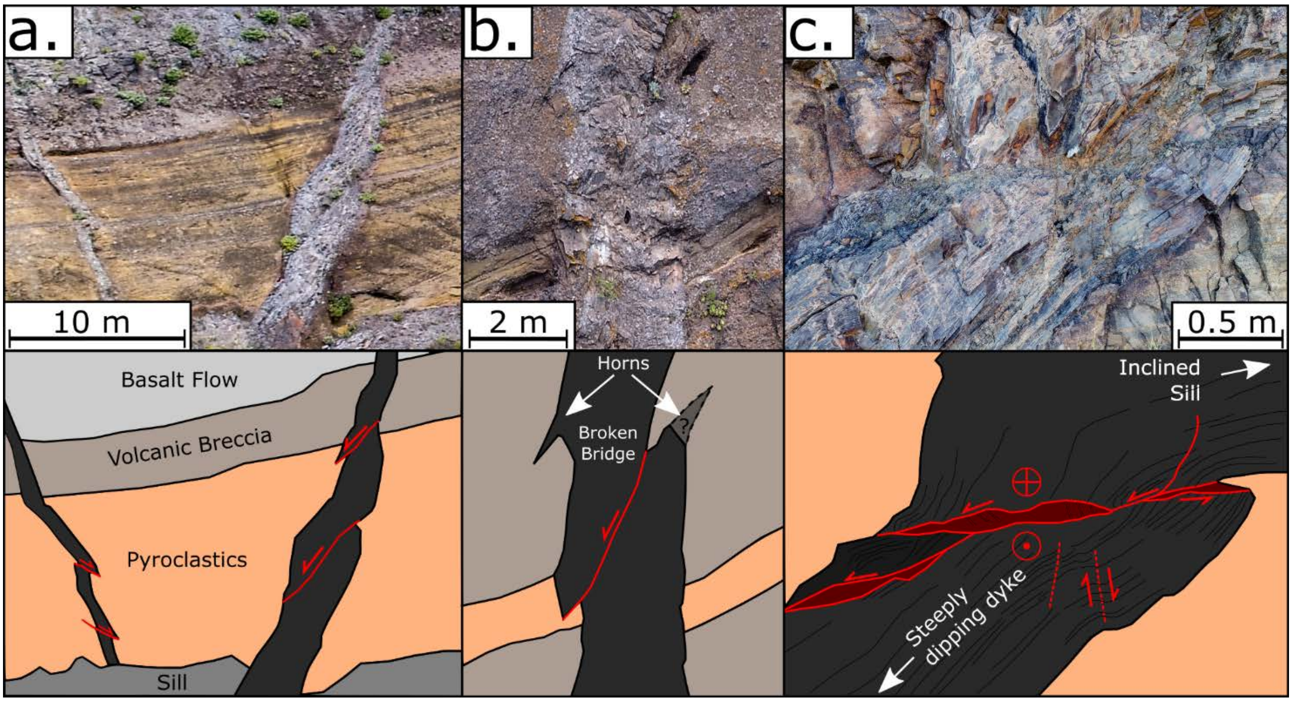

Fig. 1: Examples of the small faults observed crosscutting dykes in Caldera Taburiente. Note that the faults appear to initiate at geometric complexities in the dykes, such as broken-bridges (b) and changes in orientation (c), and that their offsets are consistent with gravitational loading.

Structural and Fluid Mechanical Controls on the Formation of Ni-Cu-PGE Trapping Chonoliths

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Intrusion-hosted Ni-Cu-PGE magmatic sulphide deposits accumulate within crustal-scale magma plumbing systems that transport mantle-derived mafic and ultramafic magmas from mantle sources to the surface. Magmatic sulphide mineralization within such systems occurs in a variety of traps that form due to a combination of structural and fluid-mechanical processes. Ore-hosting structures include tubular chonoliths (e.g., Nebo-Babel and Limoiera), ribbon-shaped sills (e.g., Noril'sk and Nkomati/Uitkomst), funnel-shaped jogs within conduits (e.g., Voisey's Bay Ovoid), elongate funnel-shaped flares within dyke-like intrusions (Eagle, Tamarack) and blade-shaped dykes (e.g., Expo-Ungava). Considerable research has been focused on the links between lithospheric architecture and Ni-Cu-PGE mineralization and the geochemical origins of sulphide mineralization. Far less work has addressed the physical processes involved in the transport of the host magmas, how high-flux channels develop, and where sulphide liquids separate and accumulate to form ore deposits. Based on constraints from field obervations, 3D seismic surveys and bore hole drilling data, we discuss the form and emplacement mechanisms of pipe-, tube- and ribbon-shaped chonoliths. Using existing theory and preliminary laboratory experiments, we hypothesise that chonoliths emerge from planar dykes and sills by elastic, viscous and thermal instabilities and then widen and elongate by thermo-mechanical erosion. Such emergence is often strongly controlled by pre-existing country rock structure. We also suggest that chonoliths form linking conduits in crustal-scale sill systems, which explains the association between Ni-Cu-PGE sulphide deposition and high magma fluxes.

Melt flux through the root of a magmatic arc under static versus dynamic conditions

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Melt–rock interaction in crustal rocks is rarely documented due to the inherent complexity of crustal rock types and melt compositions, and a lack of criteria for identification of the former flux of melt. We contrast static versus dynamic styles of melt flux throughout a homogeneous host rock, the Pembroke Granulite in Fiordland, New Zealand. Field relationships and microstructures demonstrate that melt–rock interaction involved little to no crystallisation of melt within the modified rocks, and the mineral assemblages and microstructures that were produced during melt–rock interaction are common in lower crustal rocks. Key changes common to both melt flux styles involve hydration and an increase in the mode of amphibole. All rock types contain microstructures indicative of the former presence of melt. The static melt flux styles involved widespread growth of pargasite-bearing coronae around pyroxene throughout the entire Pembroke Granulite followed by the development of localised tschermakite–clinozoisite gneiss and migmatite. The dynamic styles of melt-rock interaction formed distinct minor rock types hosted within the Pembroke Granulite, including melt-bearing high-grade shear zones and hornblendite. The static melt flux styles are inferred to involve diffuse porous melt flow with low melt flux occurring at the kilometre-scale and channelled high melt-flux occurring at the metre-scale, leading to local migmatisation. In contrast, the dynamic styles of melt flux only occurred at the metre-scale, hosted in shear zones. Significant metasomatism to form hornblendite in some shear zones indicates an increased cumulate flux in these examples, in comparison to the static styles of melt flux.

Distinguishing hydration in shear zones by aqueous fluid versus silicate melt

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Fluids are the main agents of mass and heat transfer within the Earth's crust. Shear zones within the crust acts as an important conduit for the migration of these fluids (Losh, 1989). Although, the rheological effect of the presence of aqueous fluid versus silicate melt in shear zones is less known, it is likely that these would be different. This work distinguishes the role of aqueous fluid versus silicate melt in hydration of granulite basement within shear zones of the intracontinental Alice Springs Orogeny, Central Australia. Hydration in shear zones significantly weakens the crust through reaction softening, perhaps enabling intracontinental orogeneis (Raimondo et al., 2014). The study shows a role for aqueous fluid in shear zones in the Reynolds-Anmatjira ranges based on field observation of quartz veins, microstructural observations typical of mylonite zones, and hydration to greenschist-amphibolite facies assemblage including muscovite and chlorite. In contrast, within shear zones in Strangways Range, field investigations identify granitic dykes and lenses that retain igneous texture. Microstructures indicative of the former presence of melt include felsic minerals that form films along grain boundaries or show low dihedral angles, and string of beads texture. These suggest influx of silicate melt drove hydration in the shear zones in the Strangways range while such evidence lacks in the samples from Reynolds-Anmatjira ranges. In addition to the field and microstructural criteria, REE patterns are shown to be useful in distinguishing between aqueous fluid and silicate melt hydration of the granulites.

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Patterns of strain localization in heterogeneous, polycrystalline rocks – a numerical perspective

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Strain localisation fundamentally controls a material's rheological response to deformation, and there is well documented evidence of the major role that localization plays in governing the development of important tectonic and economic structures. Shear zone initiation and development is, therefore, widely studied at all scales. However, speculation remains regarding the mechanisms and patterns of strain localization, including the influence of the rheology and geometry of pre-existing heterogeneities, and the importance of weakening and strengthening processes.

We use the microdynamic modelling platform Elle to investigate the impact of the spatial distribution (i.e. the pre-deformation microstructure) and stress related evolution for a 20% weak phase on the bulk strength and strain localising behaviour of a material deformed in simple shear. The model is extended to simulate material weakening by allowing the strong phase to dynamically transition to weak, based on a stress threshold. Material strengthening is also simulated by allowing the weak phase to strengthen based on a time threshold. Systematic testing of the stress and time thresholds are undertaken.

Our results highlight that during simple shear, if dynamic weakening with or without strengthening feedbacks is present, strain is quickly localized into an interconnected weak layer (IWL), where an increasing proportion of weak material increases the interconnections between the IWLs, thereby increasing the anastomosing character of the shear zones. The results show the geometry of a shear zone can provide relative viscosity where it crosses a lithology boundary. Shear zones are wide and anastomosing compared with narrow and concentrated where viscosity is lower and higher, respectively.

We also establish the temporal patterns of shear zones are sensitive to the dominance of the weakening or strengthening process. Consequently, shear zones are dynamic in time and space within a single deformation event and therefore, the pattern of finite strain can be an incomplete representation of the evolution of a shear zone network.

Episodic Tectonic Behaviour from Crystal-Plasticity to Seismicity

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This paper is emphasises that deforming, chemically reacting systems in the Earth operate as nonlinear dynamical systems held far from equilibrium by the influx of energy and mass. The nonlinear behaviour leaves its mark as apparently stochastic distributions of mineral assemblages, mineralisation, structures and seismic activity. However these irregular (apparently random) distributions are deterministic and, in principle, contain all the information required to understand the dynamics of the underlying mechanisms. Tectonic systems in common with most large nonlinear systems such as weather and ocean circulation systems are characterised by being forced to evolve by energy supplied at a large spatial scale; to do so mechanisms of evolution are adopted that involve dissipation of energy at finer and finer spatial scales. Thus, plate tectonic motions driven by cooling of the Earth at a global scale drive the development of through-going lithospheric faults and associated damage zones that focus mantle derived fluids. Energy is dissipated by these deformation processes and by the flow of fluids through the deformed regions. Energy continues to be dissipated by exothermic chemical and deformation processes such as hydrothermal alteration, fracturing and sliding on faults. These processes occur at increasingly finer scales until ultimately any energy in the system is either stored by endothermic reactions such as melting, the deposition of sulphides, non-hydrous silicates and metals (such as gold) or is dissipated by heat conduction and advection to the surface of the Earth. Processes of dissipation at finer and finer scales resemble energy cascades which are multifractal in their energy distribution. Thus tectonic systems are multiscale dynamical systems and need to be studied using the insights and tools developed to study such systems. This involves knowledge gained from statistical mechanics and the thermodynamics of chaotic systems. We explore the phase space for these nonlinear interactions and illustrate the transitions between different modes of operation with different attractors in phase space. Finally, the complexity of these systems can be fully quantified both in space and time using recurrence quantification and multifractal analysis.

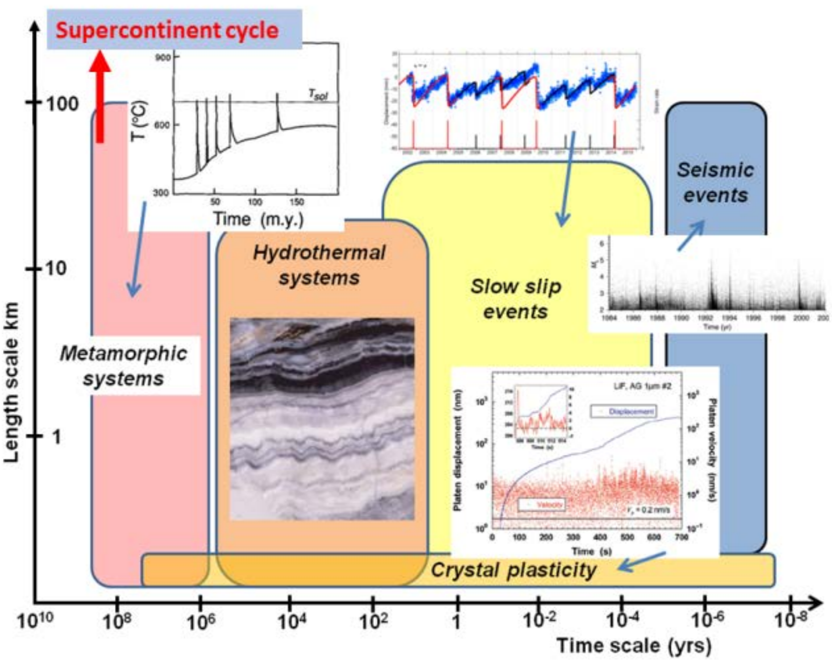

Fig. 1: Time and length scales associated with episodic behaviour in the Earth.

Quantification of Structural Geology

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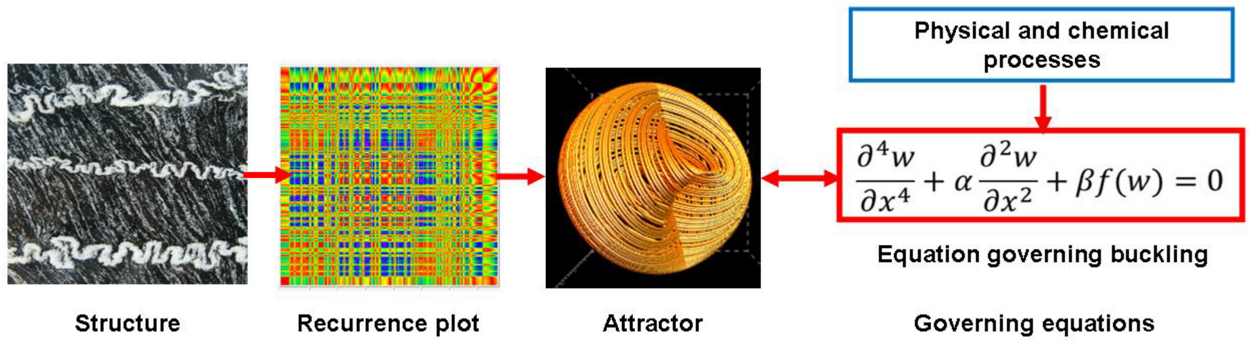
One of the aims of structural geology is to describe and understand the processes that operate during deformation and metamorphism to enable the conditions (P, T, strain-rates, stresses, rates of other processes such as grain-size reduction) that control these processes to be identified. In this paper we explore ways of quantifying the geometry of deformed metamorphic rocks in ways that are directly related to and reflective of the processes that operated. We propose that structures we observe in nature are the result of coupling between nonlinear processes and hence deforming metamorphic systems behave as nonlinear dynamical systems. As such the descriptions of such systems should utilise the toolbox of methods that have been developed for dynamic systems over the past 50 years or so. These methods include the construction of attractors, multifractal analysis, recurrence plots and dynamical network analysis.

We illustrate the approach first using numerical models of fold systems, with linear and nonlinear constitutive relations and with and without initially imposed noise (imperfections). We then extend the illustrations to consider natural fold systems. Our conclusions are that the irregularity we see in natural fold systems is the result of nonlinear constitutive laws and not that of initial imperfections. Methods based on nonlinear dynamics provide a powerful procedure for quantifying naturally deformed rocks and in deriving the processes responsible for their formation.



Implicit 3D Time-Aware GeoStructural Simulator

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One of the great challenges in resource exploration and geological research is to predict and represent geology in 3D. Building 3D models, even with the advent of implicit techniques, is still a highly specialised and costly task (both in time and computing resources) and often only adapted to “simpler” basin geometries.

There is currently a critical technology gap in our 3D geological modelling workflow. Current platforms only use a subset of the geological information available which makes building 3D geological models of hard-rock terranes very difficult. The integration with geophysical imaging is limited to the use of interpretative cross- sections as input data or a posteriori inversions that ignore geological data and information. Finally, uncertainty is extremely high and usually not quantified nor utilised. These three shortcomings in the modelling process conspire together to promote the production of geologically unrealistic models.

Although part of a bigger research project, we are presenting here the first attempt at a “Time-Aware Geological Modelling Engine” that allows modelling of poly-deformed terranes and in particular, modelling of multiple generation of folding events overprinting each other. The method is based on modelling each foliation and fold axis as scalar fields (lineations are modelled perpendicular to a scalar field) one after the other, starting with the youngest foliation and progressing backward until the primary foliation is modelled. The fold profile and geometry are derived from structural data analysis including Fourier frequency analysis to model parasitic folds and multi-wavelength folds. (Jessell et al., 2010; Laurent et al., 2017).

This abstract introduces the basic concepts required for the work of Grose et al., 2017 (this conference) on geostatistical characterisation of fold geometries and modelling.

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A Probabilistic Method for Modelling Folds from Structural Data

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We present a probabilistic method for characterising the geometry of folded surfaces from structural data. A new method for geometrical fold modelling uses a fold frame with scalar fields representing the directions of the finite strain ellipsoid (X – extension, Y – intermediate and Z – shortening) for each folding event. The shortening direction represents the axial foliation of the fold and particular iso-values represent fold axial surface geometries. The fold axis can be locally defined by rotating the intermediate field direction by the local value of the fold axis rotation angle (the pitch of the fold axis in the axial surface of the fold). The orientation of the folded surface can then be locally characterised by rotating the fold frame around the fold axis by the fold limb rotation angle (complementary angle to fold vergence). The fold axis and limb rotation angles capture the geometry of folds and need be interpolated throughout the model volume. We use a modified Fourier series where the multiple wavelengths (different scales) can be included, to represent each of these rotation angles. The fold wavelengths and Fourier coefficients are represented by prior probability density functions (PDFs) that represent reasonable parameter ranges. A semi-variogram calculated within the fold frame for each rotation angle is used to automatically identify the pervasive wavelengths present in the data set and these values are used to prior PDF for the wavelength parameters. We sample from the joint posterior distribution for the parameters representing both the fold axis and fold limb rotation angles using a Markov Chain Monte Carlo sampler and a Gaussian likelihood functions. We demonstrate this approach using a doubly plunging parasitic fold train where 500 models are produced. The resulting models are compared highlighting the areas with the highest geometrical variability. The highest region of variability occurs in the most structurally complex area e.g. hinges of folds.

Sunday 12th November

Tectonics

Unraveling and applying the rules of plate tectonics for the last billion years

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Traditionally the tectonic history of the Earth in "deep time", over a billion years and more, has been reconstructed by means of "motorboat tectonics", where continents move around the surface of the Earth like boats on a lake, with relatively little consideration for the network of plate boundaries that may be implied by these reconstructions. A new generation of plate models is now emerging that considers evolving plate boundary topologies through time, opening up the possibility to investigate and apply the "rules of plate tectonics" that should govern such reconstructions. These rules relate to both relative and absolute plate motions, and can be used to help discriminate between competing plate models, and help us to understand how cycles of passive margin formation, continental and intra-oceanic subduction zones behave through major tectonic cycles. These models are revolutionary in the sense that they provide complete surface velocity boundary conditions for geodynamic models that allow us to investigate how the plate-mantle system behaves during supercontinent assembly, stability, and breakup/dispersal. Some basic rules have emerged that govern these reconstructions. Absolute continental plate speeds are largely limited to less than 10 cm/yr, with rare exceptions, and it has been shown that both the percentage of Proterozoic regions as well as cratonic area as part of any continent impedes plate motions, i.e. large, old continents with substantial lithospheric keels do not move very fast. Equivalently, the migration speed of subduction zones is generally characterised by slow retreat between 0-3 cm/yr, ranging from relatively fast trench retreat of 5cm/yr to slow trench advance of up to 2 cm/yr. Global average continental RMS speeds in these models are below 5 cm/yr in the last 200 Ma, with a mean around 3 cm/yr. Pre-Pangea plate models with evolving plate boundary topologies display different characteristics. Global continental RMS speeds rise to over 15 cm/yr, while trench retreat reaches values of over 10 cm/yr and trench advance reaches peaks of ~ 10cm/yr. None of these values are considered geodynamically reasonable, and are far outside the range of values characteristic of the behaviour of continents and plate boundaries for the last 200 million years. The mobility of subduction zones in some of these reconstructions results in subduction zones crossing over the present-day location of LLSVPs. Whether this is reasonable or not remains to be tested. In addition, if the long-term stability of deep mantle piles, termed LLSVPs, is used to orient the positions of plates in such models, as has been suggested, independently testing the idea of LLSVP stability becomes impossible. Models with imposed plate motions are currently the most practical way to test contrasting models for the long-term evolution of the mantle, and plate-mantle interaction, informed by the geological record. In order to apply these well-established techniques to model the Phanerozoic and beyond, absolute plate models need to be designed that do not depend on assuming LLSVP stability and abide by some "rules of plate tectonics" informed by post-Pangea plate tectonics, including limits on subduction zone migration speed, RMS speeds of continents and/or net rotation of the plates. I will outline how such models can be constructed and used for studying the long-term evolution of the plate-mantle system.

Along-strike variation in the structural architecture of Sikkim Himalayan Fold Thrust belt: Insights from blind Lesser Himalayan duplex

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Fold thrust belts (FTB) are characterized by shortening structures formed along convergent plate boundaries. These structures generally change their geometry along-strike resulting in lateral variation in the overall structural architecture of the mountain belt. Some of the recognized causative factors are, (1) presence of lithological variation along the decollement horizon, (2) lateral variation in the stratigraphic thicknesses of the initial basin, (3) lateral variation in the initial width of the sedimentary basin, (4) presence of transport-parallel transverse zones that partition shortening along the transport direction (5) long-term variation in erosion rates (6) lateral variation in the convergence vector.

We focus this study on the Sikkim Lesser Himalayan FTB where there is a significant lateral variation in its structural geometry over a distance of ~15 km. The structurally lower Lesser Himalayan (Rangit) duplex (Bhattacharyya and Mitra, 2009) is not exposed east of the Teesta valley in eastern Sikkim. The overlying thrust sheets of the Rangit duplex, i.e., the Pelling and the Ramgarh thrusts, are more intensely folded in eastern Sikkim than in western Sikkim. Additionally, the number of Lesser Himalayan imbricates vary from east to west in the roof thrust of the Lesser Himalayan duplex. At a first-order, such along-strike structural variation indicates strain partitioning at the scale of constituent thrust sheets.

We construct a transport-parallel, retrodeformable regional balanced cross-section, and estimate a minimum orogenic shortening of ~403 km in the eastern Sikkim Himalayan FTB, south of the South Tibetan Detachment system. Based on the balanced cross-section and bedding-cleavage relationships, the Rangit duplex is constrained as a foreland-dipping to hinterland-dipping blind duplex along the eastern Sikkim. The location of footwall ramp varies laterally in this region causing the Rangit duplex to be blind in the eastern transect. The blind Rangit duplex with fewer horses transferred more slip to the roof thrust in eastern Sikkim, due to gentler horses with longer forelimbs. Thus, dip of the horses is a stronger factor in slip-transfer and shortening partitioning than the number of horses or their exposure level in a duplex. Although, 2D strain analysis results reveal that there is no systematic decrease in the strain magnitude (Rx/z) from the hinterland to the foreland, the latter record lower penetrative strain. The hinterland thrust faults do not track the early layer parallel shortening strain, while the foreland thrust faults do. 3D strain result suggests a dominance of flattening strain. A comparison of minimum shortening estimates between the studied region with the available data from western Sikkim transect (Bhattacharyya et al., 2015) suggests that the eastern transect records ~47 km lower minimum shortening. Lateral variation in location of footwall ramp, initial width of the Lesser Himalayan basin, and presence of a lateral ramp explain the structural variation in Sikkim Himalayan FTB.

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The Meso-Cenozoic tectonic evolution of the western Tian Shan, Uzbekistan and Tajikistan

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The Tian Shan is the worlds largest intra-continental mountain range. It stretches ~2500 km east to west, with the easternmost margin in Xinjiang, China, and the westernmost extent reaching central Uzbekistan. The Tian Shan represents a unique opportunity to investigate the evolution of a mountain range away from plate margins, and understand the complex deformation relationships that occur in intra-continental settings. Within the Tian Shan the bulk of research has focused on the eastern and central segments of the Tian Shan in China, Kazakhstan, and Kyrgyzstan. This research has made valuable contributions to understanding the tectonic evolution of the Tian Shan. However, constraints on the tectonic evolution of the western extent of the Tian Shan remain relatively few. In this study, we aim to investigate the tectonic evolution of a major terrane in the western Tian Shan and integrate our findings into models for the tectonic evolution of the Tian Shan as a whole.

The Chatkal-Kurama terrane represents the northwestern extent of the Tian Shan straddling the borders of Uzbekistan, Tajikistan, and Kyrgyzstan. In this study, we analyseed 30 samples from major faults throughout the Chatkal-Kurama terrane with three thermochonometers applied; (1) zircon (U-Th-Sm)/He dating (closure temperature ~180°C), (2) apatite fission track thermochronology (partial annealing zone ~120-60°C) and (3) apatite U-Th-Sm/He dating (closure temperature ~80-40 °C). The spread of thermochronological ages indicate that the southwestern margin has been more deeply exhumed than the northwestern margin. Thermal modeling has identified Triassic – early Jurassic rapid cooling, followed by slow cooling in the late Jurassic – Cretaceous samples, before the onset of rapid cooling in the Palaeogene.

The three phases of cooling can be related to three distinct tectonic phases experienced in the Chatkal-Kurama terrane: (1) rapid exhumation associated with the collision of the Qiantang terrane and/or the Rushan-Pshart collision on to the Eurasian margin at ~225 – 180 Ma, (2) a period of erosion and tectonic queiscence from ~160 – 95 Ma, before (3) a second phase of exhumation from ~25 – 18 Ma due to the India – Eurasia collision. The tectonic evolution of the Chatkal-Kurama is mirrored in the greater western Tian Shan, which experienced a similar tectonic history of deformation, quiescence, and reactivation. This history differs considerably from models for the central and eastern Tian Shan, which suggest periodic deformation from the Triassic to the Cretaceous. Thus, the Chatkal-Kurama terrane represents a key element in understanding the tectonic evolution of the Tian Shan.

The c. 2730 Ma onset of the Neoarchean Yilgarn Orogeny

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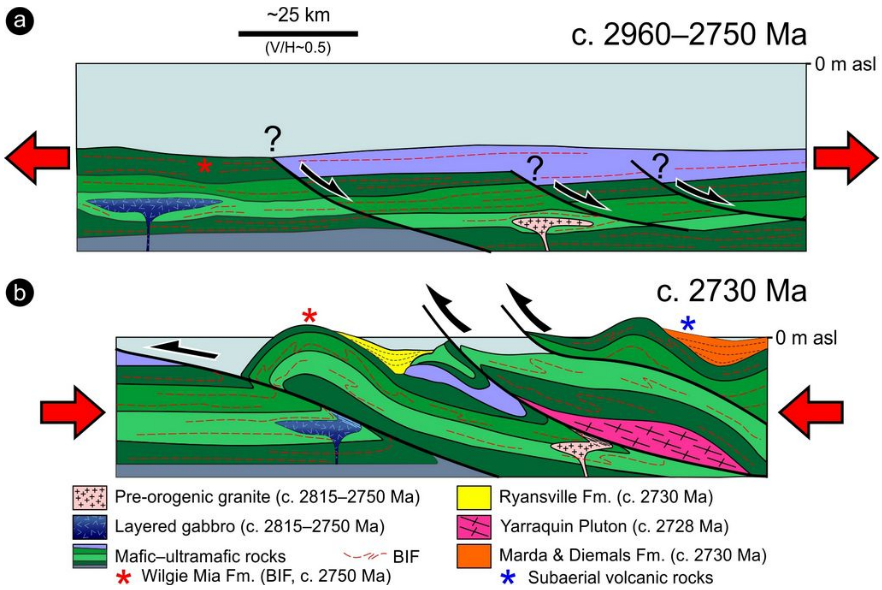
The Archean Yilgarn Craton of Western Australia is a wide granite-greenstone terrain that formed mainly in the c. 3050–2600 Ma time span. The Neoarchean Yilgarn Orogeny, which is thought to have occurred in the c. 2700–2630 Ma time span (Vearncombe, 1998), was accompanied by widespread granitic magmatism. Although syntectonic plutons represent a vast source of information for our understanding of orogenic processes, structural studies in the Yilgarn Craton have been traditionally focussed on the better exposed and economically important greenstone belts. The case study presented here provides an example of how structural analysis focussed on large syntectonic plutons represents a fundamental tool for our understanding of large-scale tectonic processes.

The timing of the onset of an orogeny is commonly constrained indirectly, because early orogenic structures are rarely exposed, or are overprinted. Establishing the onset of an Archean orogeny is considerably more challenging, because of the more fragmented geological record and the general lack of consensus about Archean geodynamics. In this talk I will combine existing tectono-stratigraphic data with new structural and geophysical datasets to establish the onset of the Neoarchean Yilgarn Orogeny (Yilgarn Craton, Western Australia). The stratigraphic record of the Yilgarn Craton is dominated by a c. 2960–2750 Ma deep-marine greenstone sequence, developed during a protracted period of dominant lithospheric extension and emplacement of large volumes of mantle-derived magma. This sequence was uplifted and unconformably overlain by a c. 2730 Ma, syntectonic clastic succession, deposited in shallow marine to subaerial conditions, and derived from the erosion of the deep-marine greenstone sequence. At around the same time, at deeper crustal levels, the c. 2728 Ma Yarraquin pluton was being emplaced along an active, large-scale shear zone network. Meso- and microstructural analysis shows that fabric development in the granite and its country rocks occurred during pluton emplacement, and was largely assisted by magma-present shearing. Overall, these structures reflect an important event of syn-emplacement crustal shortening. Thus, the regional unconformity and the syndeformational emplacement of the Yarraquin pluton are both expressions of a c. 2730 Ma regional deformation event associated with significant crustal thickening, marking the onset of the Neoarchean Yilgarn Orogeny.



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Tracing Jurassic-Cretaceous volcanism offshore eastern Australia: Insights from detrital zircons from Papua New Guinea and the Queensland Plateau

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The complex and destructive geodynamics of Australia's northeast plate margin has left very little preserved crust of Jurassic and Cretaceous age. This provides a challenge for understanding the pre-Cenozoic plate dynamics of the region. However, evidence of semi-continuous Jurassic-Cretaceous volcanism along the eastern margin of Australia exists in the detrital record of the Great Artesian Basin and within volcanic provinces such as the Whitsunday Igneous Provence and the Lord Howe Rise. We present new findings that suggest Jurassic to Eocene volcanism extended further to the north beyond the extent of current datasets. These findings result from investigations into detrital zircons of the Cretaceous-Eocene Port Moresby Beds of southeast Papua New Guinea, and from drill core of DSDP site 209 on the northeast Queensland Plateau. An extensive record of detrital zircons were dated using laser ablation ICP-MS for U-Pb isotope analysis. Cretaceous volcanism is prevalent in Port Moresby with over 200 zircons dated between 120 Ma and 90 Ma with the main peak at ca. 100 Ma. The same trend exists on the northeast Queensland Plateau with over 100 detrital zircons dated between 120 Ma and 90 Ma with the main peak at ca. 90 Ma. However, there is also evidence for prolonged and continued volcanism beyond these main age populations, with over 50 detrital zircons dated between 90 Ma and 70 Ma on the northeast Queensland Plateau. This trend is notably absent in the samples from Port Moresby. There is also smaller populations of Jurassic detrital zircons, with peaks occurring at ca. 150 Ma, 170 Ma and 190 Ma, in samples from both the Queensland Plateau and Port Moresby. We will also present Lu-Hf isotope analysis for Port Moresby detrital zircons, which will provide further insights into the tectonic setting and nature of volcanism, and therefore, help piece together the Jurassic and Cretaceous tectono-magmatic evolution of Australia's north-eastern margin.

Thermotectonic evolution of the western Siberian margin from apatite double-dating and REE systematics

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The Neoproterozoic tectonics of the Yenisey Ridge, on the western edge of the Siberian craton, is the topic of considerable debate. Competing hypotheses either locate the Yenisey ridge at the centre of a Grenvillian age collision along the Siberian margin, or alternately at a distance of 1000 km from the Siberian Craton during the early Neoproterozoic. Here we present a case study, building on published zircon U-Pb data, illustrating the power of complementary apatite and zircon U-Pb analysis to resolve tectonic questions. Samples from throughout the stratigraphy of the region were dated with these methods in an attempt to improve our understanding of the age and source of the units. We combine apatite U-Pb and fission track analysis with a characterisation of the trace and REE elements in individually dated grains to chart the thermotectonic evolution of the western Siberian margin over the last billion years.

Apatite U-Pb results show a much greater contribution of Neoproterozoic material to the Cryogenian and Ediacaran units of the Yenisey Ridge than previously thought, and have important implications for the stratigraphy and tectonic evolution of the region. Additionally, low-temperature fission track thermochronology records a thermal event that postdates deposition and that reset a large population of grains. The data suggests that the region then experienced cooling concurrent with the eruption of the Siberian Traps and the initiation of rifting in the West Siberian Basin at ~250 Ma. These improved constraints on the age of critical stratigraphic units will help develop a more complete model for the thermotectonic evolution of the Yenisey Ridge and clarify its position in Neoproterozoic plate tectonic reconstructions.

Apatite fission track thermal history of the Bole-Nangodi Shear Zone (northern Ghana, West African Craton): Insights into Equatorial Atlantic rifting

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The West African margin has been subjected to deformation and exhumation in response to Gondwana break-up. The timing and extent of these events are recorded in the thermal history of the margin. Apatite fission track (AFT) data were obtained from Palaeoproterozoic basement rocks along the primary NE-SW structural trend of the Bole-Nangodi shear zone in northwestern Ghana. The results display bimodality in AFT age and length distributions, supported by differences in apatite chemistry (Cl and U concentrations). The bimodal AFT results and associated QTQt thermal history models provide evidence for two thermal events: (1) a Late Triassic – Early Jurassic thermal event, which may be related with the emplacement of the Central Atlantic Magmatic Province (CAMP) and (2) an Early Cretaceous cooling phase, which is thought to be associated with exhumation during Early Cretaceous rifting of West Africa from Brazil.

In addition, our data record differential exhumation of the crust with respect to the Bole-Nangodi shear zone, preserving older (CAMP) cooling ages to the south and younger (rifting) cooling ages to the north of the shear zone, respectively. This suggests that the Palaeoproterozoic BN shear zone has been reactivated during the Cretaceous as a result of rifting in the Equatorial Atlantic Ocean. Our results thus indicate that Cretaceous rifting likely reactivated pre-existing shear zones within the West African Craton, which acted as zones of weakness and may have ultimately influenced the orientation of fracture zones within the Equatorial Atlantic.

Provenance of the New Caledonia basement

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The island of New Caledonia constitutes the second largest exposure of Gondwanan continental crustal basement in the southwest Pacific region (after New Zealand), and the only known basement exposure of north Zealandia. The crustal basement rocks of New Caledonia (Teremba, Koh-Central and Boghen Terrane) are suggested to be equivalent to rocks in eastern Australia (Gympie Terrane) and New Zealand (Brook Street, Murihiku Dun Mountain-Maitai Terrane) but correlation between these terranes and the tectonic evolution of the New Caledonian basement remains unclear. We present a new, extensive, detrital zircon geochronological dataset from late Paleozoic-Mesozoic basement terranes in New Caledonia. These data are complemented by petrographic studies and point counting analysis. In contrast to previous models, results show that the Teremba Terrane has a distinct age spectra when compared to the Koh-Central and Boghen Terranes, suggesting that these terranes occupied different tectonic settings along the eastern Gondwana margin. The Teremba Terrane detrital age spectra are dominated by proximal volcanic sources that are contemporaneous with deposition of the strata (short source to sink span), while the Koh-Central and Boghen Terranes are dominated by older, continental-interior ages (i.e., Gondwanan age populations). Our results place new constraints on the tectonic evolution of the New Caledonia basement along the Late Paleozoic-Mesozoic margins of eastern Gondwana.

Hunter - Bowen deformation in the Percy Group of Isles, offshore central Queensland

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South Percy Island is located approximately 140 km southeast of Mackay in the Northumberland group of islands. The island is dominated by a disrupted ophiolite mass known as the Northumberland Serpentinite and contains a diverse array of metamorphosed felsic and mafic rocks that record several episodes of magmatism and deformation from the Permian to Early Cretaceous. Deformation is localised in a NNE-striking, 300 – 500 metre wide tectonic contact that juxtaposes serpentinised ultramafic rocks against metamorphosed pillow lavas of the Chase Point Metabasalt to the east. The main episode of deformation (D_2) resulted in the development of several fabric elements, with early ductile fabrics comprising a penetrative schistose foliation (S_2) that is overprinted by symmetrical conjugate shear bands. The style of deformation suggests that D_2 involved bulk flattening strain under general shear conditions. Cross-cutting and overprinting relationships between intrusive phases and deformation features provide a relative chronology for the tectonothermal evolution of the area, while U-Pb and ^{40}Ar / ^{39}Ar geochronological data constrain the absolute timing of the major deformation, metamorphism, and magmatism. U-Pb zircon dating indicates that a pre-kinematic quartz-monzonite dyke and a syn-kinematic diorite dyke were emplaced at *ca.* 260 Ma and *ca.* 245 Ma respectively, thus constraining the timing of initiation of D_2. ^{40}Ar / ^{39}Ar dating from the pre-kinematic quartz-monzonite dyke yielded an age of *ca.* 248 Ma, which is *ca.* 12 Ma younger than the intrusion. We therefore interpreted this age to represent syn-kinematic recrystallization during retrograde metamorphism under waning greenschist conditions. The age of deformation and metamorphism (D_2 and M_2) is therefore constrained to approximately 250 ± 10 Ma. In addition, the trace element compositions of mafic and felsic (meta-) igneous rocks record a change from MORB-like prior to *ca.* 277 Ma to subduction-related by *ca.* 260 Ma. We correlate the *ca.* 250 Ma deformation, metamorphism, and arc magmatism in South Percy Island with deformation and magmatism associated with the second phase of the Hunter-Bowen Orogeny, which affected much of the central and northern parts of east Australia at around the Permian – Triassic boundary. These results provide new constraints on the timing and kinematics of Hunter – Bowen deformation in offshore central Queensland and support previous suggetions that regional deformation occurred alongside arc magmatism in a supra-subduction zone setting.

VARIATIONS IN REGIONAL STRESSES, GEOMETRY AND SHAPE OF LOW STRENGTHS ZONES CONTROLES THE PERIODIC ALICE SPRINGS OROGENY

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The intracontinental Alice Springs Orogeny (ASO), central Australia, is a long lasting polyphase orogeny spanning a period from 450 Ma to 300 Ma. Due to the periodic nature of ASO orogenesis, a numerical modelling using the software Basil was performed to model the deformation in the ASO. The model used as parameters the lithospheric stress propagation from N-S and E-W, representing the possible Gondwana-Laurussia amalgamation and the periodic extensional and compressional movement of paleo-Pacifc subduction system, respectively. Additionally, a weaker rheological crustal element representing the Larapinta rift was added to understand the tectonic implication of a submissive wedge in the ASO deformation. We conclude that a combination of compressional or extensional movement of the paleo-Pacific plate, added to a soft rift system in the west, best represents the deformation in ASO.

Uncovering *terra incognita*: new insights into the evolution of Antarctica and constraints for ice sheet models

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An understanding of the evolution of the Antarctic plate has contributed to incredible insights into the Earth-system as a whole, including supercontinent cycles in deep time, as well as global cryosphere, ocean and climate evolution. Antarctica contains some of the oldest known crust on Earth, built over billions of years, and the breakup of Gondwana shaped the modern continent, leading to the opening of the Tasman and Drake gateways, development of the Antarctic Circumpolar Current, paving the way for the Cenozoic-modern ice sheet.

Today, the Antarctic plate continues to impart significant forcings on the ice sheet and ocean circulation, which are not well captured in models that seek to describe ice sheet behaviour and forecast ice mass discharge and sea level change. Antarctic geology also records past ice sheet changes that can inform on future scenarios in a warming world. Yet there is much to learn, as the Antarctic continent reveals less than 1% of its rugged subglacial topography and its submarine margins remain poorly explored.

Here we review recent progress in uncovering Antarctica – we focus on the Wilkes, Queen Mary and Wilhelm II regions of East Antarctica, that represent part of the Australian and Indian conjugate margins, where multiple datasets including seismic tomography, aerogeophysical data, and rock- and sediment-based geological analysis provide new insights into the tectonic evolution and geological architecture of the Antarctic plate. These datasets also provide opportunities to address solid Earth-cryosphere interactions, such as the magnitude and spatial variability of geothermal heat flux to the base of the ice sheet, and ice sheet extent during past glacial cycles, with the aim of reducing uncertainties in models of the past and future evolution of the Antarctic ice sheet.

Paleoproterozoic basin development on the northern Yilgarn Craton, Western Australia

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Basins formed on the northern Yilgarn Craton developed as a response to both extensional and compressional processes in the early Paleoproterozoic along the craton margin. Early rifting and basin formation coincided with the Ophthalmian Orogeny, the result of the convergence and accretion of the Archean to Proterozoic Glenburgh Terrane with the Pilbara Craton, and led to the formation of the Yerrida Basin at c. 2180 Ma as a single sub-basin containing the Windplain Group. This led to the eventual development of the Bryah and Mooloogool Sub-basins of the Yerrida Basin at c. 2030 Ma, and voluminous extrusion and intrusion of mafic rocks. The depth and nature of the Bryah Sub-basin suggests formation in response to rifting, with its orientation corresponding to the rift axis. Continued rifting along the northern Yilgarn margin resulted in subduction of the Yilgarn Craton beneath the composite Glenburgh–Pilbara craton. Eventual collision was marked by cessation of volcanism and rift-sediment deposition in the Bryah and Mooloogool Sub-basins, the onset of a pro-foreland basin (Padbury Basin) in the west, and approximately NE–SW rifting further east (the Earaheedy Basin), all at c. 2000 Ma. Banded iron-formation and granular iron-formation in the Robinson Range and Frere Formations was deposited much later (c. 1890 Ma) in a large basin that deepened from east to west, covering the Earaheedy and Yerrida Basins. The deepest parts of this basin coincide with the Bryah Sub-basin, which represents the most rifted portion of the Yilgarn Craton in this region. Subsequent deformation in this region, during the Capricorn Orogeny led to the development of complex structures such as refolds and disharmonic folds, whereas in other areas structural development was much simpler with the development of gentle to open folds and large scale, mostly linear faults. Deposition in all basins probably ceased with onset of the Capricorn Orogeny at c. 1820 Ma.

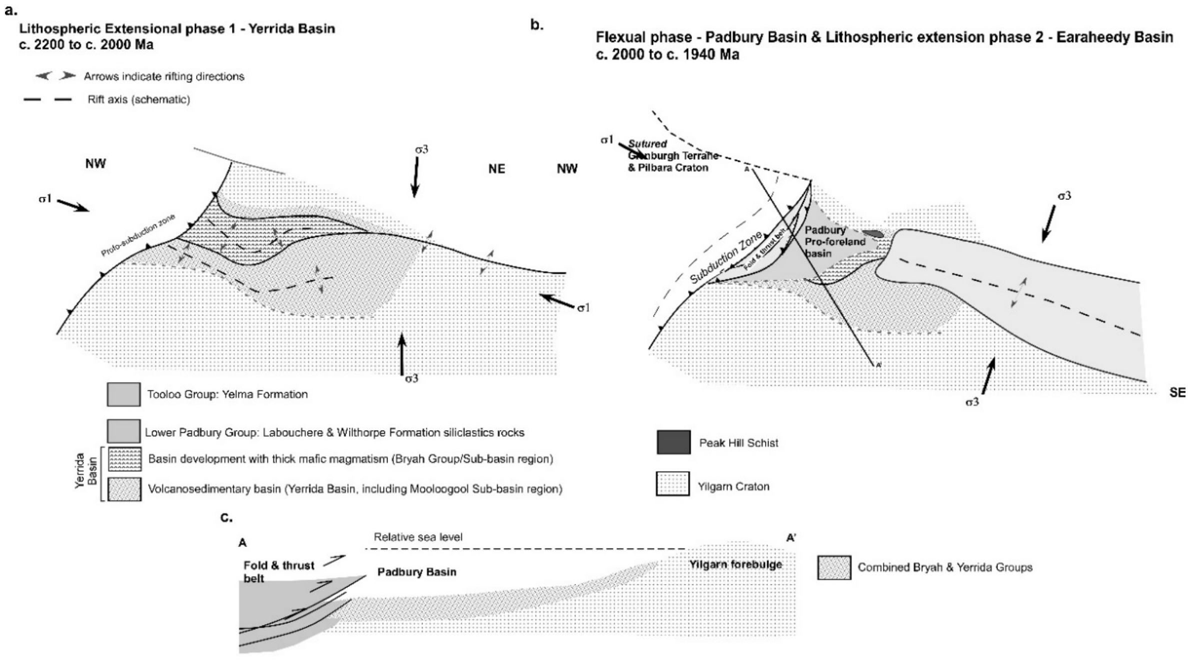

Fig. 1: Model for basin development along the northern Yilgarn Craton margin. a. Early lithospheric extension; b. Flexure, and pro-foreland basin development in the west, and extensional basin development in the east; c. Cross-section A-A[1] in b.

Proterozoic and Palaeozoic evolution of a crustal-scale shear zone system in the northeastern Aileron and Irindina provinces, central Australia

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The Palaeoproterozoic northeastern Aileron Province, central Australia, is characterised by a system of primary and secondary shear zones that bounds a series of 500–1000 km^2 tectonic domains. The primary structure is the >250 km-long, west- to northwest-trending, steeply south-dipping Delny Shear Zone. A ~4 km-wide, ~40 km-long system of anastomosing (ultra-)mylonites of the Delny Shear Zone and its west-southwest-trending splay, the Entire Point Shear Zone, marks the northwestern boundary between Aileron Province in the north and Neoproterozoic-Palaeozoic Irindina Province in the south. The petrological and structural record preserved in these mylonites coupled with new monazite and zircon petrochronologic data (Reno et al., 2017) provides previously unrecognised key evidence for the Palaeoproterozoic and Palaeozoic tectonothermal history of the region.

The earliest preserved deformation structures along the shear zones are (proto-)mylonites (S_1) that formed during normal movement under extensional conditions. This movement is contemporaneous with an increase in pressure towards P_{max} in the hanging walls (ca. 1.76 Ga). A decrease in pressure at ca. 1.76–1.73 Ga is accompanied by the renewed formation of transpressional (proto-)mylonitic fabrics (S_2, ca. 1.73 Ga). S_2 is axial planar to asymmetric folds with axes plunging moderately, parallel to the stretching lineation. This fabric is locally preserved in boudins bound by extensive granulite-facies (ultra-)mylonites (S_3, ca. 1.72–1.69 Ga) that formed axial planar to asymmetric folds. Progressive deformation during retrograde D_3 caused asymmetric fold and minor sheath folding with fold axes plunging moderately, parallel to the stretching lineation. A decrease in pressure in all tectonic domains to ~0.4 GPa at ca 1.72–1.70 Ga is accompanied by sinistral, possibly inclined transpression along the fault system during D_3.

Passive, asymmetric folding of $S_{2,3}$ with moderately plunging axes occurred at the dm- to km-scale resulting in local development of axial planar mylonites (S_4), lacking retrograde overprint. New monazite growth at ca. 1.63–1.57 Ga restricted to S_4 mylonites indicates renewed sinistral transpression, contemporaneous with the Liebig and Chewings orogenies, previously unrecognised in the north-eastern Aileron Province.

The youngest preserved ductile deformation structures are m-scale, greenschist-facies mica-rich mylonites (S_5) that formed axial planar to dm-scale passive folds with sub-horizontal fold axes. Ca. 0.47–0.46 Ga metamorphic monazite restricted to the S_5 mylonites grew contemporaneous with the formation of the main fabric in the Irindina Province during the extensional, Larapinta Event; ca. 0.37 Ga monazite overprinting S_5 records thermal overprint during the Alice Springs Orogeny. Several mylonitic fabrics that formed at ca. 0.45–0.44 Ga are restricted to rocks in the Irindina Province.

Mylonitic fabrics that formed during the Palaeoproterozoic (S_1-S_3) are remarkably similar in orientation and style to fabrics that formed during the Mesoproterozoic (S_4). Palaeozoic fabrics that formed in the Irindina Province resemble S_1-S_4 of the Aileron Province, whereas the Palaeozoic S_5 fabric is restricted to discrete shear zones that share orientation, but not the style of older mylonitic fabrics. This indicates remarkably stable stress and strain conditions, as well as strain localisation along the Delny Shear Zone system throughout its history.

References

Reno, B.L. et al., 2017, SGTSG Abstract

Dome-side-down sense of shear and uniform magnetic fabrics in the Mt Edgar dome, East Pilbara craton, WA

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The 3.53-3.17 Ga East Pilbara block of the Pilbara craton consists of ovoid granitoid domes of Tonalite-Trondhjemite-Granodiorite composition flanked by an approximately coeval, variably deformed volcano-sedimentary sequence (greenstone). This overlying sequence nearly everywhere dips away from granitoid dome rocks and the contact between the granitoids and greenstone is often mylonite to ultramylonite. The East Pilbara block has been the subject of decades of research into early earth crustal processes. We present a new structural dataset comprising field fabrics, microstructural kinematic analysis of boundary rocks using both light microscopes and electron backscatter diffraction (EBSD), and anisotropy of magnetic susceptibility (AMS) of the Mt Edgar granitoids. First, deformed granitic rocks form the Mt Edgar dome boundary show dominantly dome-side-down sense of shear, which translates into a reverse shear sense with the wallrocks dipping away from the batholith. Shear sense was determined both in the field and using microstructures. These data are consistent with non-plate tectonics models of deformation (convective overturn), but only if diapiric upward flow occurs in the middle of the pluton and downward flow occurs at the margin. In contrast, an anisotropy of magnetic susceptibility (AMS) study of the internal Mt Edgar batholith shows a consistent, NW-oriented foliation with a subvertical lineation. Statistical analysis of AMS ellipsoids suggest that fabric from across the dome comprise a unimodal, normally distributed sample, with the exception of the oldest granitoid unit, the 3.44 Ga Fig Tree gneiss. These data are consistent with at least two episodes of granitoid deformation, one of which may be attributed to a late-stage, pervasive regional deformation. Together, these data indicate that significant information constraining the tectonic history can come from studying the internal fabrics of Archean domes, even when the fabrics are too weak to directly observe in the field.

Poster Session 3

Potential field constraints on the 3D structural architecture of the Batten Fault Zone, southern McArthur Basin

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The McArthur Basin forms part of a Proterozoic basin network that formed across large areas of the North and South Australian cratons. The basin contains 5-15 km thick successions of non-metamorphosed marine and terrestrial sedimentary rocks with interbedded volcanics deposited within an intracontinental setting. These sediments accumulated over 400 million years within several stacked and superimposed basins which can be correlated with the Leichhardt, Calvert, Isa and South Nicholson super-basins in Queensland.

The Batten Fault Zone is a 50-80 km wide, north trending fault zone located in the south-eastern McArthur Basin. The region exposes sequences from the Tawallah, McArthur, Nathan and Roper Groups. These groups represent stratigraphic sequences from several stacked basins, which evolved in response to changes in the regional extensional direction, likely related to far-field stresses from the southern and eastern margins of the Proterozoic Australian continent. Within the Batten Fault Zone, changes to the regional extensional direction and the pre-exisiting fault architecture compartmentalised the basin during deposition of the McArthur Group. There is some uncertainty regarding the orientation of structures controlling the basin architecture at this time, and in particular structures controlling the prospective Barney Creek Formation. The McArthur Group is host to the world class sediment hosted Zn-Pb deposit, McArthur River (formerly HYC), and an improved understanding of the structural architecture will expand our knowledge of factors and processes controlling mineralisation.

We aim to constrain the 3D architecture and structural controls of the Batten Fault Zone, with particular focus applied to understand sub-basin development within the McArthur Group through the analysis and interpretation of geophysical data. Gravity, magnetics, radiometrics, airborne electromagnetic and seismic data were used to produce a structural and lithological interpretation of the region. 2D forward modelling of the gravity and magnetic data, constrained by seismic data where available is applied to understand the architecture of the fault zone in 3D. Preliminary interpretation suggests that sub-basins within the McArthur Group are forming in local transtensional zones confined by N-S trending strike-slip and E-W, NW-SE and NE-SW trending normal faults.

Mid-Lithosphere Discontinuity and Layering within Subcontinental Lithospheric Mantle

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Recent seismic studies reveal a sharp velocity drop mostly at ~70-100 km depth within the thick mantle keel (generally extending to ~200 km depth) beneath cratons, termed the mid-lithosphere discontinuity (MLD). The MLD marks the top boundary of a relatively low-velocity layer within the cold, high velocity mantle keel. Its common appearance in cratonic regions is therefore a manifestation of vertical structural variation or layering within the subcontinental lithospheric mantle (SCLM). The nature and origin of the MLD and the formation of such SCLM layering are closely associated with the process of generating a thick, buoyant and strong cratonic root in the Archean time, and with the long-term evolution and modification of the SCLM. The MLD beneath cratons probably also has a genetic relationship with the lithosphere-asthenosphere boundary (LAB) in tectonically active regions, given that the depths of the two discontinuities are broadly comparable. Moreover, the MLD and the underlying (relatively) low velocity layer may indicate a mechanically weak layer within the overall strong cratonic SCLM. How such a weak layer in the SCLM could have affected the ensuing evolution of cratons may provide valuable clues for elucidating the ways of destroying presumably stable cratons. A comprehensive understanding of all the above issues demands detailed information of the MLD structure (such as thickness and magnitude of velocity drop) and associated layering of the SCLM. Such information, mostly coming from seismic studies, remains lacking at the present time, but is expected to be increasingly available with the ongoing rapid improvement in data coverage and imaging techniques.

Fluid Flow through the Fortescue Group Volcanics, Pilbara, Western Australia.

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Mafic volcanic rocks of the Fortescue Group form the lowermost stratigraphic unit of the 100,000 km[2] Hamersley Basin on the southern margin of the Archean Pilbara Craton, Western Australia. A regional burial metamorphic gradient extends across the basin from prehnite–pumpellyite facies in the north to greenschist facies in the south (Smith et al., 1982). Folding during the Ophthalmian orogeny produced topographic and/or tectonic driving forces for regional-scale fluid flow, interpreted as driving metasomatic fluid northwards across the Hamersley Basin (Rasmussen et al., 2007 and references therein). Phase equilibria calculations (White et al., 2014) support previous interpretations linking the Ophthalmian orogeny, fluid flow and upgrading of Hamersley iron ore deposits. We present coupled deformation-fluid flow-thermal transport-chemical reaction modelling to first test the geodynamic veracity of the pressures and temperatures derived for the metamorphism and metasomatism, and second test the hypothesis that this fluid flow extends to the Fortescue Group, the metasomatism of which has leached Fe from part of the Fortescue Group mafic volcanic sequence and may have contributed a source of Fe to the Hamersley iron ore deposits.

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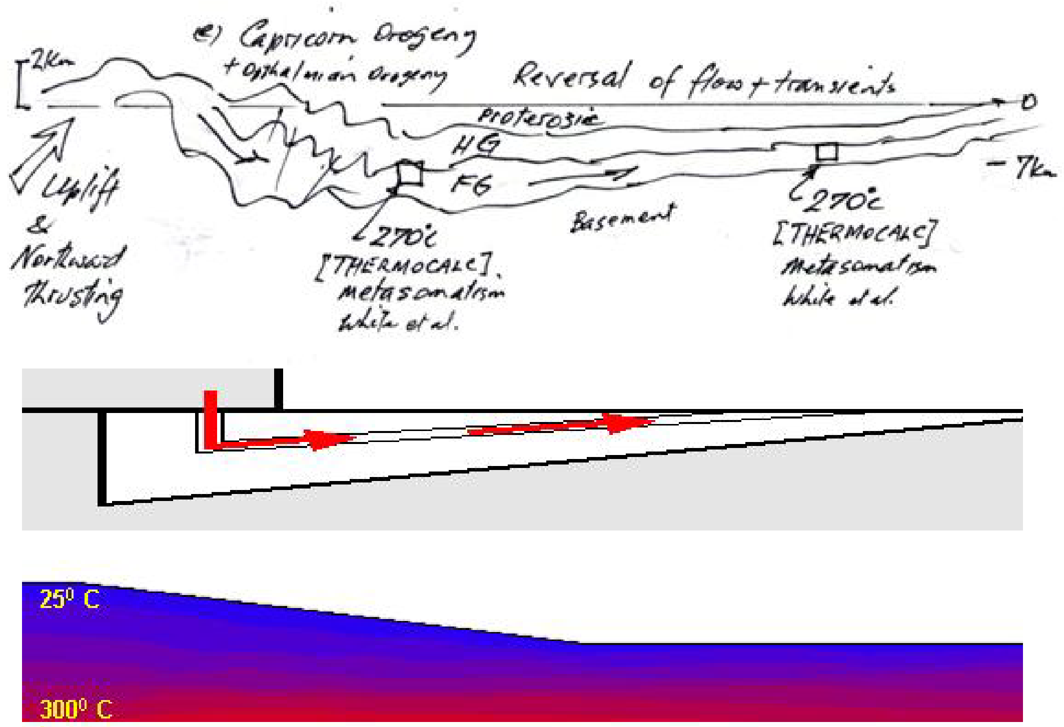

Two billion years of thermal evolution in the northern Gawler Craton, South Australia

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The Gawler Craton, South Austalia preserves a complex thermal evolution, from deep crustal levels to shallow crustal levels, over its ~2.5 Ga history. This includes numerous orogenic and magmatic events, along with the formation of world-class mineral deposits, such as Olympic Dam. Due to its complex and protracted tectonic history, the thermal evolution of the Gawler Craton is still poorly understood. In this study we present new apatite U/Pb (550 – 350 °C) and apatite fission track (AFT; 120 – 60 °C) data, in conjunction with new and previously published $^{40}Ar/^{39}Ar$ and (U-Th-Sm)/He data, to unravell the thermal evolution of the northern Gawler Craton.

Apatite U/Pb data preserves five distinct deep to mid-crustal cooling periods from 2.3 Ga to 1.3 Ga. The Sleaford, Cornian, Kimban, and Kararan Orogenies and Hiltaba Event are all recorded, in addition to younger ~1.3 Ga compression relating to the collision of the West Australian Craton and the South Australian Craton. In the Neoproterozoic and Phanerozoic cooling is predominanently restricted to upper crustal levels and is separated into two regions; the central and northern Gawler Craton, and the Olympic Domain. Regional cooling within the central and northern Gawler Craton is recorded by AFT data at ~600 Ma. The main phase of cooling in the northern Gawler Craton is interpreted to be southward thrusting of the Karari Shear Zone resulting from the southward compression by the Alice Springs Orogeny to the north of the Gawler Craton during the Carboniferous. This timing matches the break in sedimentation between termination of the Officer Basin and deposition of the Arckaringa Basin. A younger Triassic thermal perturbation is recorded by AFT data within the central Gawler Craton. Comparitively, AFT data from the Olympic Domain records regional cooling at ~1 Ga and at ~400-300 Ma, with a late Jurassic thermal event recorded near Olymic Dam. Spatially, the Olympic Domain data produces a NNW-SSE trending corridor of younger ages that aligns with major mineral deposits within the region. Overall, mid crustal cooling within the northern Gawler Craton is predominately caused by the Hiltaba event and Kararan Orogeny while upper crustal cooling is predominately caused by the Alice Springs Orogeny.

Episodic Gondwanide deformation in eastern Australia: The Hunter-Bowen Orogeny and Gympie Terrane in context

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The mechanisms that drove Permian – Triassic orogenesis in Australia and throughout the Cordilleran-type Gondwanan margin is a subject of debate. Here we present field-based results on the structural evolution of the Gympie Terrane (eastern Australia), with the aim of evaluating its possible role in triggering widespread orogenesis. We document several deformation events (D_1-D_3) in the Gympie Terrane, and show that the earliest deformation, D_1, occurred only during the final pulse of orogenesis (235-230 Ma) within the broader Gondwanide Orogeny. In addition, we found no evidence for a crustal suture, suggesting that accretion of the Gympie Terrane was not the main mechanism driving deformation. Rather, the similar spatio-temporal evolution of Permian – Triassic orogenic belts in Australia, Antarctica, South Africa, and South America suggest that the Gondwanide Orogeny was more likely linked to large-scale tectonic processes such as plate-reorganization. In the context of previous work, our results highlight a number of spatial and temporal variations in pulses of deformation in eastern Australia, suggesting that shorter cycles of deformation occurred at a regional scale within the broader episode of the Gondwanide Orogeny. Similarly to the Cenozoic evolution of the central and southern Andes, we suggest that plate coupling and orogenic cycles in the late Paleozoic to early Mesozoic Gondwanide Orogeny have resulted from the superposition of mechanisms acting at a range of scales, perhaps contributing to the observed variations in the intensity, timing, and duration of deformation phases within the orogenic belt.

Nested Sills from the Taoudeni Basin, Mauritania

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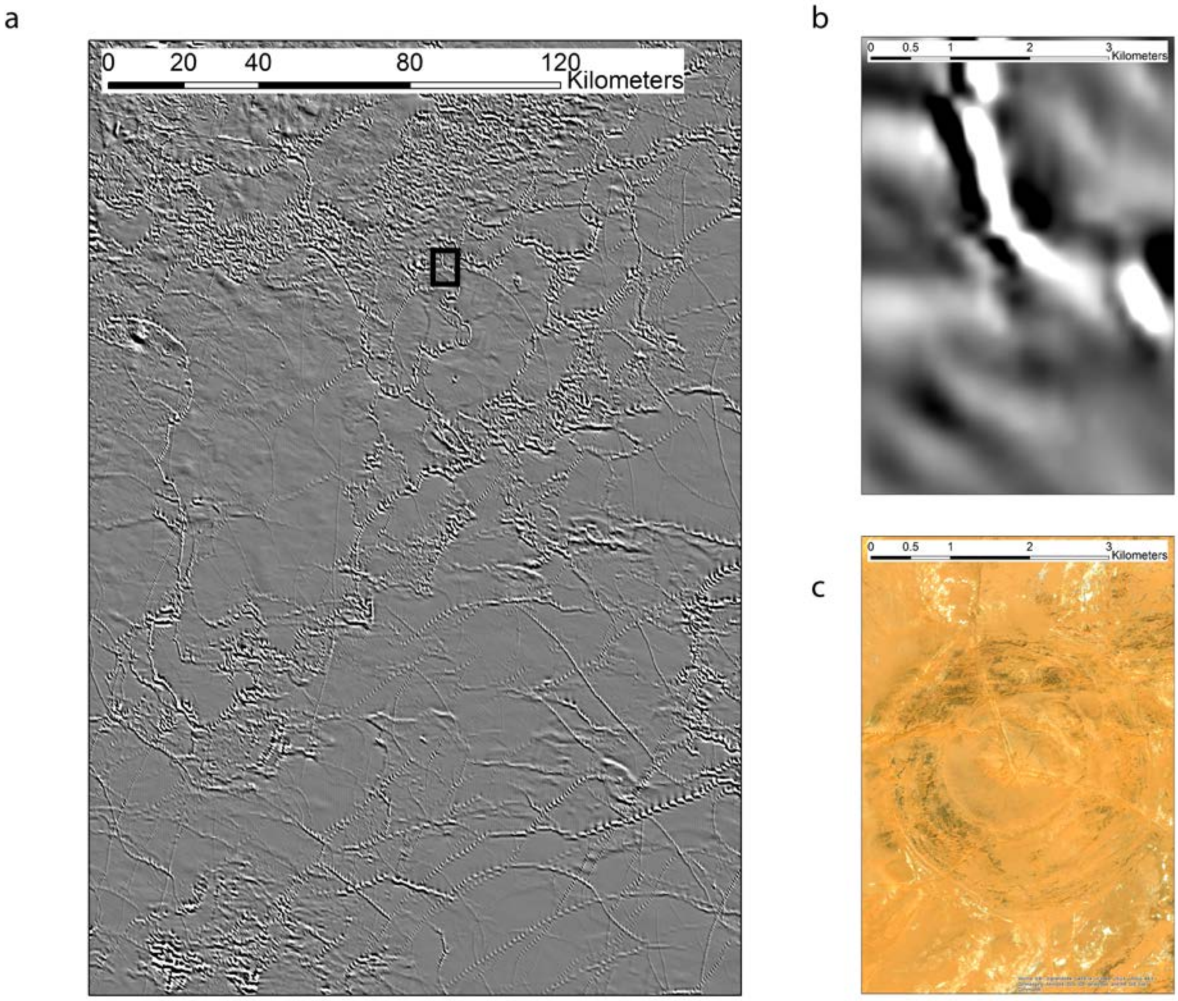
The airborne magnetic database for the northern Taoudeni Basin, Mauritania reveals a complex array of curvilinear magnetic features (Fig. a: magnetics RTP/1VD, showing inset location of b & c) that correlate with similar feature mapped by Verati et al. (2005) as a series of CAMP-aged (198 Ma) dykes and sills in nearby northern Mali. The use of high-resolution satellite data allows us to map out the intrusions which on the large scale formed interconnected arcuate patterns, but in detail are often following pre-existing fractures (Fig. b:magnetics & c: satellite). Based on the observed patterns and forward magnetic modelling of simplified shapes we believe that the curved dykes are in fact the upturned rims of saucer-shaped sills (Polteau et al., 2008). The sill's circumferential upturned rims would act as limits to sill propagation by lateral extrusion with further magma emplacement favouring sill thickening.



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Fragmentation, dissolution-precipitation and fluid-solid flow – the structured life of hydrothermal fault zones

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Silicified fault rocks typically show structures resulting from repeated stages of fragmentation, dissolution-precipitation of matter, and flow of fluid-solid suspension as well as silica gel. These processes interact episodically and result in complex structures on various scales. Based on field and microstructural data, the spatial-temporal connections between the different processes were investigated using the examples of the Pfahl Fault (Bavaria, Germany; Yilmaz et al., 2014), the Fountain Range Fault (Mt. Isa Inlier, Australia), and the Rusey Fault (Cornwall, UK).

All faults comprise an up to 100 m wide central compact quartz zone composed of various generations of quartz masses and veins. Despite differences in detail, similarities between structures, structure-forming processes, and the chronology of processes are obvious. (i) After a first phase of fragmentation, the wall rocks are replaced partly or completely by fine-grained quartz through dissolution and precipitation. (ii) Fragmentation and dissolution-precipitation cycles are repeated several times. During quartz crystallization larger subhedral quartz may replace previous generations of fine-grained quartz partly or totally. Quartz partly crystallizes from moganite, with probably previous presence of silica gel (Yilmaz et al., 2016). (iii) The first stages of fragmentation are followed by the formation of differently oriented sets of µm- to cm-thick quartz veins, mostly filled with blocky quartz but not necessarily of palisade structure. (iv) Again, fragmentation and dissolution-precipitation phases may follow. (v) Final sets of quartz-filled veins typically show geode structures. (v) During the stages of fragmentation, fluidized particle as well as particle silica-gel suspensions are temporarily present and form distinct flow structures.

All these structures point to (i) cyclicity of fragmentation and dissolution-precipitation processes, (ii) the dissolution and precipitation of large volumes of matter, and (iii) the presence of silica gel during certain stages of silicification during fault development. Material transport along large-scale hydrothermal fault zones is at least partly related to flow of highly mobile matter. This may cause weakness of fault zones and may have implications for rates of tectonic displacements.

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Non random strain heterogeneity, Wyangala Granite, Cowra, Eastern Lachlan Fold Belt

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The Silurian Wyangala Granite is a foliated, porphyritic, marginal S two mica- to mainly biotite granite intruded around 425 Ma, altered, then intruded by quartz-epidote veins and deformed from ~ 365 Ma (Lennox et al. 2014; 2016). Mapping at regional and local scale such as in the Wyangala Dam spillway (95% exposure, 200 by 400 m) indicates the presence of north-south trending, linear zones of more deformed granite. These zones themselves consist of heterogeneously deformed granite with highly strained elongated zones mixed up with lower strain sections. The lower strain sections furthermore contain mesoscopic shear bands or C structures on a centimetric scale. In rare cases there is a magmatic compositional hetereogeneity which does not control deformation hetereogeneity.

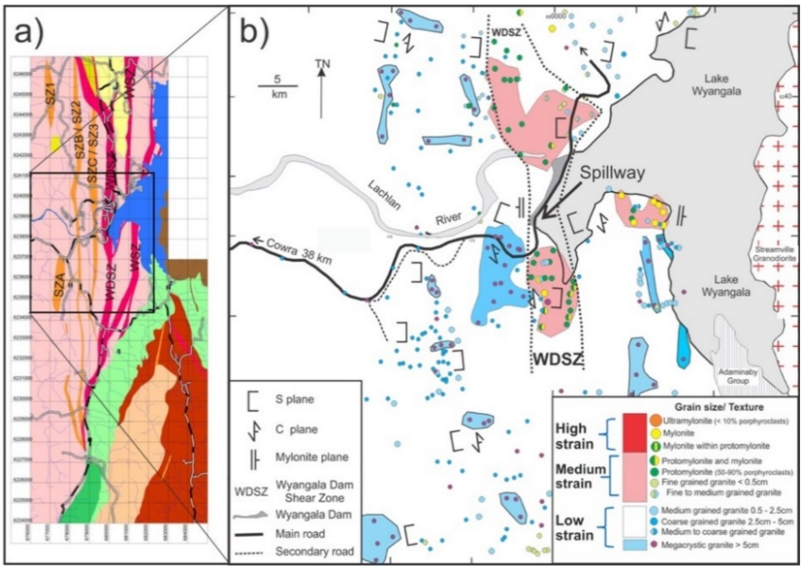

Fig. 1: a) Map showing the distribution of high- and low- strain shear zones (White 2005); b) the irregularly shaped low to high strain zones at a district scale after data from more field stations.

Original mapping of shear zones near the eastern margin of the Wyangala Granite was based on the grain size of K feldspar phenocrysts and the presence or absence of mylonite zones enabled definition of ~ 200 metre wide, kilometres-long, north-south linear strike-slip shear zones spaced 200 m to 1 km apart (Figure 1a). Reclassification of strain based on the presence or absence of S/C fabrics and mylonites provides a better criteria to separate low and high strain areas (Figure 1b). Densification of field stations resulted in the more linear zones across the district becoming rounded blobs and elongated rounded rectangular areas of higher or lower strain. This is in the context of theory and well exposed field outcrops which suggests shear zones should be elongated and not blobby.

Strain determination in the spillway based on the degree of mylonitisation has been supplemented by, and correlated with AMS studies, quartz aggregate shapes and enclave shapes to better map the strain hetereogeneity. Spacing appears to be clustered in a non-fractal manner due to different geological factors at the three different scales.

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Localisation of high strain and high temperature into the Chalba Shear Zone, Gascoyne Province

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The Chalba Shear Zone is a bounding structure between metamorphic zones in the Gascoyne Province, WA. A history of reworking, mantle-tapping potential, and occurrences of Mo-W, U and precious gems indicate that detailed structural, metamorphic and petrochronological analysis is required to constrain the evolution of the shear zone and localisation of mineralisation. Structural mapping, microstructural and petrological observations are constrained by simultaneously collected U-Pb dates and trace element compositions of monazite and xenotime, as well as P-T estimates using bulk-rock composition of sillimanite-bearing metapelite samples. Structural observation indicate progressive high strain deformation forming dominant dextral, strike-slip movement along a west-northwest to east-northeast ductile shear zone. Prismatic sillimanite pseudomorphs on andalusite indicate an increase in temperature to >640°C (3-4 kbars), fibrolite growth at ~600-640°C, and later retrogression of biotite and breakdown to ilmenite to temperatures below ~530°C. Metamorphic monazite and xenotime predate the main deformation, and their trace element compositions indicate that they grew during peak metamorphism forming sillimanite. Overall ages of 1030 Ma and 920 Ma link high temperature metamorphism to the 1030-950 Ma Edmundian Orogeny. Localisation of deformation and heat into large-scale structures like the Chalba Shear Zone has implications for the formation of high temperature magmatic deposits such as Cu-Au, Mo-W and gemstones, and remobilisation of earlier deposits.

Multifractal topography: a case study of structurally-controlled landforms across the Menderes Massif, western Turkey

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Geological structures exert a first-order control upon the evolution of topography. The Menderes region of western Turkey presents an ideal example, in which Miocene crustal extension, coupled with uplift and erosion, has exposed the Menderes Massif generating a prominent basin and range type topography. Normal and strike-slip faulting produced an east–west-striking horst and graben system that bounds the mountain ranges, controlling the dominant landforms. Using topography profiles extracted from SRTM data for the Menderes region, we investigate whether important insights into a region's structural evolution can be obtained from a detailed examination of the resulting topographic expressions.

Multifractal analysis is a well established and effective means of signal quantification that has expanded into the realms of geology and geophysics. The technique applies varying sizes of a wavelet (Figure 1a) to interrogate the signal dynamics over a range of length scales. This multiscale approach allows the signal to be decomposed into its component parts, including abrupt fluctuations referred to as *singularities*. The multifractal properties of the master signal are then quantified based on the diversity of fluctuation intensities present, and their frequencies of occurrence (their fractal dimensions). These multifractal measures are often complemented by Hurst exponent and recurrence analyses, which quantify the degree of signal predictability, and recurrence of behaviours, respectively.

In this study multifractal, Hurst exponent and recurrence plot analyses are carried out on four strategically-positioned arrays of parallel topographic profiles across the Menderes Massif (Figure 1b). Two sets of profiles are oriented east–west, parallel to the strike of the main grabens; two are north–south, perpendicular to strike. Key metrics from each of the analyses are used to construct 'multifractal cross-sections' (Figure 1c) to document variations in topographic behaviour across each of the arrays. The aim is to test whether variations in these signatures can be linked to the underlying structural and tectonic processes responsible for their development.

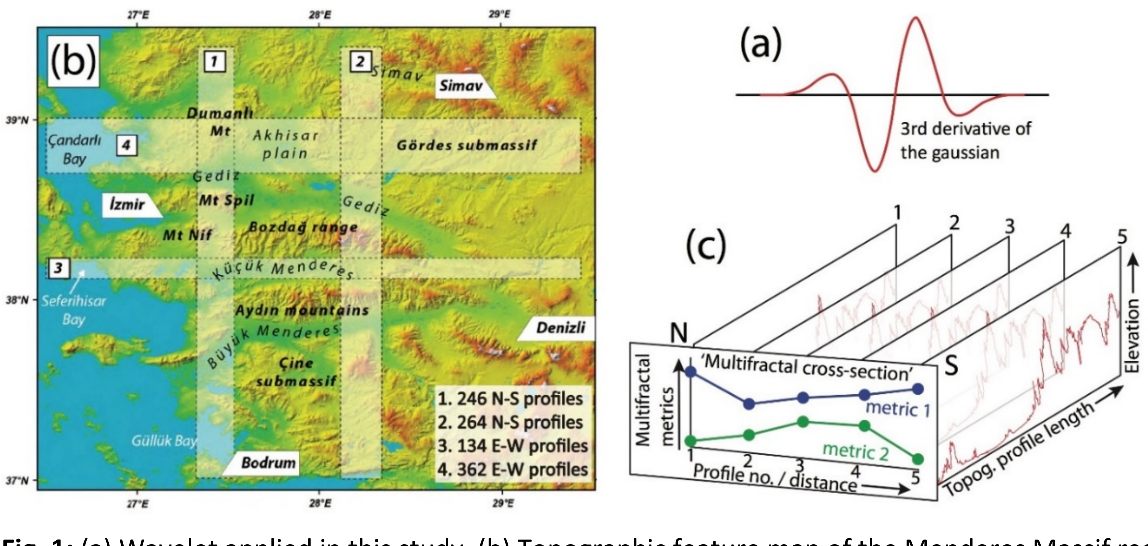

Fig. 1: (a) Wavelet applied in this study. (b) Topographic feature map of the Menderes Massif region showing the positions of the profile arrays used in the study and number of parallel profiles in each. (c) Schematic example 'cross-section' plot of changing multifractal metrics across one of the transect arrays.

3D structural model of the West Gawler Craton as constrained by seismic and gravity data

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A new 3D model of the western Gawler Craton has been constructed using constraints from the interpretation of the deep crustal seismic line 13GA-EG1 (Dutch, et al., 2015), a revision of deep crustal line 08GA-OM1 (Korsch et al., 2010) and extension of forward modelling of gravity data (Stewart and Betts 2010, van der Wielen et al., 2015). Forward modelling and inversion of the gravity data in 3D allowed projection of the features seen in the seismic profile into the volume between the two seismic lines and was also extended further south almost to the coastline.

The model was divided into domains as defined by mapped geology and into smaller blocks as defined by major structural lineaments. The physical properties of density and magnetic susceptibility were modelled to look at the consistency of properties across the domains and compared to adjacent domains. Differences in physical properties clearly show the difference in lithologies and metamorphic/intrusive histories of upper crustal domains overlying the Western Gawler Seismic Province compared to either of those overlying the Central Gawler Seismic Province or the Coompana Province. However, similarities between blocks within each domain support the current domain definitions.

In the middle crustal Wirinjinna and Karari seismic subdomains, differing physical properties indicate that they have either differing origins or have undergone differing tectonic histories, leaving unanswered questions and reflect the sparsity of geological constraint within these regions. At lower crustal levels, modelling indicated that the differing crustal blocks of the Western Gawler Seismic Province appear to have similar properties and hence is it proposed that the Craton is floored by a consistent and continuous layer.

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Death of an orogen, birth of a craton

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Orogens represent unstable portions of the Earth's crust that with repeated reworking become progressively strengthened and, ultimately, cratonized. Reactivated intraplate orogens typically display significant crustal thickening and vertical exhumation but this style may not apply to all intraplate orogens. The Proterozoic Capricorn Orogen, Western Australia, records a complex history of intraplate reworking and reactivation over about 1.5 billion years. Initial reworking at 1.8 Ga spanned the entire width of the orogen but subsequent reworking events affected progressively smaller areas with a final event at 1.03–0.90 Ga confined to a narrow corridor in the center of the orogen. This history of reworking was followed by a major episode of mainly dextral strike-slip reactivation of discrete faults and shear zones across the orogen. New $^{40}Ar/^{39}Ar$ geochronology of mica combined with *in situ* SHRIMP U–Pb geochronology of xenotime shows that orogen-wide reactivation of pre-existing crustal-scale structures occurred between 0.92 Ga and 0.86 Ga just as reworking came to an end. Reactivation involved lateral extrusion of Archean to Paleoproterozoic crust toward the west as it was squeezed out from between the Pilbara and Yilgarn cratons, most likely during north-south compression. We find no evidence for substantial crustal thickening during reactivation, and our findings do not support earlier suggestions of tectonic activity caused by collision with an unknown craton to the west. Our new data shows that orogenic activity was succeeded by a breakout reactivation event that marked cratonization of the orogen.

500 Ma of post-Mesoproterozoic intracontinental reactivation in the west Musgrave Province, Central Australia

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The Musgrave Province is a Mesoproterozoic orogen exposed at the junction between the North, West, and South Australian Cratons. The post-Mesoproterozoic reactivation of the province is currently attributed to the 580–520 Ma Petermann Orogeny. We use field mapping, deep seismic reflection data, and two approximately N–S transects of thermochronology samples, collected across the main structures, to demonstrate that intracontinental reactivation was long-lived and extended from the Neoproterozoic to the early Jurassic.

Ar–Ar thermochronology samples were collected along a transect that extends from the hinterland to the core of a post-Mesoproterozoic orogen and near the trace of the 11GA-YO1 (YOM) deep seismic reflection line. In the southernmost part of the hinterland, the development of the Talbot Sub-basin anticline and south-directed reverse faults was dated at c. 715 Ma by Ar–Ar on muscovite and U–Pb on titanite. The northern part of the hinterland (i.e. the Mitika area) records the development of a west-verging fold and thust system. The time of peak metamorphism is dated by U–Pb analyses of zircon overgrowths from garnet–kyanite schists at c. 630 Ma. This was followed by exhumation and cooling below 400 °C at c. 590 Ma. The lower-grade periphery of the Mitika area cooled below 400 °C at 623 ± 5 Ma to the south and 613 ± 2 Ma to the north. The gneissic core (i.e. the Wanarn area), is a regional-scale antiformal stack bounded to the south by the Mitika Fault and to the north by the Woodroffe Thrust that records the crystallization of pegmatite veins at 592 ± 6 Ma and 545 ± 39 Ma. The southern Wanarn area cooled below 300 °C at 584 ± 3 Ma, while the northern Wanarn area cooled below 550 °C at 589 ± 4 Ma and then below 400 °C at 567 ± 3 Ma. This suggests differential cooling of the Wanarn area during the development of the regional antiformal stack.

(U–Th)/He thermochronology samples were collected along a N–S transect that extends from the orogenic core into the foreland fold and thrust belt toward the north. While half of the (U–Th)/He dataset indicates cooling related to the 580–520 Ma Petermann Orogeny, the second half of the dataset shows that out-of-sequence thrusting and internal reactivation of the core of the orogen and of the fold and thrust belt postdates the Petermann Orogeny. In particular, the orogenic core cooled below 200°C between 480 and 400 Ma, indicating that the Woodroffe Thrust was still active at that time. A single but robust (U–Th)/He date on zircon shows that internal deformation of the fold and thrust belt occurred until 200 Ma with substantial exhumation along the Wankari detachment.

The west Musgrave Province records long-lasting, intracontinental reactivation that is not the sole result of the Petermann Orogeny. This multi-disciplinary approach allows constraining fault reactivation and fluid mobility during post-magmatic events and is applicable to help understanding the evolution of all circum-craton orogens of Western and Central Australia.

Stratigraphy and Architecture of the Paleoproterozoic Bryah and Padbury Basins, Capricorn Orogen: Towards an Understanding of Basin Evolution

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The Paleoproterozoic Bryah and Padbury Basins are located in the southeastern part of the Capricorn Orogen, which is currently the target of a major multi-institution and multidisciplinary research project - The Capricorn Distal Footprints Project. This project aims to understand the crustal evolution, tectonic processes, and mineralization systems of the Capricorn Orogen. In this context, magnetic and gravity data together with petrophysics, drill core logging, geological mapping, and 2D geophysical modelling were integrated aiming the characterization of the stratigraphy and architecture of the Bryah and Padbury Basins, and hence to better understand the basin evolution.

The Bryah Basin formed along the northern Yilgarn Craton margin due to extension and tectonic processes prior to the Glenburgh Orogeny. This lithospheric extension resulted in the deposition of sedimentary and magmatic rocks of the Bryah Group (c. 2030 to 2014 Ma), which has its bulk formed by the Narracoota Formation's magmatism. The Padbury Basin overlies the Bryah Group, and is formed by carbonate, siliciclastic and banded iron formation rocks of the Padbury Group (c. 2000-1890 Ma) deposited in a pro-foreland basin. Deposition in these basins ceased with the initiation of the Capricorn Orogeny at ca. 1820 Ma, which was responsible for the structural reworking of the basins, resulting in the reactivation of pre-existing faults, and the input of hydrothermal fluids that resulted in gold mineralization.

Different geophysical data and methods can be used to characterize volcano-sedimentary basins. The Bryah and Padbury Basins are characterized by long magnetics lineaments which are both easterly and northerly trending. However, only easterly trend features are exhibited in the gravity data, in a convex geometry (NW-SE/SW-NE trend). These are sub-parallel to structures related to the southern boundary of the basins (e.g. Goodin and Murchison Faults). Based on the magnetic data, fourteen magnetic domains are distinguished in the Bryah and Padbury Basins and surroundings terranes, while four main domains based on the Bouguer Anomaly are recognized. In the southern part of the basins, a regional positive gravity anomaly trending EW/NE-SW is coincident with mafic magmatism in the Narracoota Formation. This anomaly may be due to an approximately 5km thick package of higher density mafic rocks, and it can help to elucidate processes that occurred during the precursor rift of the early stages of the Bryah Basin. This anomaly is also particularly important to delineate contacts between magmatic rocks and the sedimentary fill, which can assist VMS exploration models. Additionally, observations made in drill holes at several localities in the basins provided a better understanding of the basins infill, subsurface lithologies and structural information, as well as the contact between the Archean basement and the sediments in the underlying Yerrida Group that was formed in a sag basin.

Proterozoic tectonothermal evolution of the northeastern Aileron Province, central Australia

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The Aileron Province in central Australia preserves a succession of Palaeoproterozoic metasedimentary and (meta-) igneous rocks at the southern margin of the North Australian Craton. The northeastern sector of the Aileron Province comprises a series of 500–1000 km^2 tectonic domains separated by a west-trending primary shear zone and associated northwest- and northeast-trending secondary fault zones that accommodated movement between these domains during Palaeoproterozoic metamorphism and deformation (Weisheit et al., 2017). New integrated field and monazite and zircon petrochronologic data for rocks from each domain indicate a single long-lasting regional tectonothermal cycle in the Palaeoproterozoic in areas previously interpreted to have experienced a series of short-lived events (e.g., Yambah and Strangways events).

Rocks in each of the studied domains experienced different degrees of metamorphism during the Palaeoproterozoic, with one group of domains preserving extensive migmatites and locally-derived granites, and another group of domains having experienced subsolidus metamorphism aided by the intrusion of externally-derived granites. Although each of the major domains had unique pressure–temperature–time evolutions, they each experienced the same three basic phases of a single tectonothermal cycle:

Metamorphism in all domains was initiated by intrusion of bimodal magmas into a back-arc basin sedimentary sequence during the period of ca. 1.79–1.77 Ga. Intrusion of these magmas heated rocks of the subsolidus domains to 540–640 °C at a pressure of ~0.3 GPa. In contrast, rocks of the migmatitic domains were at pressures up to 1.0 GPa during this initial pulse of magmatism, facilitating temperatures of up to ~920 °C necessary to cause partial melting. Partial melt generated in migmatitic domains was injected semi-continuously into the subsolidus domains between ca. 1.77–1.74 Ga. This long-lasting igneous activity provided an advective heat source necessary to keep the subsolidus domains at a high enough thermal gradient to maintain a long-lived metamorphic cycle.

All domains experienced an isothermal or near-isothermal change in pressure during the period ca. 1.77–1.73 Ga. The migmatitic domains experienced a decrease in pressure of about 0.6–0.2 GPa as they were exhumed to higher levels in the crust, whereas the subsolidus domains experienced an increase in pressure of about 0.1 GPa as they were taken to lower crustal levels. The relative movement of the domains to each other was accommodated by movement along the bounding shear zones (Weisheit et al., 2017).

All domains were at the same pressure of ~0.4 GPa by ca. 1.73–1.69 Ga, which marks the last recorded pressure in the domains. The interiors of the domains were at the same approximate relative crustal level and did not experience significant (>0.1 GPa) differential vertical movement with respect to each other after the Palaeoproterozoic. These data are interpreted to indicate a single tectonothermal cycle at the southern margin of the North Australian Craton that lasted between ca 1.79–1.69 Ga.

References

Weisheit, A. et al., 2017, SGTSG Abstract

Edible geology: a novel approach to teaching structural geology.

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Divising ways to demonstrate large scale phenomena, such as continental inversion, can be challenging for educators. Analogue models composed of quartz sands or various polymers have been utilised since 1815 and are excellent tools for use in the laboratory. They are, however, too cumbersom to utilise when teaching field trips. We have devised a food-based analogue experiment which can be taught in most environments and culminates in a delicious and educational meal. The experiment is student-centred and utilises reflective and collaborative learning experiences to demonstrate various structural regimes. The basic template for this session can be employed to suppliment most structural field trips and provides an avenue for demonstrating the evolution of large scale phenomena.

Ingredients: (sufficient for 4 experimental teams and, with the addition of a salad, dinner for 20 students)

- 1kg non-chunky salsa
- 20x burritos
- 1x large tub of chocolate paste
- 20x large pancakes
- Rulers, sketch books and pencils
- Sterile gloves (if you want to eat the resulting meal)
- Cheese, sour cream, jalapenos and ice cream optional

Method:

1. Pre-heat the oven to 200 degrees Celsius and bake the burritos until crisp (this step can be completed prior to the trip).
2. Stack half the burritos - brittle deformation.
3. Cover half the burritos with a thick layer of salsa* and stack - brittle deformation with rheology contrast.
4. Stack half the pancakes - ductile deformation.
5. Cover half the pancakes with a thick layer of chocolate paste and stack - ductile deformation with rheology contrast.
6. Deform!

*Trade salsa for melted cheese when modelling extensional systems.

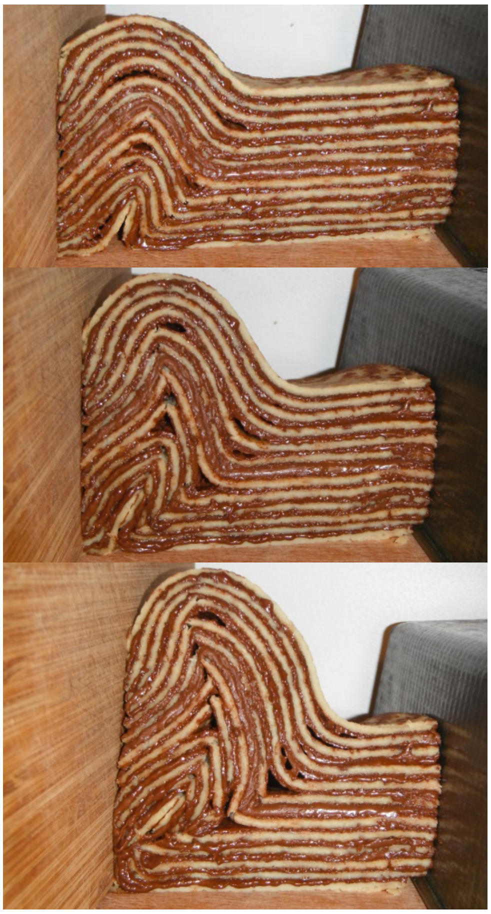

Figure 1: Pancakes are used to model the folded and faulted turbidites found at Cape Liptrap, VIC.

Students are encouraged to reflect on the structures seen in the field and to attempt to model them. They work in teams to assemble, manipulate and sketch the models as they progress through various deformation events. Students can measure the compression or extension ratio, offset on faults or the amplitude and wavelength of folding at various deformation stages. When the experiment is complete, add additional toppings and serve!

An assessment of the Strabo Field Geology Application during a postgraduate field course in Japan

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StraboSpot is a data system for the structural geology and tectonics community developed in the United States and funded by the National Science Foundation (Leads: Julie Newman (Texas A&M), Basil Tikoff (Wisconsin), Doug Walker (Kansas)). There are both field and desktop applications, and plans to incorporate microstructures, petrology, and sedimentology into the system. The field application (hereinafter 'the App') allows researchers to directly record primary data in the field, make basic maps, and share the data. The system is compatible with GIS systems.

During a postgraduate short course in Structural Geology and Tectonics of Hokkaido in June-July 2017, we installed and used the App on 2 iPads, 7 iPhones, and an Android device. A cellular network was accessible by 1 iPad, and 5 of the iPhones for 2 of the 4 field days. Other students used more traditional field methods, documenting observations in pencil in notebooks and on field maps.

We found our efficiency in documenting field relationships increased very quickly as we learned the App's capabilities. By the end of our second field day those using the App were able to document reconnaisance-level information at the same rate as those using notebooks. Time-consuming activities in the App include definition of a site of interest, and description of a geological unit. This could be overcome by voice or bluetooth keyboard input. Conversely, the App was more efficient than traditional field methods for acquisition of photographs, since it records the 'viewing direction', location, time, and explicitly links the photograph to the location, and for acquisition of structural measurements. Working with the data in the office should also be more efficient, because manual input should not required, but our inexperience meant our data recording methods were not optimised for subsequent electronic use.

StraboSpot has an 'In-App' compass and GPS, which rely on the inbuilt orientation and location services of the hosting device. To test the accuracy of these, we acquired duplicate location data using (i) the App's GPS, (ii) a GARMIN GPSMAP 62SCJ, and (iii) by locating ourselves with respect to landmarks on a topographic map, and duplicate structural orientation data using a number of different digital and analogue devices, including (i) StraboSpot App, (ii) Rick Allmendinger's Stereonet App, (iii) Silva compass-clinometers, (iv) Brunton compasses, (v) a KRANTZ brand compass. 8 total comparative location measurements and 91 total comparative structural orientation measurements were recorded on at least two of these devices.

Qualitatively, we observed surprising similarity between measurements taken by all the devices. For the most part these were within 5-10 degrees in both strike and dip. However, with both iPads, once we lost cellular data, StraboSpot strike measurements were discordant with those obtained by any other method – including the Stereonet App on the same device – by around 100 degrees of azimuth. This error was not recovered when cellular data coverage was restored. We will present statistical information about the angular deviation of the measurements by different devices in Denmark.

We were generally dissappointed by StraboSpot's ability to accurately determine our position. Even with cellular coverage, in a few cases the position it determined was around 500 m from the true location determined by examination of the base topographic map used in the device.

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Pearce

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