CCFS LITHOSPHERE DYNAMICS WORKSHOP

Program

	Speaker	Title
Monday 4th Nov		
8.00 - 8.50	Registration	
8.50 - 9.10	Campbell McCuaig (CET)	Introduction + welcome
9.10 - 9.30	Sue O'Reilly (CCFS)	Tackling the giant 4-D sudoku of the lithosphere
9.30 - 10.15	Brian Kennett (ANU)	Unveiling a continent: the nature of the Australian lithosphere from seismic methods
10.15 - 10.45	Morning break	
10.45 - 11.30	Alan Aitken (UWA)	The past, present and future of crustal structure modelling from potential field data
11.30 - 12.00	Discussion	
12.00 - 13.00	LUNCH	
13.00 - 13.45	Nathaniel Butterworth (University of Sydney)	Linking slab pull forces and lithospheric deformation through time
13.45 - 14.30	Juan Carlos Afonso (CCFS)	Thermochemical Tomography of the Lithosphere from multi-observable probabilistic inversions
14.30 - 15.00	Discussion	
15.00 - 15.30	Afternoon break	
15.30 - 17.00	POSTERS 2 min presentation followed by poster session	
17.00 - 19.00	Drinks and Nibbles	
Tuesday 5th Nov		
8.00 - 8.45	Franco Pirajno (GSWA/UWA)	Mantle-lithosphere interactions and their role in the making of mineral systems
8.45 - 9.30	Bill Griffin (CCFS)	Cratonic SCLM: What we think we know
9.30 - 10.15	Jon Hronsky (UWA)	Major translithospheric structures, their evolution and their relationship to major ore deposits
10.15 - 10.45	Morning break	
10.15 - 11.00	Graham Begg (CCFS)	Continents and mineralization processes: A Global Lithospheric Architecture Mapping (GLAM)
11.00 - 12.00	Discussion	
12.00 - 13.30	Lunch + POSTER SESSION	
13.30 - 14.15	Steve Reddy (Curtin University)	Modern margins and ancient analogues: Are ocean - continent transitions important to Precambrian tectonic interpretations?
14.15 - 15.00	Martin Hand (University of Adelaide)	Deformation in central Australia: a natural laboratory to explore the drivers for large scale intraplate strain localisation
15.00 - 15.30	Discussion	
15.30 - 16.00	Afternoon break	
16.00 - 16.45	Tracy Rushmer (CCFS)	Understanding Dynamic Earth: Insights from Experimental Laboratory
16.45 – 17.00	Discussion	

This workshop has been made possible through generous support of the following sponsors

CCFS LITHOSPHERE DYNAMICS WORKSHOP

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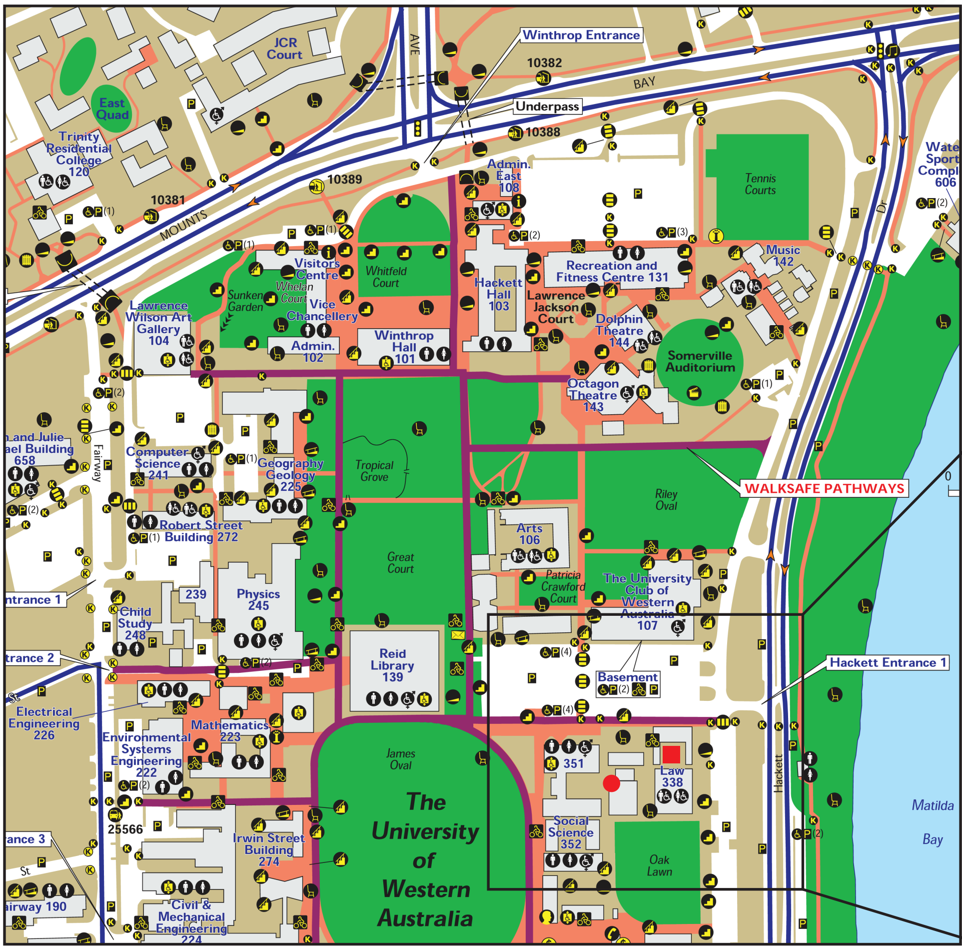
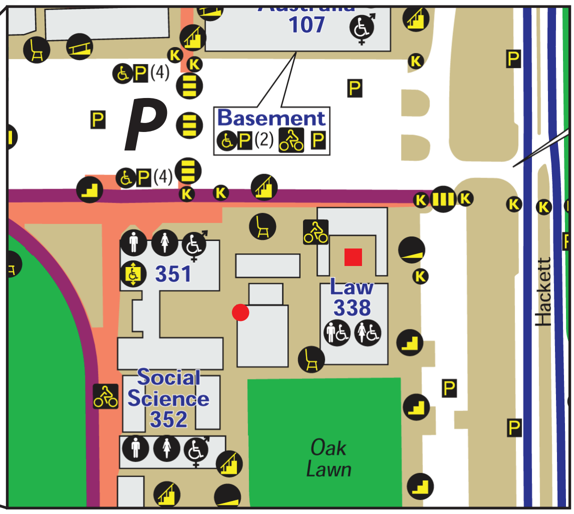
Wednesday 6th Nov

8.00 - 8.45	Giampiero Iaffaldano (ANU)	Observational constraints on global quantitative models of the coupled plates/mantle system
8.45 - 9.30	Fabio Capitanio (Monash University)	Subduction zones modelling: exploring the link between plate tectonics and mantle convection
9.30 - 10.15	Patrice Rey (Sydney Uni)	Hot continental tectonics: Deformation, flow, stress and strain
10.15 - 10.45	Morning break	
10.45 - 11.30	Discussion	
11.30 - 12.15	Sandy Cruden (Monash University)	3-D laboratory modelling of lithosphere dynamics: from earthquake surface rupture patterns to crust-mantle interaction
12.15 - 12.30	Discussion	
12.30 - 13.30	Lunch	
13.30 - 14.30	Poster session	
14.30 - 15.00	Campbell McCuaig (CET)	Wrap up and final remarks





LOCATION

Registration will be held at:
Moot Court

Lectures will be held at:
Social Sciences Lecture Theatre (Ground Floor Room G130)

P paid parking

This workshop has been made possible through generous support of the following sponsors

Geoconferences (WA) Inc.
Curtin University
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Macquarie University
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POSTERS

SPEAKERS ABSTRACTS

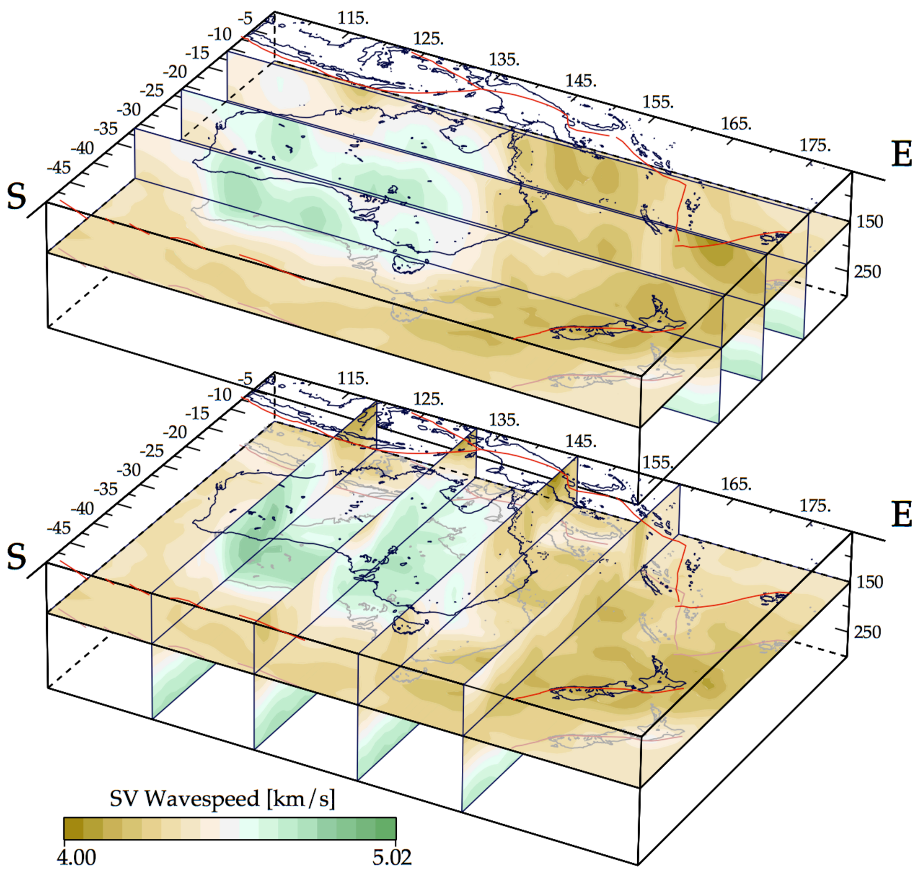
Unveiling a Continent: the nature of the Australian Lithosphere from seismic methods

B.L.N. Kennett

(Research School of Earth Sciences, The Australian National University, Canberra ACT 0200, Australia)

The favourable distribution of earthquake belts to the north and east of Australia has allowed high quality surface wave tomography to map out the larger scale variations in shear wave speed variation. At the crustal scale a sustained program of reflection profiling by Geoscience Australia in association with the State Surveys has provided detailed information on areas of potential economic importance. Receiver function studies at portable and permanent stations provide insight into crustal and uppermost mantle conditions. The broad-scale deployment of portable instruments has allowed the exploitation of seismic noise correlation methods to extract information on higher frequency surface waves and thereby image the crustal structure. Analysis of broadband seismograms from regional events exploiting both body wave and surface wave arrivals provides information on the structure in the mantle. Surface wave tomography exploiting the matching of observed and synthetic waveforms provides detailed coverage for the continent and its surroundings.

The many different seismological methods and analyses provide complementary viewpoints on structure in the crust and mantle components of the lithosphere. As a result we are close to being able to map out the 3-D variations in the full lithosphere at larger scales across the whole continent, and in some detail in the southeast.



All of the information gathered so far in the many strands of work has been brought together in the AuSREM project, a fully interpolable seismological model of the Australian continent with a 0.5-degree resolution down to 300 km depth. The crustal component consists of a detailed crustal model of P-wave speed, S-wave speed, density and depth to major boundaries such as the depth to basement and the recently completed representation of the depth to Moho. The mantle component of the model is less detailed but includes P-wave speed, S-wave speed and density. A challenge remains to provide a satisfactory representation for the Lithosphere-Asthenosphere boundary.

The past, present and future of crustal structure modelling using potential field data.

A.R.A. Aitken

(Centre for Exploration Targeting)

Gravity and magnetic data (potential field data) yield valuable information about the lithosphere, including delineating major crustal elements, resolving the location and geometries of major faults, defining crustal interfaces including basins and the Moho and understanding geodynamic states of the lithosphere (e.g. thermally driven uplift). The key virtue of these data is that they are relatively easy and cheap to collect on the ground and from satellites and so they typically have much better coverage than other geophysical data types. The key limitation is that they carry no inherent depth information except the weak constraint formed by the wavelength content in the signal – which provides only a maximum depth constraint. Thus inferences about crustal structure at depth are inherently uncertain, and some other element must be included in modelling to achieve a meaningful result. Approaches to this problem essentially can be grouped into four main philosophies: Deterministic modelling, probabilistic modelling, structural-tectonic modelling and process-oriented modelling.

Deterministic modelling, implemented in many inversion routines, and exemplified by the UBC-GIF approach, essentially relies on the data to derive a property distribution, plus usually a few simple rules regarding model smoothness and depth-sensitivity. This approach works well for structurally simple, high amplitude anomalies, but breaks down under more complicated conditions.

The probabilistic approach essentially relies on the generation of stochastic pseudo-random changes to the model volume conforming to a petrophysical model, and subject to a data-fit criterion. This approach works well where the probability density function of the crustal volume of interest is known well and can be implemented in the software (often limited to isotropic Gaussian distributions). In addition to these potential limitations, there are often problems with “speckle” where the data are an insufficiently strong constraint, and also in the distribution of results in areas of low-sensitivity – which often harbor the more inconvenient parts of the PDF.

The structural-tectonic approach relies on a solid geological understanding to define a-priori crustal structure, which can then be modified to suit the potential field data. This method has worked well in settings where geology is quite well known, and where subtle, yet distinctive, potential field signals are present. Most commonly, a forward-modelling approach is used, however this suffers from being labour intensive, hard to replicate, ill-suited to robust uncertainty analysis, and prone to human bias and error. Lithostratigraphic inversions that can contain complicated geological information are currently very popular, although this complexity and the addition of unknowns to the model increase model uncertainty significantly.

Process-oriented modelling relies on the (usually) gravity field being considered the result of some tectonic process that can be understood and modelled. This works well where one process is clearly dominant in the - e.g. lithospheric flexure for foreland basins, thermally driven lithospheric attenuation and crustal stretching for rifts. This approach typically fails in more complicated environments where several non-complementary processes (or superimposed processes from different times) are present.

Research opportunities for all philosophies exist to achieve larger, higher resolution models more efficiently. For the more direct deterministic and probabilistic approaches, robust joint inversion is a key goal. More geologically relevant and more versatile regularisation methods that accommodate, for example, structurally anisotropic properties, and skewed, logarithmic and bimodal property distributions are necessary. Better capturing of model uncertainty is a particular problem of the deterministic approach. In the structural-tectonic methods research opportunities exist in developing a better understanding of the influences of both categorical and quantitative uncertainty in input models as well as better characterisation of model variability under inversion, given the extra degree of freedom. Process-oriented modelling has the outstanding research opportunity to include potential field data as an active constraint on increasingly detailed and realistic numerical modelling that can be undertaken. This would largely supersede current approaches.

Linking slab pull forces and lithospheric deformation through time

Nathaniel Butterworth

(EarthByte Research Group, School of Geosciences
The University of Sydney, Australia)

Large tectonic plates are known to be susceptible to internal deformation, leading to a range of phenomena including intraplate volcanism. However, the space and time dependence of intraplate deformation and its relationship with changing plate boundary configurations, subducting slab geometries, and absolute plate motion is poorly understood. We utilise the plate reconstruction software, GPlates, along with lithospheric thicknesses derived from paleo-age grids, to build time-dependent 3D plate representations for use in subduction driven geodynamic models. We are able to produce a series of geodynamic models through time in which the plates are driven only by the attached subducting slabs and mantle drag/suction forces. We investigate the contribution of subducting slabs through time on plate motion and subsequent plate-scale deformation, and how this is linked to intraplate volcanism. These models have implications for comparing intraplate deformation history with those types of intraplate volcanism that lack a clear age progression and are not related to plume/hotspot volcanic products. Modeling suggests that changes in subduction zone topology may cause intraplate deformation to trigger volcanism along linear seafloor structures, mostly by reactivation of existing seamount chains, but occasionally creating new volcanic chains on crust weakened by fracture zones and extinct ridges.

Thermochemical Tomography of the Lithosphere from multi-observable probabilistic inversions

Juan Carlos Afonso

(ARC Centre of Excellence for Core to Crust Fluid Systems and GEMOC,
Dept. of Earth and Planetary Sciences,
Macquarie University, NSW 2109)

A detailed knowledge of the present-day thermal and compositional structure of the lithosphere and sublithospheric upper mantle is an essential prerequisite to understanding the formation, deformation and destruction of continents, the physical and chemical interactions between the lithosphere and the convective sublithospheric upper mantle, the long-term stability of ancient lithosphere, and the evolution of surface topography. Unfortunately, a holistic and detailed thermochemical characterisation of the lithosphere-asthenosphere system remains a technically and conceptually challenging problem. In this talk, I will discuss recent advancements in thermodynamically-constrained multi-observable probabilistic inversions, which have the potential to overcome some of the problems affecting other inversions schemes and provide realistic estimates of the present-day thermochemical structure of the lithosphere and upper mantle.
I will present results for both synthetic and real case studies, which serve to highlight the advantages and limitations of our approach compared to others. I will also discuss future work towards the application of this technique to the Australian continent and the incorporation of such an approach into global thermo-mechanical simulations/inversions to study the intricate connections between the thermochemical structure of the upper mantle and the evolution of plates.

Mantle-lithosphere interactions and their role in the making of mineral systems

Franco Pirajno
Geological Survey of Western Australia; Centre for Exploration Targeting, University of Western Australia

Intraplate tectono-thermal events are explained by mantle-lithosphere dynamics, which call on mantle plumes, or lithospheric delamination, slab roll-back in back arc settings, on the concept of stagnant subduction slab and of hot translithospheric strike-slip fault zones. These are summarised in the bullet points below:

- Mantle plume (deep); from Core Mantle Boundary (CMB)
- asthenospheric upwellings (lithosphere extension and delamination);
- slab break-off and asthenospheric upwelling;
- Flat subduction slab;
- "Hot" trans-lithospheric strike-slip faults

All of these phenomena generate melts, formed within the rising mantle plume, or in a convecting asthenosphere upwelling, all of which impinge on the sub-continental mantle lithosphere (SCML), inducing doming of the crust and rifting. In the SCML, variable degrees of contamination or metasomatism, due either to entrained subduction components or to migration of alkaline fluids and volatiles (e.g CO_2, H_2O) from the mantle, result in the generation of a range of magmas including, *inter alia*, alkaline and peralkaline igneous complexes, kimberlites, lamproites and carbonatites.

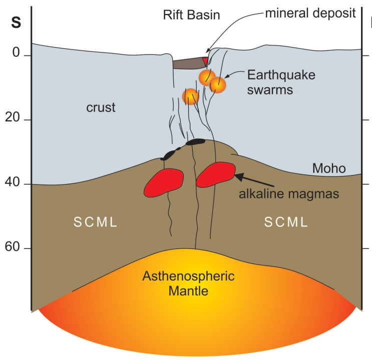
Impingement of mantle plumes is the favoured mechanism that could account for the generation and rise of asthenospheric liquids through rifts and crustal fractures. There is evidence that the source of continental rift alkaline magmas is metasomatised lithospheric mantle. Large quantities of CO_2, F and Cl are emitted from modern rifts, suggesting that continental rifts are the sites of upwelling asthenospheric melts rich in Cl, F, C, P etc. These melts penetrate the lithosphere, metasomatising it and causing further partial melting and developing thermal anomalies. This phenomenon of mantle degassing and metasomatism may also explain the origin of kimberlites and lamproites, which may be carriers of diamonds. It is probably for this reason that numerous breccia pipes, the expression of catastrophic volatile exsolution, are associated with alkaline magmatism.

Alternative views that explain particular aspects of intraplate magmatism include upwelling of asthenospheric melts or shallow mantle plume, during extensional processes commonly resulting from delamination of the lithosphere or from slab roll back or breakoff. Evidence from high resolution seismic tomography shows that diffuse igneous provinces, dominated by alkaline chemistry, form as a result of asthenospheric upwelling due to lithospheric mantle and lower crustal delamination and/or slab breakoff. Lithospheric delamination and/or slab roll back, are specifically linked to a different kind of intraplate magmatism, which typically extend discontinuously over vast areas, as in the case of Late Mesozoic to Quaternary intraplate volcanic fields of eastern Australia and the volcanic fields of eastern China, Mongolia and the Baikal region.

Mineral systems that are associated with large igneous provinces related to upwelling mantle plumes include magmatic Ni-Cu-PGE in mafic-ultramafic intrusions, epithermal systems, breccia pipes, polymetallic hydrothermal veins, granitoid-related greisen and rare earth pegmatites, as well as carbonatite and kimberlite fields. In the Altai-Sayan (Siberia) and NW China regions, for example, orogen-scale translithospheric strike-slip faults provided the channels for the emplacement of magmas, resulting from lateral flow of mantle melts along the base of the lithosphere. Lateral flow from mantle plumes head was sustained or facilitated, during stages of extension and movements along the orogen-scale strike-slip faults (pull-part basins). Flow of mantle melts into translithospheric strike-slip structures also caused partial melting of a thinned and metasomatised lithosphere, resulting in alkaline magmatic products and a wide range of related mineral systems, from polymetallic veins to greisens to alkaline systems. Partial melting of the lower crust can also produce A-type granitic magmas that may locally vent to the surface, forming calderas hosting epithermal and porphyry systems.

In Western Australia, the west-northwest trending Ti Tree shear zone, on the southern margin of the 1820-1775 Ma Minnie Creek batholith in the Gascoyne Province is characterised by a penetrative foliation, which is almost pervasively overprinted by a quartz-sericite±chlorite alteration assemblage. Along this shear zone are calc-silicate rocks in places cut by tourmaline veins and quartz stockworks, locally with scheelite mineralisation. Further to the west-northwest within the same corridor defined by the Ti Tree Shear Zone are Mo(Cu-W) and Cu-Pb-Mo occurrences and 950 Ma Be-Nb- and Ta-rich pegmatites. Field relations and age dating of all these prospects strongly suggest that they are not part of the hosting Minnie Creek batholith, but were emplaced much later. This idea is supported by recent apatite dating of the Gifford Creek ferrocarbonatites yielding a 1075 Ma age (Pirajno et al., in prep.) and spatially associated with the Lyons River Fault that runs parallel to the Ti Tree shear zone. The 1075 Ma of the carbonatites is coincident with the age of the 1.2 x 10^6 km^2 Warakurna LIP. Therefore, it is possible that the 1075 MaWarakurna event and related mantle plume activity affected the Gascoyne Province by lateral flow, which was mainly channelled along trans-crustal lithospheric boundaries, such as the Ti Tree and Lyons River shear zones, from the Musgrave Province "hot spot".

The combination of lateral mantle plume flow and subsequent upwellings into translithospheric structures, earthquake swarms along strike-slip faults, and pulses of magmas and fluids are ultimately responsible for the emplacement of intraplate alkaline complexes. Repeated pulses of fluids released during seismogenic activity are one of the important causes of protracted hydrothermal fluid migration and the formation and/or re-working of related mineral systems.



Modified from Vauchez and Tommasi, 2003. Geol Soc, London, Sp Publ

Major translithospheric structures, their evolution and their relationship to major ore deposits

Jon Hronsky

(Centre for Exploration Targeting and Western Mining Services)

It has long been known in the mineral exploration industry that the most fundamental and robust concept in regional targeting is an empirical relationship between major deposits and large-scale structures. These ideas had entered the literature by the 1930s and were strongly developed in the post-war decades by industry geologists such as E.S.T. ("Tim") O'Driscoll, whose work directly contributed to the discovery of the giant Olympic Dam deposit in 1975. Despite this however, during the last few decades of the 20th Century this topic was essentially neglected by the mainstream economic geology community which at that time was strongly focused on geochemical modelling of ore-formation at the deposit scale. Many in the community felt that the empirical relationships observed by O'Driscoll and others were perhaps spurious and also that they were difficult to reconcile with the new plate tectonic paradigm. That these postulated ore-controlling structures typically manifested as complex patterns of structural discontinuities rather than obvious mappable structures at the surface, and hence were often only recognisable as "lineaments", created further doubt in the minds of many. However, the explosion in availability of regional to continental scale geophysical imaging that began in the early 1990s made it unequivocal that such structures did exist and did correlate with major ore deposits. Therefore understanding the nature and evolution of these features and their precise relationship to ore-formation has become one of the most important scientific questions in the field of economic geology.

An integrated synthesis is presented here that is based on the author's experience of many regional-scale metallogenic targeting studies and has been heavily influenced by the work of Graham Begg's GLAM project and research carried out by the GEMOC group at Macquarie University (now CCFS). This synthesis is strongly oriented towards understanding the features most important for predictive targeting. The set of structures that control ore-emplacement are referred to here as "master conduits".

Master conduits represent translithospheric features, providing effective channels for ore-related magmas and fluids from the mantle to be emplaced into the upper crust, or for fluids from the hydrosphere to be circulated to depth and back again. Master Conduits are relatively steep-dipping to vertical; they are never regional-scale flat-dipping thrusts and extensional shear zones, although these are some of the most important structures in orogens. This is interpreted to reflect the importance of these structures accessing the steepest possible fluid-pressure gradients. For this reason, these structures tend to have linear traces in plan, distinct from the curvilinear patterns of many other major structures. Apart from simply providing channels for magmas and fluids, the fertility of these structures may also relate to their localisation of mantle upwellings and related magmatism if they represent the boundaries of relatively thicker volumes of lithosphere or zones of slab-tear (when they are behaving as transforms).

These structures have a very long-lived, multiply-reactivated history. Wherever the available data allow, it can usually be demonstrated that these structures originally related to boundaries between lithospheric domains during the previous orogenic cycle. They must represent zones of fundamental weakness in the lithospheric mantle (probably because they are continually rehydrated) and consequently are readily reactivated in an appropriate stress field. This means that these structures are vertically accretive; ie they grow upward over time, propagating up through younger rock sequences. This explains why they commonly manifest as lineaments. The recent recognition that continental extension commonly decouples crust from underlying lithospheric mantle provides a mechanism for the lateral propagation of ancient structures into domains with much younger crust. Although long-lived, master conduits will only be metallogenically active if they are favourably oriented for movement in the prevailing regional stress field. This is because permeability requires active fracture creation. This concept is very important in increasing targeting resolution by helping predict which sub-set of the network of these master conduits will be fertile during a particular metallogenic event.

These master conduits may occur within the context of larger scale lithospheric domain boundaries. For example the Boulder Lefroy fault, a good example of one of these structures, occurs within and associated with a larger-scale entity imaged by isotopic data – the eastern margin of the Youanmi Craton.

Many important questions remain to be answered about these master conduit structures. Do they originally all represent heterogeneities that can be traced back to the earliest period of lithosphere formation? How do they propagate from the lithospheric mantle into the upper crust, and in particular how do they manifest in the lower crust, which is expected to be more ductile? Is there a critical dip that is required? Do they have a consistent internal architecture that is relevant to ore formation? Better 3D crustal imaging and higher resolution Sm-Nd and Lu-Hf isotopic data are keys to resolving these questions in the future.

One particular, larger-scale aspect of this topic requires further consideration. The most controversial concept advocated by the late Tim O'Driscoll was that major structural discontinuities, which empirically related to the distribution of major ore and petroleum deposits, could be traced around the globe. This idea appeared to be in obvious violation of the tenets of plate tectonics so was naturally dismissed by the community. However recent advances in fluid dynamics and in particular their application to oceanography suggest that these ideas need to be reconsidered. Recently the concept of *Lagrangian Coherent Structures* has been developed. Lagrangian Coherent Structures are emergent features that arise in complex fluid flow which impart an organisation to this fluid flow. They have been described as the "skeleton of fluid flows" and most prominently recently used to explain why the Deep Horizon Gulf of Mexico oil spill did not end up contaminating the beaches of Florida. If we consider the convecting mantle as a fluid, it is perhaps reasonable to expect that it may also contain such Lagrangian Coherent Structures that in this instance produce patterns of organisation that control plate motions. Is it possible that Tim O'Driscoll's "Tethyan Twists" represent such structures? If Lagrangian Coherent Structures do exist in the mantle, defining them will not just be important for mineral exploration but might also help constrain paleo plate-tectonic reconstructions.

Continents and mineralisation processes: The Global Lithospheric Architecture Mapping (GLAM) perspective

G. C. Begg[1,2], W.L. Griffin[1], Suzanne Y. O'Reilly[1], J. M.A. Hronsky[1,3]

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[2]Minerals Targeting Intl., 17 Prowse St., W. Perth, WA 6005, Australia
[3]Western Mining Services (Aust.) Pty Ltd, 17 Prowse Street, W. Perth, WA 6005, Australia

Ore deposits represent the outcome of the conjunction of a series of factors that result in economic accumulations of the commodity in question. Such factors include tectonic processes, melting processes, fluid and metal transport mechanisms, and metal accumulation processes. A commodity-fertile source region is generally an important starting ingredient. This may be convecting mantle (e.g. Ni, Cu), metasomatised lithospheric mantle (e.g. Au, diamonds), lower crust rich in incompatible elements (e.g. Sn, W, U), or upper crustal rocks amenable to metal leaching by oxidised fluids (e.g. Cu, Pb, Zn, U). All of these aspects require a physical framework that is supplied by the interaction of geodynamics and continents. More specifically, by the interplay of global dynamics (mantle convection, mantle plumes, plate tectonics) and the sub-continental lithospheric mantle (SCLM).

Economic geologists have a solid understanding of the tectonic & lithospheric settings in which particular types & styles of ore deposits are formed. These associations include:- intracratonic diamondiferous kimberlites; craton margin mafic-hosted Ni-Cu-PGE; pericratonic basin-hosted ultramafic Ni-Cu-PGE; craton flank-hosted layered intrusion (PGE, Fe-Ti-V); magmatic arc-related porphyry & epithermal metal (Cu-Mo-Ag-Au, Cu-Au, Sn-W, Au-Ag); oceanic back-arc VHMS (Cu-Zn-Pb-Au-Ag); inverted (pericontinental) rift back-arc orogenic (Au); continental retroarc porphyry, epithermal & iron oxide (Cu-Au-Mo, Au-Ag-Te); intracontinental basin sediment-hosted base metal (Ag-Pb-Zn, Cu-Co), active foreland MVT (Pb-Zn), continental basin (U); continental shelf BIF (Fe).

Our interpretation of multidisciplinary geoscientific data over a period of 10 years, coupled with geochronological (e.g. U-Pb on zircons) and isotopic investigations (Re-Os on SCLM mantle sulphides, Lu-Hf on zircons), indicate that approximately 70% or more of today's continental lithosphere formed between ca 3.6-3.0 Ga. It was the appearance of this bouyant, physically durable, highly viscous SCLM that forced a re-organisation of plate tectonics to look much like we see in the modern Earth. The subsequent interaction of global dynamics with the SCLM facilitated the appearance of the above tectonic & lithospheric settings, favored development and preservation of many of the aforementioned source regions, and triggered ore formation in discrete episodes. None of the resultant deposits are preserved through tectonic cycles unless they reside over SCLM, with those in intracontinental settings particularly favored. In contrast, the relatively dense oceanic lithospheric mantle is easily removed (subducted, delaminated) and associated deposits destroyed.

The absence of significant mineral deposits older than about 3Ga is attributed to either of a failure to survive due to reworking (melting, thickening, thinning, erosion) of the crust, or to the absence of a key ore-forming factor. Plate tectonics (forces, fluids, magmas) has resulted in metasomatism, fracturing, melting and suturing of the SCLM. These processes, along with the impact of mantle plumes and the rise of atmospheric oxygen, have provided the metals, energy and focus for ore systems in a range of associated crustal environments.

Cratonic SCLM: What we think we know

W.L. Griffin and Suzanne Y. O'Reilly

(ARC Centre of Excellence for Core to Crust Fluid Systems and GEMOC,
Dept. of Earth and Planetary Sciences,
Macquarie University, NSW 2109)

Data sources for composition and structure:

(1) Xenoliths in kimberlites, some lamproites
(2) Garnet concentrates from diamond exploration and kimberlites (O'Reilly and Griffin, 2006)
(3) Inclusions in diamonds
(4) Exhumed ultramafic massifs

Data sources for ages: Whole-rock Re-Os model ages, sulfide/alloy Os model ages, inferences from seismic tomography interpretation.

Limitations:

(1) Uneven and unrepresentative sampling – kimberlites and other magmas sample weak zones variably affected by metasomatic modification
(2) Most work has been done on garnet-bearing peridotites, or garnet concentrates of peridotite facies – because they can be located spatially (depth, temperature)
(3) Scarcity of studies on garnet-free rocks from depths 100-50 km
(4) Some cratons (e.g. Yilgarn) have few kimberlites or other mantle-derived magmas, so no samples of lithospheric mantle (SCLM) domains
(5) Garnet-based techniques are by definition sampling only the metasomatised parts of the section – and it can be hard to evaluate the proportional contribution.

Lithospheric mantle (SCLM) Profiles: What we can see

(1) Most cratonic roots are 150-250 km thick, made up mainly of originally highly-depleted peridotites (dunites and harzburgites), variably refertilised to garnet harzburgites, lherzolites and a variety of pyroxenitic rocks.
(2) Metasomatism tends to be concentrated in zones around 100-120 km, and near the Lithosphere-Asthenosphere Boundary (LAB; O'Reilly and Griffin, 2010)
(3) Mafic rocks (e.g. eclogites) tend to concentrate near the LAB, making up limited zones that may be about 50/50 peridotite/eclogite. These zones also are a focus of metasomatism, affecting both peridotites and eclogites
(4) Metasomatism, including the precipitation of diamonds, was ongoing at the time of kimberlite eruption in most cases.
(5) The shallow SCLM is dominated by extremely depleted harzburgites (chromite-bearing) and dunites, which are much less metasomatized than the deeper SCLM. Consequently they are Mg-rich, and have a relatively low density and high seismic velocity.

(6) Archean SCLM peridotites are significantly Fe-depleted compared with (and compositionally distinct from) younger lithospheric peridotites, such as oceanic lithosphere, at any degree of depletion and any tectonic setting.
(7) Original Archean SCLM makes up at least 70% of existing SCLM.

SCLM Ages: What we can measure

(1) Os model ages for peridotite xenoliths (whole-rocks and low-Re sulfides) peak at 2.9-3.0 Ga; although these are minimum metasomatic ages, there is no evidence for the existence of SCLM prior to 3.5 Ga.
(2) Os model ages extend up through the Proterozoic, and peaks correspond to known crustal-generation events; this suggests episodic additions of material from the asthenosphere.
(3) It is very difficult to date the mafic components of the SCLM; most reported "isochrons" probably are mixing lines.

SCLM Origins: what we can infer

(1) Most Archean SCLM worldwide formed between ca 3.5-2.8 Ga, some perhaps as late as 2.5 Ga; this appears to mark a major change from Hadean tectonics.
(2) This SCLM formed by very high-degree melt extraction at depths ≥ 250 km (evidence from geochemical correlations and experiments); buoyant residues rose as far as possible to generate continental nuclei.
(3) This process occurred in bursts corresponding to episodic mantle overturns, as predicted by modeling of the evolution of Earth's heat budget.
(4) There is no evidence that subduction of oceanic lithosphere contributed significantly to SCLM generation; the low Fe of Archean SCLM requires high-P melting. Oceanic lithosphere is dense enough to be delaminated during subduction.
(5) Eclogites near the LAB are best explained as frozen infiltrating melts, and their fractionates and cumulates, trapped near the LAB, a rheological and compositional boundary. The compositions of most eclogites are completely modified by metasomatic processes and carry no primary information on their origin.
(6) Metasomatic modification of Archean SCLM refertilises it, and much relatively fertile Proterozoic SCLM probably represents modified Archean SCLM.

The Yilgarn: What to do?

We only have 2-3 localities with garnets, and none with xenoliths, within the Yilgarn craton – they do not tell us much. How to get more data?

References:

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Modern Margins and Ancient Analogues: Are Ocean - Continent Transitions Important to Precambrian Tectonic Interpretations?

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Much of our understanding and interpretation of ancient orogens is based on insights from younger, and often better-exposed Phanerozoic case studies. Yet despite an increasing recognition of the importance of continental margins in understanding tectonic processes in the lithospheric evolution of young orogens, the significance of such continental margins in ancient Proterozoic and Archaean orogens has received much less consideration. Establishing the role of continental margin evolution in the development of ancient orogens has the potential to significantly challenge existing ideas around the geometric evolution of lithospheric architecture and geochemistry, both of which, in turn, play a fundamental role in a mineral systems approach to understanding ore deposit formation and therefore informing future exploration strategies. In this presentation, the characteristics and potential importance of continental margin evolution, and the importance of ocean-continent transition (OCT) zones, during both formation and subsequent destruction, will be explored, and considered with regard to Precambrian tectonism.

The latest research shows that modern rifted continental margins differ considerably from 'classical models' of margin architecture. Hyper-extended continental margins may be spatially heterogeneous comprising extensional allochthons of continental material and exhumed subcontinental mantle lithosphere. Differences in the amount of extension, and associated exhumation, across the OCT may lead to spatial variations in the metasomatic modification of exhumed subcontinental mantle lithosphere in distal and proximal parts of the margin. Although best developed from studies on modern continental margins, case studies from the European Alps indicate that similar complexities can be inferred in OCTs that have been significantly modified by subsequent convergence and collisional orogenesis. Eclogite facies mafic and ultramafic rocks in the Alps also seem to represent the preserved remnants of previously subducted extended continental margins rather than true oceanic crust – an idea that negates the need for complex, and difficult to justify, juxtapositions of continental and oceanic rock units within a subduction channel.

These examples illustrate the following aspects of hyper-extended continental margins that have significance for understanding ancient orogens:

1) A complex, pre-collisional architecture that may be mistakingly assigned to architecture developed during subsequent shortening.
2) Spatially variable geochemical enrichment of subcontinental mantle around the continental margin.
3) No *a priori* requirement for associations of ultramafic, mafic and sedimentary units to represent true oceanic crust or mark the position of sutures within collisional orogens.

These ideas will be applied to a few ancient examples to indicate the potential importance of continental margin development to the understanding of Precambrian tectonics.

Deformation in central Australia: a natural laboratory to explore the drivers for large scale intraplate strain localisation

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Mostly continents do not undergo large-scale internal (intraplate) deformation, so orogenic intraplate deformation represents an intriguing end member of the tectonic spectrum. Not surprisingly, the mechanisms that lead to the localization of orogenic-scale strains within continental interiors are still debated. Essentially the problem can be broken into two end members (a) drivers that are internal to the plate and (b) drivers that are external. The internal to the plate view is that the deformation is driven from the bottom up. In other words, mantle instabilities provide the fundamental driving force for orogeny. These models result in characteristic time scales for contractional and extension phases of deformation that should be reconcilable with natural examples. The external view is that deformation is driven from active plate boundaries, with strain localised into areas of comparatively weakened lithosphere. Localised lithospheric weakening could be due to a number of reasons; however the most obvious are the existence of major structural defects such as suitability oriented lithospheric-scale faults or the development of regions of thermal anomalism. In principal deformed continental interiors provide natural laboratories to explore mechanistic models for large scale intraplate deformation.

The central part of the Australian continent contains a record of long-lived intraplate deformation recorded by the development three orogenic systems that formed during essentially continuous intraplate deformation over nearly 300 Ma from the late Neoproterozoic to the mid Palaeozoic. The consequences of this tectonic activity shaped the lithospheric-scale architecture of central part of the continent and produced some of the most dramatic geophysical anomalies recorded on any of the continents.

A common feature of Australia's intraplate orogens is the development of comparatively narrow deep foreland basins that in some cases are coupled with significant crustal depression beneath large thrust sheets that migrated out from the orogenic core. These observations point to the involvement of weak lithosphere in the intraplate orogenesis, and provide some support for the notion that deformation might have been driven from the plate boundary, and focused into regions of comparative lithospheric weakness. Further support for this comes from the apparent synchronicity between phases of intraplate deformation, and the timing of deformation events along the active plate margin. If deformation was indeed focused into areas of lithospheric weakness, the reasons that weak zones developed is still not well understood. Some have argued that the unusually elevated rates of crustal heat production in central Australia made the continental interior very thermomechanically sensitive to small changes in burial of crust, beneath for example developing sedimentary basins.

However one of the features of intraplate deformation in Australia are apparent cycles of contraction and extension that are quasi regularly spaced in time. Such a record is more in keeping with the predictions of bottom driven orogenesis controlled by mantle instability. Work is continuing to try and chracaterise the timing of these cycles and to ascribe them to a specific structural character.

Therefore central Australia contains an intriguing record of large-scale intraplate deformation that appears to record hallmarks expected from both externally and internally driven orogenesis. The accessible scale of the orogens and the excellence of preservation of both the orogen cores and the flanking foreland basins makes central Australia one of the best natural laboratories in the world to explore the reasons for orogenic scale intraplate deformation.

Understanding Dynamic Earth: Insights from Experimental Laboratory

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Geoscientists need to use laboratory and computer experiments to try to recreate the enormous pressure–temperature conditions in the deep Earth and then measure the properties of minerals under these conditions. In the field of high-pressure mineral physics and chemistry, we apply mineral properties, stress–strain relationships in multiphase rocks, and processes such as partial melting at high pressures and temperatures, to geophysical observations of the deep Earth. Studies have constrained the pressure dependence of deformation of minerals such as olivine under subduction zone conditions, and the slip systems in high-pressure minerals such as wadsleyite and perovskite. These results have important implications for the depth variation of mantle viscosity, the geodynamic interpretation of seismic anisotropy and changes in mantle rheology as a function of composition. Specifically, many experimental studies have focused on the rheological properties of silicate mantle minerals and rocks at the high temperatures and low differential stresses appropriate for the asthenosphere because our experimental equipment was better designed to do these kinds of experiments. As a result, relatively few studies have explored deformation behavior of common silicate minerals at lower temperatures, under lithospheric conditions. Here, flow occurs by mechanisms not observed in high-temperature. Therefore, significant uncertainty exists in our knowledge of the strength of the lithosphere as a function of depth and under low temperatures, consistent with those of the subducting slab. The early studies have constrained the pressure dependence of deformation of minerals such as olivine and at higher pressures, the slip systems in minerals such as garent, wadsleyite and perovskite. The most recent work (2006 and onwards) owes its existence to the newly developed D-DIA, which has a working pressure up to 12 GPa and allows experiments to be carried out at a synchrotron x-ray beamline in making stress, pressure, and strain measurements in-situ. However, there is still much to be done. Fortunately, technical developmental work has been undertaken over the past 10 years in the USA and scientific advances have been helped by the development of high-P–T apparatuses and imaging, such as the large volume D-DIA and tomography. This has opened up the possibility of determining and imaging physical and chemical processes in the upper mantle down to the transition zone in the Earth's mantle in-situ. Figure 1 shows how the high-pressure geoscience community has played a central role in emerging fields, such as developing superhard and novel materials, because many of the tools developed in the high-pressure geosciences have been adopted across the scientific community as the best techniques for probing matter and synthesizing new materials at extreme conditions (e.g., semi-conductors and ceramics for nuclear-waste disposal). Figure 2 shows the D-DIA module. To develop the capability to participate in this exciting new area of research, we are now developing a high-pressure facility at the Australian Synchrotron and are bringing the D-DIA to Australia to perform state-of-the-art experiments on the Melbourne-based synchrotron. In this talk, we describe the background and current research that is being conducted in other synchrotron high-pressure facilities and what will now be possible for the Australian Synchrotron.

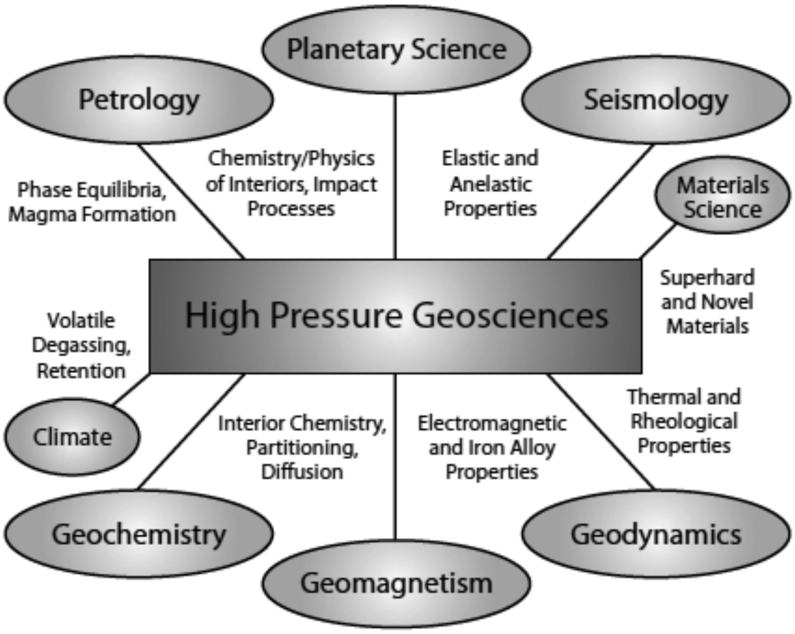

Figure 1: The interdisciplinary nature of high-pressure geoscience research. From "Understanding the Building Blocks of the Earth: Long-range Planning for High Pressure Geoscience" NSF COMPRES workshop 2009.

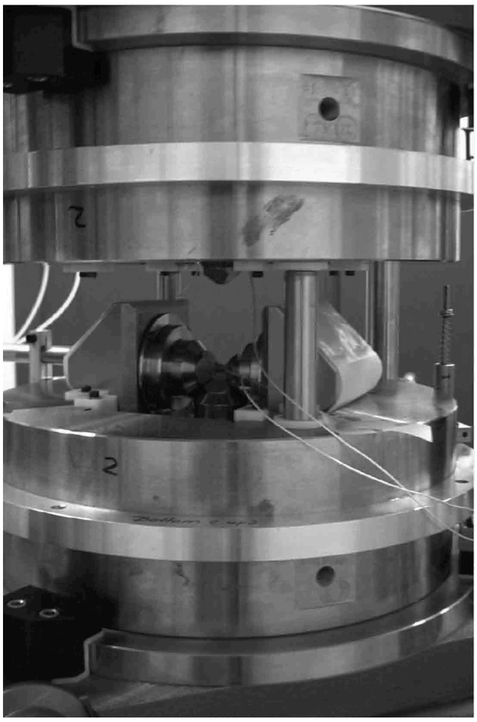

Figure 2: D-DIA module

Observational constraints on global quantitative models of the coupled plates/mantle system

Giampiero Iaffaldano
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In the years following the birth of the theory of plate tectonic, it became clear to Earth scientists that plate motions are the surface expression of convection within Earth's mantle. Despite this knowledge, over the past decades two separate communities have been exploring through quantitative models the dynamics of Earth's mantle on the one side, and of lithospheric plates on the other. This chiefly owes to the technical challenge of simulating the ductile mantle flow together with the brittle nature of the colder lithosphere within the same model. In the past decade, however, the emergence of links between deep and shallow processes from the geological record has made the need of global quantitative models of the coupled plates/mantle system a compelling one within the Earth Sciences. In this talk I will present some observational constraints to these models. Initially, I will recall, by mean of a simplified geodynamical problem, some key inferences on the torque balance of tectonic plates. I will then build on these inferences to discuss recent evidence derived from observations of plate kinematics as well as of the strength of tectonic faults and plate margins. More specifically, I will illustrate how high strain rates need to coexist with low stresses along plate margins, in order for plate tectonics to operate in the way the geological record shows. Finally, I will review the ability of current quantitative models to meet such a condition, and provide an outlook on future perspectives.

Subduction zones modelling:
exploring the link between plate tectonics and mantle convection

F.A. Capitanio
(School of Geosciences Monash University)

The subduction of lithosphere is one of the most fascinating processes of our dynamic planet. The sinking of old, dense lithospheric slabs in the mantle exert first-order controls on mantle mixing, geochemical differentiation and planetary cooling, but also provide the fundamental force driving plate motions and tectonics, from mountain building to the dismembering of continents and the formation of intervening oceans. Additionally, subduction provides the link between plate tectonics and mantle convection, and their feedback regulates the long-term planetary evolution and processes such as the Wilson cycle, plate reorganizations and continental evolution. The result is a variety of scale-dependent, behaviour rich problems. Modelling the physics of subduction and subduction-related processes has provided many solutions and has considerably shaped our understanding of the Earth in the last 40 years, through a wide diversity of approaches, differently leveraging approximations, observations and validations. Part of this talk will illustrate some milestones of subduction modelling and discuss their impact. Yet, the focus will be on those aspects that have remained to date unclear and/or largely debated, as these hold the key for the next 40 years of subduction modelling.

Hot continental tectonics - deformation, flow, stress and strain

Patrice F. Rey

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Rocks that formed in the deeper crust can be found at the Earth's surface along modern and ancient mountain belts and orogenic plateaux, and - in Archean cratons - deep crustal rocks can be found in anorogenic gneiss domes surrounded by greenstone belts. The exhumation of the deep crust into the upper crust requires that space be made either via lateral displacement of the upper crust via extension or via a downward return flow of the upper crust (sagduction), or localized erosion, or a combination of these mechanisms. Importantly, the transfer of rocks, fluids, and heat during exhumation drives the formation of ore deposits. As deep rocks approach their solidus, their viscosity decreases strongly and deep crustal terrains become very sensitive to lateral pressure gradients. Normal to oblique extension of the upper crust leads to such lateral pressure gradients in the deep crust that drive horizontal and upward flow of low-viscosity crust into the extending upper crust. Although deep crustal flow is dynamically linked to upper-crust extension, tectonic regimes in the upper crust and deeper crust are decoupled as semi-rigid divergent motion in the upper crust triggers convergent flow in the ductile deep crust. This process explains simultaneous lower crust contractional structures (upright folds, vertical foliation and high-strain zones) and upper crust extension/basin development in and around gneiss domes. This process poses an interesting challenge: Since tectonic regimes can be strongly partitioned vertically and laterally, can we infer regional tectonic regimes from the observation of finite strain in the ductile crust?

3-D laboratory modelling of lithosphere dynamics: from earthquake surface rupture patterns to crust-mantle interaction

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Since its beginning in the early 1800's experimental tectonics (a.k.a., analogue modelling) has been a powerful tool for testing hypotheses in structural geology, tectonics and geodynamics. Despite enormous advances in numerical modelling techniques, laboratory experiments are still important for the geodynamics toolbox because of their inherent 3D nature and high spatial and temporal resolution. However, unlike their numerical counterparts the results of analogue models have traditionally been evaluated in terms of geometrical and kinematic similarity to nature with less emphasis on rheological and dynamic similarity and temperature-time dependence. Recent advances within the experimental tectonics community mean that closer comparisons between analogue and numerical models and with nature are now possible. The introduction of new analogue materials combined with sophisticated rheological measurements means that rheological similarity between the flow of model materials and power-law creep of rocks is now feasible. The adoption of 2D and 3D Particle Imaging Velocimetry (PIV) imaging techniques, combined with digital photogrammetry and laser scanning gives experimentalists the ability to quantify progressive deformation and surface topography evolution with high temporal and spatial resolution. This in turn opens up comparisons between model results and GPS velocity fields and (dynamic) topography in regions of active tectonics. Temperature dependent materials and digital stress gauges mean that fully dynamic, thermo-mechanical laboratory experiments are now possible with enormous potential for modelling large-scale geodynamic processes in 3D.

In this talk we will review several applications of experimental tectonics over a range of spatial and temporal scales from earthquake surface rupture patterns to crust-mantle interaction and plate boundary evolution. Using a simple shear box that simulates deformation of cover rocks and sediments above a linear basement fault, we show that cohesive powders like dry talc are required to reproduce surface rupture patterns in poorly consolidated sediments, such as those associated with the 2010 Greendale earthquake, New Zealand. Using a combination of linear viscous and granular materials we illustrate the dynamic topography and upper crustal deformation responses of the lithosphere to a negative Rayleigh-Taylor instability (a.k.a. drip tectonics) at the lithosphere-asthenosphere boundary, with implications for intraplate basins and orogeny. Finally, using temperature-dependant materials and a thermo-mechanical apparatus we illustrate how the complex 3D evolution of convergent plate boundaries is controlled by feedbacks between slab dynamics and deformation of the over riding plate.

POSTERS ABSTRACTS

Investigating the crustal architecture of the West African Craton: a 3D approach

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Determining subsurface geology in remote regions often relies solely on gravity and magnetic data. Earth models derived from potential field data are inherently non-unique, but an infinite number of solutions is not the same as "anything is possible". Thankfully, reasonable models can be derived with considered choice of method and incorporation of geological and petrophysical data. The West African geophysical data was modelled using the VPmg software package (Fullagar Geophysics) using two inversion styles: heterogonous property inversion and combined geometry and heterogeneous property inversion. The question is which inversion type is the best choice? What should "drive" inversion in this particular geological setting: changes in the physical property distribution or domain structure? Two main considerations regarding appropriate inversion type are: (1) the primary objective of determining the 3D geometry of geological units with different densities and (2) unknown depth extent and geometry of major faults, and to what extent is the inversion outcome going to honour the assumed nature of these faults? An experiment was conducted involving different models of the upper crustal architecture of the Baoule-Mossi domain in Ivory Coast using different inversion types.

Five petrophysical/geological models of the study area were created based on geological knowledge. These models extent to a depth of 20 km and are variants of a two-layer crustal model representing the Proterozoic (upper layer) and the Archean (lower layer). This suite of models was used as an input for the different styles of 3D gravity inversion. Different scenarios of geological unit geometry and special relationships were displayed by adding the structural elements of the Greenville and Brobo Faults. The density chosen for geological units in the input models is a mean value of sample populations derived from laboratory measurements. The inversion parameters (number of iterations and RMS residual) for all inversions were consistent across all inversion processes.

This modelling experiment showed that heterogeneous property inversion on its own was good enough to determine subsurface density distribution. 3D inversion results from both inversion styles produced expected ranges of density and were within the RMS residual. This experiment showed that the different depth extent of the faults does not greatly affect the model density distribution. The important question regarding their geometry (dip) still remains unanswered. This could be solved if we apply a similar approach but conducting inversion to test different assumptions regarding geometry within existing geological constraints.

Lithosphere Dynamics Workshop – ABSTRACT

Title: A geophysically constrained multi-scale litho-structural analysis of the Trans-Tanami Fault, Granites-Tanami Orogen, Western Australia

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The Trans-Tanami Fault in the poorly exposed Paleoproterozoic Granites-Tanami Orogen of Western Australia is a ~100 km long curvilinear structure with ~6 km of right lateral displacement. Early explorers believed lode gold mineralization in the orogen to be spatially related to the Trans-Tanami Fault and associated splays. Recent deposit-scale studies at the Bald Hill and Coyote areas of Western Australia concluded that gold mineralization was temporally associated with 1795 Ma D_{GTO2} deformation, and broadly synchronous felsic plutonism. Furthermore, lithosphere-scale geophysical investigations identified the importance of early crustal architecture in setting up the plumbing system for fluid flow from the upper mantle to the shallow crust. Although these studies have constrained the timing and source of mineralization, they failed to identify the significance and structural relationship between the basement architecture and the Trans-Tanami Fault.

In this study the multi-scale integration and analysis of aeromagnetic, gravimetric, 2D reflection seismic, and remote sensing data have constrained the relative timing and architectural relationships of this structure. Interpretation of long-wavelength gravity and magnetic anomalies, which are commonly used to infer first-order structures, shows that the fault is not a terrane boundary. Structural geophysical interpretation of short-wavelength aeromagnetic and gravimetric data illustrates that the structural domains on either side of the fault represent a non-homogeneous stress regime developed between the buttressing effects of rigid granitic plutons. Additionally, 2D joint forward modeling of gravity and magnetic data coupled with the interpretation of reflection seismic data confirms the vertical displacement to be negligible, indicating a predominant lateral displacement. The displacement along a portion of this structure has exploited a pre-existing north-dipping thrust fault. Where this early fault terminates, the Trans-Tanami Fault displaces previously un-faulted rock as a wrench fault step-over. These observations differ from previous findings in the area by constraining the absolute displacement of this structure, and through the recognition of a wrench fault system that includes lateral step-overs between reactivated earlier thrust faults.

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The electrical resistivity structure of the southeast Australian lithosphere

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The geophysical technique of magnetotelluric sounding has been used to investigate the resistivity structure of parts of the southeast Australian lithosphere. Broadband magnetotelluric data from a 150 km east-west transect across the southern part of the Delamerian Orogen were inverted to obtain the 2D resistivity structure of the crust. Relatively dense site spacing (~5km in western half of transect, ~1.5 km in eastern half), resolved conductive fossil fluid pathways extending from the upper mantle to the surface. Fluids could be associated with the ancient westward dipping Cambrian subduction that saw the onset of the Delamerian Orogeny. Regions of maximum conductivity within the pathways appear to coincide with locations of suspected serpentinisation. Rehydration of the serpentinite from fluids that moved through these pathways may have resulted in an increased interconnection of conductive magnetite, decreasing the overall resistivity. Additionally, phase tensor ellipse representation of the data indicates a significant resistivity change across major geological boundaries.

Preliminary work on both broadband and long period magnetotelluric data from a 250 km east-west transect across the Curnamona Province is being undertaken. Dimensionality analysis indicates substantial three-dimensionality. For this reason, interpretation of the data has so far been in the form of phase tensor ellipses, ideal for investigating major resistivity trends and faults. Current work involves 3D inversions of the data.

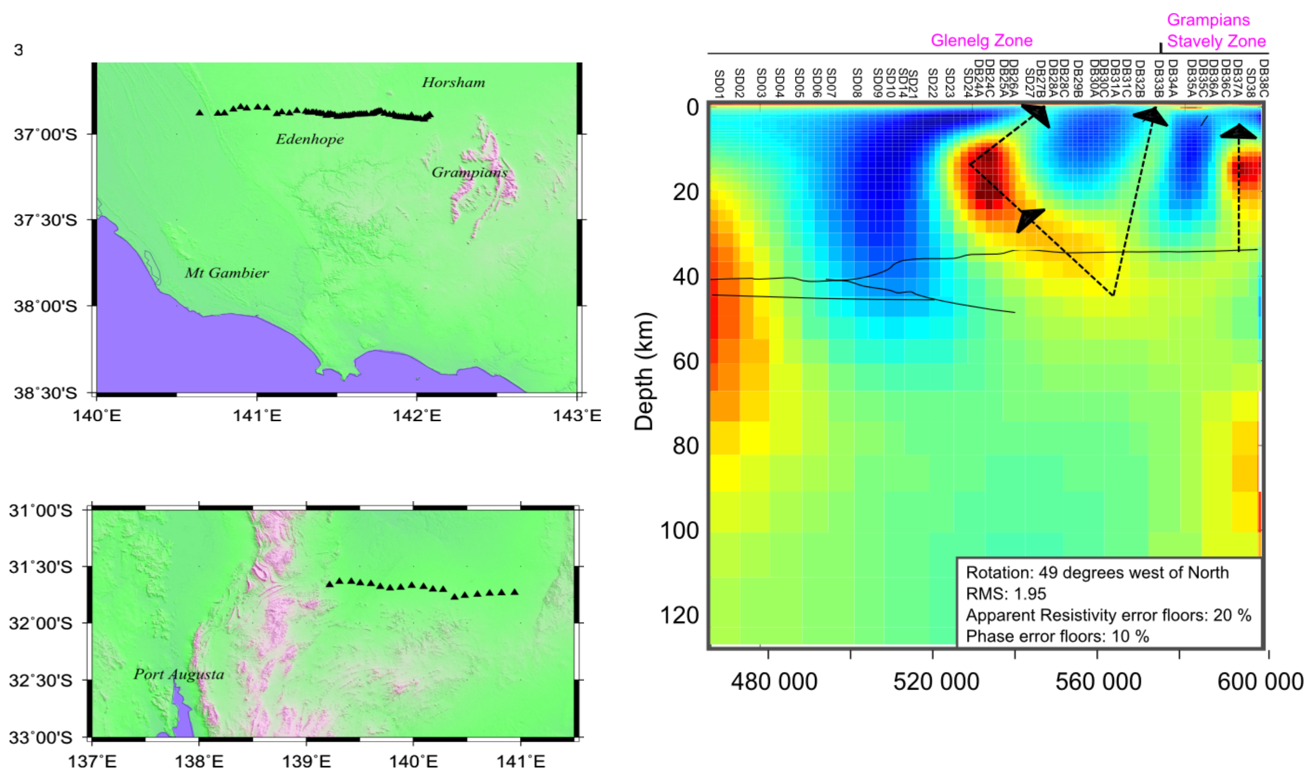

Figure 1: Top left- Triangles indication locations of Southern Delamerian magnetotelluric sites (67 stations in total). Bottom left- Locations of Curnamona Province magnetotelluric sites (18 stations in total). Right-2D inversion of Southern Delamerian magnetotelluric stations. Red is conductive, blue resistive. Arrows indicate suggested fluid pathways. The Moho is marked.

3D crustal structures in north Tibet revealed by ambient noise tomography: implications for the growth of the Tibetan Plateau

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Tibet is our planet's natural laboratory for studying dynamics of continental interactions. The current crustal structures in this area record the information for understanding the evolution and processes the continent has gone through since the India-Eurasia collision starting ~50 million years ago. In this study, by investigating the crustal structures in north Tibet, we aim to address two questions: (1) whether the Tibetan plateau is growing northward and (2) if so, what is the growth mechanism, crustal shortening or channel flow.

To construct the crustal velocity structures in northern Tibet and its surrounding regions, we analyze continuous ambient noise data collected from ~280 stations in the research area. Rayleigh phase velocity maps at 10-60 sec periods are generated using ambient noise tomography. And a 3-D Vsv model is constructed based on calculated surface wave dispersion curves using a Bayesian Monte Carlo method. The resolution tests indicate that features around 80 km wide are reliably imaged throughout the study areas with locally higher resolution of ~50 km. The 3D image helps to reveal the detailed distribution of mid-crustal low velocity zones (LVZs) in north Tibet.

Our 3D model reveals strong LVZs at the middle crust between 20 and 40 km across northern Tibet with broad features similar to previous ambient noise tomography but with more details showing significant west-east variations of LVZs along the Kunlun Fault. In the west part, LVZs are confined to regions of the Kunlun Fault and the eastern Kunlun Mountain but do not appear beneath the Qaidam Basin; while in the east part, LVZs are observed to extend and penetrate northward into the East Kunlun and Qinling Orogens over ~100 km beyond the east boundary of the Qaidam Basin. The strong contrast of the distribution of LVZs in the west and east parts of the study region mainly results from the distinct tectonic units neighboring northern Tibet with a strong crust of the Qaidam Basin in the west blocking the penetration of LVZs but a probably weak crust in the Qinling Mountains allowing the flow of LVZs. Comparable mid-crustal LVZs are also observed in the northwest Qilian Orogen. There is no obvious connection between the LVZs beneath the Qilian Orogen and those in northern Tibet, which probably suggests different generation mechanisms and sources for LVZs.

The distribution and extent of LVZs in our model provide new constraints in understanding and distinguishing the existing models of the Tibetan growth.

The Curie depth of Australia, its uncertainty, and its relationship to the components of the Australian lithosphere

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The Curie depth is the point at which the Earth's crust and uppermost mantle cease to contain induced magnetisation because minerals have reached their Curie point, as a result of the prevailing geothermal gradient in the region. The deepest magnetic sources indicate where the Earth has ceased to be magnetic: in turn, this base of magnetisation is a proxy for the Curie depth, assuming there remain magnetic minerals of sufficient magnetic strength at these depths. The Curie point, and hence the corresponding Curie depth, varies for different minerals. Thus the depth to the base of magnetisation cannot always be interpreted as an isotherm. The most strongly magnetic and common magnetic mineral, magnetite, has a Curie point of ~580 ºC. This temperature is lower for titanium-bearing minerals such as titanomagnetite, with a Curie point of ~250 ºC. Other minerals are much less magnetic than these minerals and therefore contribute less to the deepest magnetic sources.

There are many methods available to extract crustal-scale magnetisation to define the base of magnetisation. The approach we have used is a one-dimensional single layer model approach, with random but self-similar magnetic sources confined to this layer. The level of self-similarity is allowed to vary in our ensemble inversion. The magnetic layer is buried beneath a variable depth non-magnetic overburden and has a finite but variable depth extent. Using uniform sampling with a regular grid search as our sampling of parameter space, we have analysed some 3600 overlapping 400x400 km windows of magnetic data to establish a preliminary depth to the base of magnetisation, and its uncertainty, for the whole of the Australian continent (Figure 1).

Our map of the depth to the base of magnetisation highlights differences and similarities between the components of the Australian lithosphere. Ongoing work is being conducted to finalise this map and to further explore the relationship between the lithospheric components and the Curie depth across Australia. Preliminary results indicate that some of the depth variation is due to thermal effects (such as beneath the Eromanga basin), and some is due to confined layers of magnetic material, such as the iron deposits of the Hamersley Basin. Our map also highlights features such as the probable extension of the Archean Yilgarn Craton underneath the Eucla Basin to the east, and the Arunta-Warumpi-Musgrave provinces underneath the Eromanga Basin also to the east.

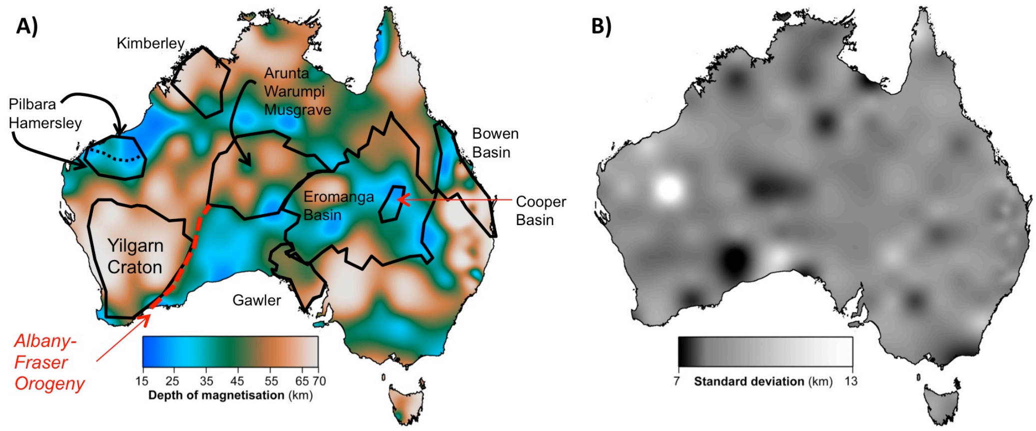

Figure 1: A) The depth to the base of magnetisation as derived by our preliminary investigations, and the outlines of major geological components of Australia; B) The uncertainty of these results, as defined by our ensemble inversion for the depth to the base of magnetisation.

Application of long period surface waves from ambient noise in regional surface wave tomography

Yingjie Yang

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Since the emerging of ambient noise tomography in 2005, it has become a well-established method and has been applied all over the world to image and study the structures of crust and uppermost mantle because of its exclusive capability to extract short period surface waves. Most of previous ambient noise tomography studies are concentrated on surface waves at periods shorter than 40/50 sec. There are only a few studies of long period surface wave tomography from ambient noise (longer than 50 sec) in continental and global scales. To our knowledge, no tomography studies have been performed using long period surface waves from ambient noise in regional scales.

In this study, we investigate the accuracy of long period phase velocity dispersion measurements from ambient noise at periods up to 200 sec and investigate the capability of using long period surface waves from ambient noise in regional tomography by comparing dispersion measurements and resulting tomography maps from both ambient noise data and earthquake data. We choose western USA as a case study where station coverage is dense and stations operate over at least two years. Our preliminary result shows phase velocity maps from ambient noise data and earthquake data are quite similar at same individual periods in the period band of 50-150 sec. The inclusion of long period surface waves in regional-scale surface wave tomography will significantly increase the path coverage in both lateral and azimuthal senses, which is essential to improving imaging of high resolution heterogeneities and azimuthal anisotropy, especially at regions with big gaps of azimuthal distributions of earthquakes.

edges, inversions and models are supported by geological observations and also by the Youanmi survey magnetotelluric data, and therefore provide important constraints to understanding the deep structure of the Yilgarn craton and its bounding structures.

Fluid residence in the lithosphere - insights from magnetotelluric sounding

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The residence of fluids in the lithosphere has implications for the lithospheric strength, temperature distribution and plays an important role in understanding mineral deposit genesis. Since the magnetotelluric technique is sensitive to electrical conductors, encompassing fluids and minor conducting phases precipitated through fossil fluid flow, it provides a unique view into the lithospheric distribution of fluids.

We present magnetotelluric surveys in South Australia revealing the resistivity distribution with varying resolution from the crust to the mantle. Three-dimensional inversions of large 2D arrays are useful to map the distribution of minor conducting phases in the mantle lithosphere. Recent results from 2D arrays across the central Gawler Craton indicate that plume modified orogeneses in the Proterozoic can still leave an electrical imprint in the mantle at 80 km and below today (*Thiel and Heinson*, 2013). Current laboratory studies suggest that hydrogen in the crystal lattice can account for enhanced conductivity in mantle olivine, yet to which degree remains controversial (*Karato and Dai*, 2009).

Higher resolution achieved through close site spacing along 2D profiles result in a detailed image of the resistivity distribution through the crust. We present two 2D inversion models of surveys comprising a total of 91 broadband and 12 long-period MT stations along two 40 km profiles across the Frome Basin to the east of the Northern Flinders Ranges. This area shows enhanced heat flow exceeding 100 mW m^{-2} due to high heat producing granites and forms an intracratonic setting (*Neumann et al.*, 2000). The inverse models show low resistivity in the lower crust and less than 10 km wide vertical zones extending to the brittle ductile transition, approximately 10 km below the surface. The mid-crustal conductors appear to be connected to the surface through narrow dipping conductive features and can be associated with gradients in potential field data indicating upper crustal fault zones. In particular, the Wooltana Fault also coincides with the location of the Beverley Uranium mine.

The resistivity images therefore show that lithospheric strength has an influence on fluid residence and flow in the crust. The data suggests that the brittle ductile transition acts as a mechanical boundary to upward migrating fluids, perhaps due to the establishment of horizontal shear zones (*Regenauer-Lieb et al.*, 2006) and resulting in high seismic reflectivity and fluid pooling beneath the transition (*Connolly and Podladchikov*, 2004).

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Noise effects on seismic history matching

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Seismic information is used to update dynamic reservoir models through a process called seismic history matching. These models have their properties updated based on variations of seismic derived attributes. However, obtaining these attributes might rely on the complexity of a seismic inversion.

From a geologist and engineer's point of view, acoustic impedance is the most appealing of the attributes, presenting direct physical relation with reservoir properties while matching traces might sound complex.

Workflows updating fluid flow models using acoustic impedance motivate this study. A coupling between a petro-elastic and fluid flow models provides an estimative of acoustic impedance for comparison with the seismic inversion results. An optimization procedure updates reservoir properties (permeability, for example) based on the match of both acoustic impedance values.

Noise is recognized as a major issue in seismic data processing and inversion - however is often neglected in these workflows. Our hypothesis is that amplitudes might be a better option diagnostic than impedance for a seismic history matching above a given signal-to-noise ratio. This simply because noise effects on seismic inversion procedures might mislead the relations between impedance and its respective water saturation value potentially resulting in no coherent reservoir properties updates.

As a preliminary test to our hypothesis we built a synthetic seismic model by convolving real log data with a 25Hz Ricker wavelet and a random Gaussian noise was added (Figure 1). Qualitatively, this shows the noise effect in the amplitudes domain producing a poor seismic image. Figure 2 presents a vertical profile of inverted acoustic impedance along with its respective log values for several signal-to-noise ratios. Increased noise levels cause severe oscillations around the reference data, particularly for signal-to-noise ratio bellow three. Clearly any attempt in using such results would require a lot of attention in dealing with noise impacts.

From this we confirmed major noise effects on seismic data and its inversion results, potentially leading to an increased estimate of uncertainty on seismic attributes. Higher or lower uncertainties might depend on the data domain used. In the future, we will run a fluid substitution to establish a relation between water and acoustic impedance variations, allowing further comparisons for history matching purposes.

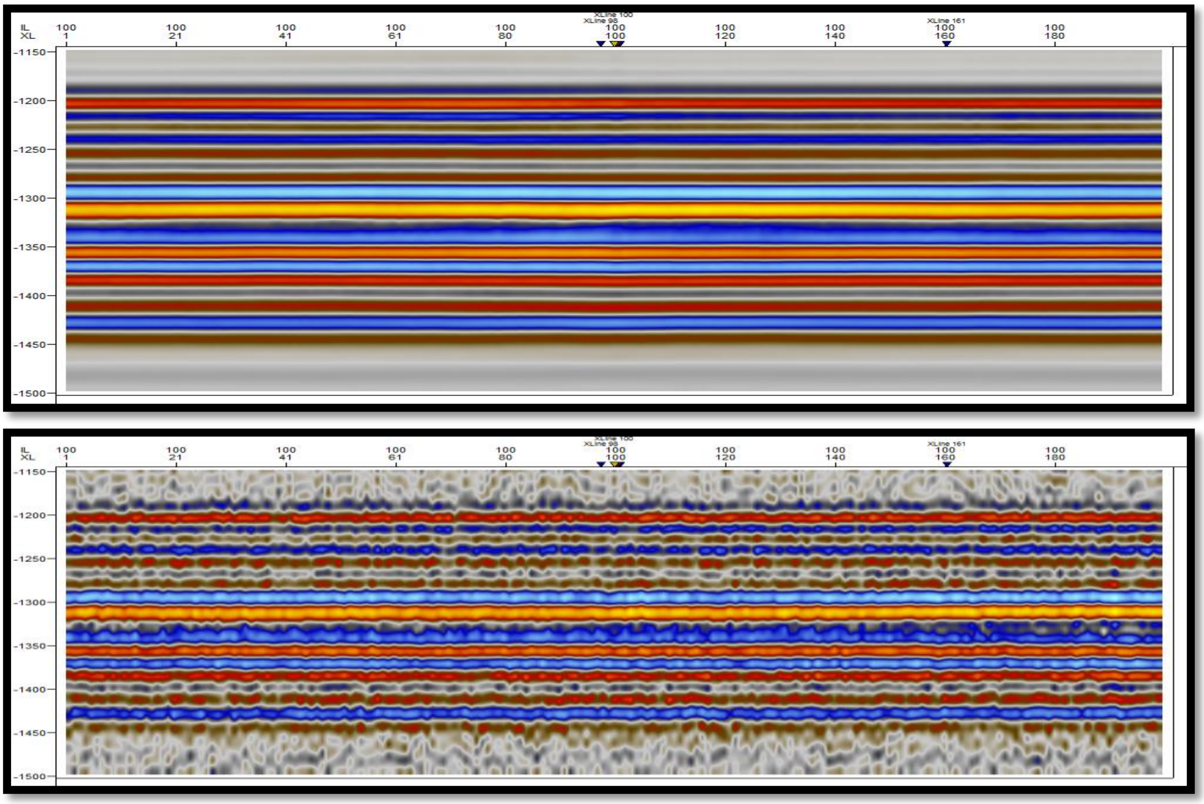

Figure 1: Synthetic seismic. Noise free(top) and SNR equals 3 (Bottom).

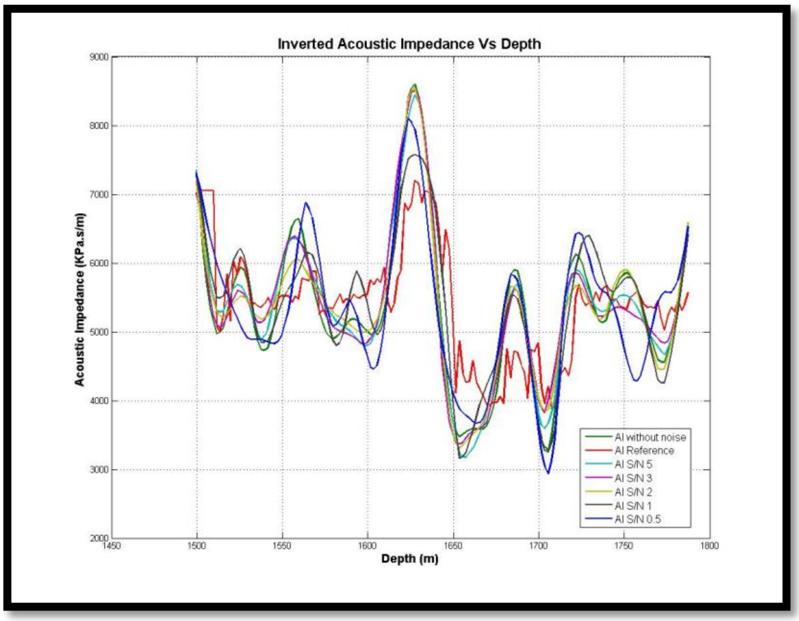

Figure 2: Inverted and real acoustic impedance values for several noise levels.

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Modelling 3D seismic wavefields through complex seafloor topography offshore NW Australia

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INTRODUCTION

Seafloor canyons and complex seafloor topography pose significant challenges when analysing seismic data from the North West shelf off the Western Australian coast (Bisley and MacNeill, 2008; Debenham and Westlake, 2012). Several prolific gas fields in this area lie beneath or proximal to the continental shelf break, which contains significant canyons on the scale of seismic wavelengths in both width and depth. These canyons cause significant seismic amplitude distortion and complex wavefield behaviour (e.g. scattering and wavefield multi-pathing), which lead to irregular and poor illumination, unreliable AVO analysis, difficulties in velocity model building and increased exploration and development uncertainty. These issues pose significant challenges when attempting to image and interpret the subsurface reservoirs near these features.

While some techniques have been presented that address these issues (e.g. Berryhill, 1986; Dent, 1983), there is not a large body of literature around this topic and in some cases these issues remain unresolved problems. To investigate these situations, we simulate elastic wave propagation through a model of the Northwest Shelf (NWS) seafloor topography to observe these full wavefield effects (e.g. scattering, multiples, amplitude distortion. By observing these directly we can better understand their dynamic behaviour and quantify the deleterious impact on seismic imaging and derivative products.

METHOD

The first step is developing an appropriate elastic model of the region. Using a bathymetry map provided to us we generate a 25km x 25km x 2.5km elastic properties model by inserting water above the seabed and rock below it assuming a constant velocity gradient of 0.25/s from 2.25km/s at the shallow parts of the seafloor to 3km/s at the model base. We also include a single flat reflector at 1km depth, which represents a discontinuity of +250m/s in the velocity profile. The model has 2000 x 2000 x 400 grid points with 12.5m grid spacing laterally and 6.25m gird spacing vertically. The bathymetry model, presented in Figure 1, shows the continental shelf break running south-east to north-west across the model and a variation in water depth from about 50m on the continental shelf to 600m on the abyssal plain. The model includes complex topography (including canyons) across the continental shelf break. The canyons' dimensions are on the order of 250m deep, 600m wide, and 2km long. Figure 2 shows a cross-section of the model where the bathymetry drops from shallow depth on the continental shelf (right) over the continental shelf break with dips of up to 45º down to the abyssal plain (left).

We model 3D wavefields using an elastic finite difference approximation with a staggered grid (Virieux, 1986). We utilise a velocity-stress formulation of the wave equation. The modelling is isotropic, uniform grid and accurate to second-order in time and eighth-order in space. The top boundary is modelled as a free surface while the other boundary regions are modelled as perfectly matched layers (PML) (Collino and Tsogka, 2001). We modify their formulation by using a quadratically increasing damping factor rather than a constant one to reduce spurious reflections on the inside of the boundary.

For our initial experiment we insert a 25 Hz Ricker wavelet as a plane wave 25m below the sea surface. The plane wave provides an initial examination of the topographic effects and is a first approximation to a brute stack from a single modelling run. The model time steps were 1ms and snapshots of the entire wavefield were output every 10ms.

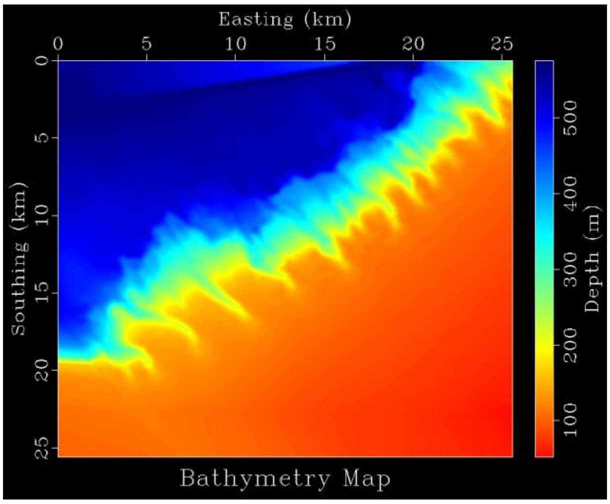

Figure 1: The bathymetry map used for the modelling in this project, clearly showing the canyons running across the continental shelf.

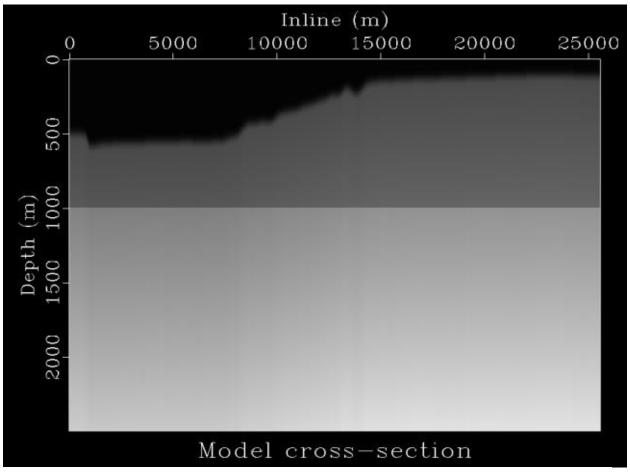

Figure 2: Cross-section of the elastic model with a single reflector at 1km depth.

RESULTS AND DISCUSSION

Figure 3 shows an amplitude map of the wave transmitted through the complex seafloor topography and flat reflector at 0.9s. Regions of the wave near the continental shelf show variation of a factor of four in amplitude over distances of less than 500m, e.g. the region indicated by the 1km scale bar. Regions directly below the canyons have higher amplitude than the rest of the wavefront, while adjacent regions have relatively low amplitude. This demonstrates the significant focusing and defocusing which can extensively violate uniform illumination assumptions made explicitly or implicitly in seismic data processing algorithms. This also produces variability in the levels of illumination over different regions. These effects lead to low illumination below the canyons and render AVO analysis unreliable.

CONCLUSIONS

Our modelling results demonstrate the challenges presented by complex seafloor topography such as canyons. Such topographic features produce significant seismic wavefield distortions and illumination variations that issues for processing and analysing seismic data. Using high-performance computing facilities we model realistic effects of complex topography accurately and at high resolution for a better understanding of the effects. It also provides opportunity to benchmark different imaging/progressing algorithms and will assist us in developing improved imaging/processing algorithms.

ACKNOWLEDGMENTS

The authors would like to thank Lisa Gavin and Mohammad Emami for their assistance in interpreting and visualising the data and Woodside Energy Ltd. for providing the bathymetry map. We would also like to acknowledge the ASEG Research Foundation, the Robert and Maude Gledden Postgraduate Scholarship and the sponsors of the UWA:RM Reservoir Management research consortium for partial funding the research. This modelling was implemented using Madagascar (www.ahay.org).

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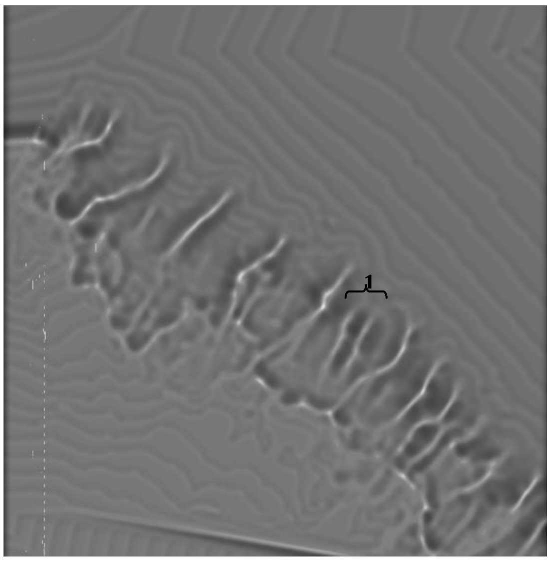

Figure 3: Amplitude map of the transmitted wavefield.

Decarbonation and carbonation processes in the slab and mantle wedge – insights from thermomechanical modelling

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Abstract: Subduction zones are one of the most geologically complex and scientifically fascinating processes ongoing through much of Earth's history. Subduction recycles crustal sediments and oceanic lithosphere, refertilizes the mantle-lithosphere and generates new continental crust through partial melting as a consequence of devolatilized fluids fluxed from the downgoing slab. Slab derived volatiles consist primarily of H_2O-CO_2 fluids. These fluids are critical in subduction evolution as they greatly affect rheology and solidus temperatures in the mantle wedge with fluid-rock interactions resulting in metasomatism. Metasomatism introduces heterogeneity in the upper mantle long after subduction has ceased. Due to H_2O's unique physical properties resulted in the main focus of scientific investigation over the past few decades leaving many open questions for the role of CO_2 transfer from the slab and how it affects the mantle-lithosphere through time. Difficulty arises in evaluating the CO_2 flux from the slab for several reasons: 1) initial conditions are dependent on extent of alteration of basalt and sediments prior to subduction 2) decarbonation is highly variable, dependent on the thermal regime of the slab and H_2O availability itself and 3) our experimental understanding of binary to C-O-H-S fluid interaction within the slab and mantle wedge. Our work is concerned with incorporating decarbonation-carbonation reactions and flux of CO_2 into the forearc and subsequent retention of carbonate into the subarc and beyond employing a fully coupled petrological-thermomechanical numerical modeling code. We resolve stable mineralogy and extract rock properties via Perple_X at a resolution of 5°C and 25 MPa. The numerical technique employed is a characteristics-based marker-in-cell technique with conservative finite-differences that includes visco-elastic-plastic rheologies (I2ELVIS). Devolatilized fluids are tracked via markers that are either generated or consumed based on P-T conditions. The fluids are allowed to freely advect within the velocity field determined by the dynamics of the system. The hosts for CO_2 in are computed via GLOSS average sediments (H_2O: 7.29 wt & CO_2 3.01 wt%), metabasalts (H_2O 2.63 wt%

& CO_2 2.90 wt%), and ophicarbonates (H_2O 1.98 wt%& CO_2 5.00 wt%). We demonstrate the feasibility of incorporating a pseudo binary fluid into geodynamic models to investigate scenarios that include CO_2 as the main fluid of interest e.g. economic mineralization tapped from a mantle source. Other applicable scenarios include 1) sediment diapirism into the convecting wedge, where thermodynamic models do not incorporate dynamics, 2) carbonate metasomatized upper mantle, exemplified through widespread CO_2 degassing in the Western Mediterranean and 3) better understanding the fate of carbonates beyond the subarc and consequent subduction into the deeper mantle within a fully coupled model framework.

Combined mechanical and melting damage model for geomaterials

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We present a new damage model combining mechanics and partial melting in accordance with the principles of non-equilibrium thermodynamics. On the mechanical side, elasto-viscoplactic damage is considered based on a self-consistent far from equilibrium thermodynamic framework; on the melt side, partial melting is calculated by using the thermodynamic MELTS Gibbs energy minimizer. In this framework the partial melt appears as an additional damage parameter. The numerical implementations are accomplished by using Abaqus® solver and the extendable User Material Subroutine (UMAT). Three continental extension models with different temperatures are used to test the approach. This new model can be applied on geodynamic problems involving brittle and ductile faulting, partial melting, magma generation and movement, and the interaction between these activities.

Influences of Temperature-Dependent Thermal Conductivity on Surface Heat Flow near major faults

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We studied the thermomechanical effects on surface heat flow near major faults from positive feedback between temperature-dependent thermal conductivity k(T) being ∝ (1/T)**bb and frictional heating in a crustal-lithospheric system using finite element simulations. Variable conductivity and frictional heating cause a drastic reduction in the thermal conductivity, and these changes can impact seriously the heat flux. When b = 1, the temperature is around 400 K higher around the fault than in the uniform conductivity case. This physical phenomenon is due to the reduction in thermal conductivity from increase in the temperature. In spite of the high temperature around the fault in the variable conductivity cases, the surface heat flux is 30% (for b = 0.5) to 50% (for b = 1) lower than in the uniform conductivity case. This thermal insulating effect may explain the lack of heat flow anomalies near major faults, such as the San Andreas fault in California and is consistent with previous hypotheses by geophysicists concerning the nature of the shear strength associated with these long transform faults.

Multiscale dynamics of hydrothermal systems

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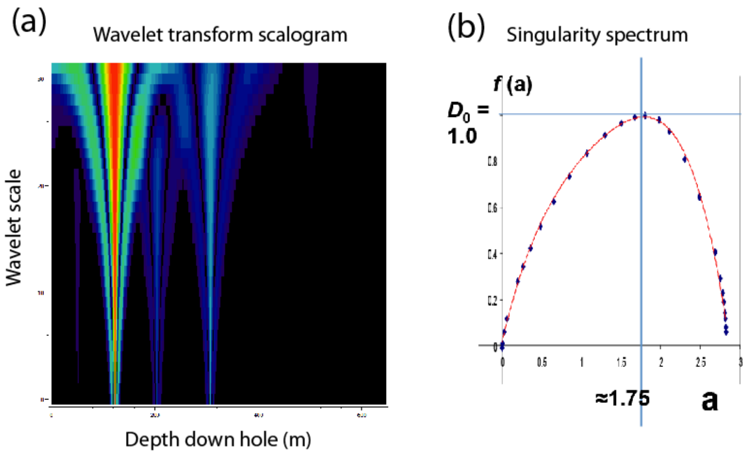
This project aims to provide an integrated framework for the generation of hydrothermal systems by linking processes ranging from lithospheric scale down to the very microscale. Key features associated with these systems will be derived from a number of systems throughout Western Australia and the Copperbelt of Central Africa. Numerical geodynamic modeling using the finite difference code I2ELVIS (Gerya & Yuen, 2007) will be used to explore the lithospheric-scale architectures that promote the development of hydrothermal systems, and the spatial and temporal scales involved in these processes.

Fracture systems, which influence fluid flow dynamics in the crust, have recently been viewed as examples of critical systems. Such critical systems may be differentiated into different behaviour regimes via their fractal dimension (D). Those characterized by massive catastrophic behaviour (labeled ‘SNAP’) in 2-Dimensions possess $1 \leq D \leq 1.5$, whereas those characterized by distributed small avalanches (labeled ‘POP’) possess $1.5 \leq D \leq 2$. Wavelet-based multifractal analysis of the fracture networks associated with hydrothermal mineral systems at the regional and mesoscales will determine whether or not they relate to SNAP or POP terrains and exhibit diagnostic multifractal signatures.

Does the distribution of alteration and mineralization assemblages at the deposit and mesoscales within hydrothermal systems possess a characteristic pattern, and how can this be quantified? Wavelet analysis of mineral phases and their chemistry from down-hole hyperspectral data permits this quantification. Analysis along individual holes, between multiple holes within a system, and between different systems (failed vs. successful, large vs. small, high-grade vs. low-grade) will investigate the presence of distinctive signatures. These signals may then be linked to causal processes such as mineral reactions, with view to establishing long wavelength vectors to mineralization for drill core and field-based exploration.



(a) Wavelet transform scalogram of gold abundance down a drill hole.
(b) Multifractal spectrum produced from the wavelet transform in (a).

The State of the Oceanic Lithosphere

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The continental crust covers about 40% of Earth's surface area, and bears the scars of a long and complex evolutionary history. The remaining surface area is covered by oceanic lithosphere, which is younger and tends to have a simpler history. In part owing to this simplicity, our collective grasp of geodynamics in continents and the Earth as a whole is strongly constrained by the state of oceanic lithosphere. The oceanic lithosphere a) interacts with continental margins by thermomechancial processes associated with collision and subduction, b) interacts with continental interiors by upper mantle dehydration-melting processes, induced convection, and underplating phenomena, and c) has been suggested to modulate the secular thermal evolution of continental mantle by regulating mantle-wide convection regimes. Moreover, as the oceanic lithosphere is essentially the exposed surface of convective mantle, heat loss and chemical exchanges between lithosphere and oceans impart major modulating roles for the thermal and chemical evolution of the Earth's interior and hydrosphere.

In this presentation we show the results of several complementary avenues of research attempting to constrain the state of oceanic lithosphere and incorporate such constraints into models of the secular evolution of the Earth. Firstly (1) we have developed new physically comprehensive thermal plate models of the oceanic lithosphere, which demonstrate that the oceanic lithosphere is significantly insulated by oceanic crust. Secondly (2) we use this new thermal plate model to revise estimates of net seafloor heat flow and the total power driving ventilated hydrothermal circulation in oceanic lithosphere. Third (3) we couple these new models of the thermal evolution of oceanic lithosphere **to the thermal evolution of continental lithosphere and secular cooling of the mantle. These models explore the partitioning of heat loss through continents and oceans over Earth history.** Fourth (4) the above secular cooling model of the Earth may be coupled with an isostatic model for eustatic sea-level changes over Earth history, allowing extrapolation of sealevel from present-day to the Archean. **Models suggest that sea-level may have been ~2 km above continents in the Archean, with secular cooling causing gradual recession of sea-level over Earth history.**

Modelling the Lithosphere-Asthenosphere System with Multi-Physics Finite Element Methods

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The physico-chemical processes governing the evolution of continental lithosphere and its interaction with the sublithospheric upper mantle occur over very different spatial and temporal scales. The details of the interactions between these different scales and the resulting integrated macroscopic effect on the evolution of plates are still poorly understood. In order to gain a holistic understanding of these multi-scale processes, we need to be able to accurately model the *multi-phase, multi-scale, and multi-component reactive* nature of the lithosphere-asthenosphere system. Unfortunately, although a few groups are making progress towards this end, most available modelling platforms in the geodynamic community are not well-suited to deal with all of the above complexities. Moreover, their scalability to a wide range of problems (e.g. from melting in cm-scale veins to mantle convection) is typically poor.

The limitations of the current platforms are at the core of the present work, which aims to offer an alternative thermodynamically- and internally-consistent numerical tool able to satisfy the present needs of the geoscience community. For this, we take advantage of a novel numerical framework, known as the Multi-scale Finite Element Method (MsFEM) [1]. The main idea is to capture small-scale details of a problem and transfer them to the macro-scale through consistent and robust coupling of the micro- and macro-problems. In terms of the numerical technique, the MsFEM replaces the basis functions used in the traditional FEM, by a new set of micro-problem-dependent functions. This development provides a new numerical platform directly applicable to modelling geological phenomena such us the generation, migration and emplacement of magmas, chemical entrainment, transport of geochemical species, deposition mechanisms of sulphide liquids, the formation of ore bodies in hydrothermal systems, etc. Importantly, our numerical framework consistently couple these "small-scale" processes to the large-scale driving tectonic processes, which allows us study the complex interactions between different scales (Figure 1). So far, the MsFEM has been successfully applied and tested in fields such as composite materials, petroleum reservoirs, and groundwater transport, but not yet employed in the large scale analysis of the lithosphere-asthenosphere system. In this presentation we will discuss some recent progress made by our group on such potential applications of the MsFEM.

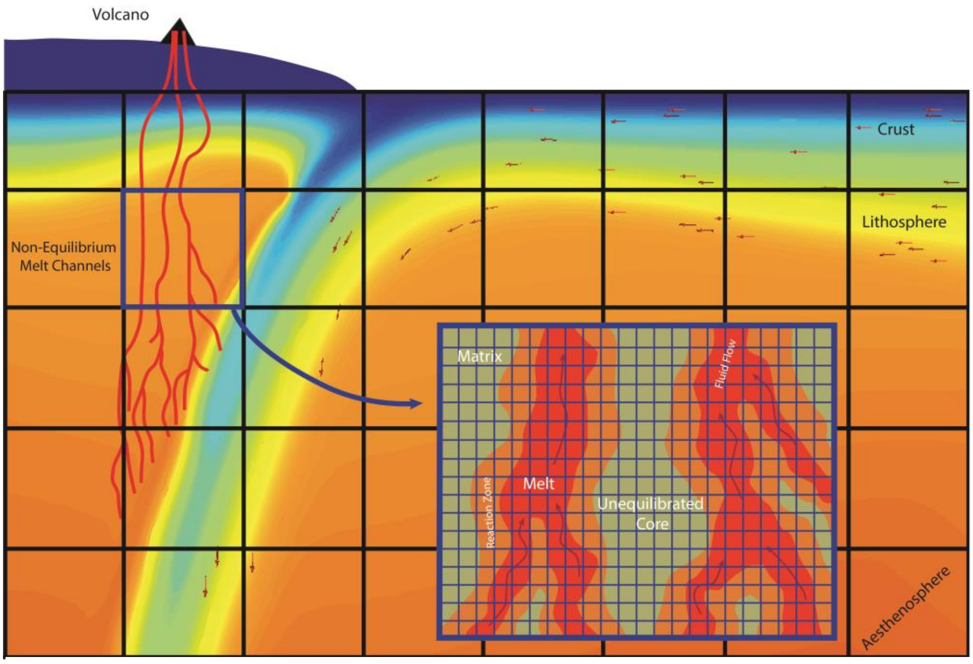

Figure 1. *MsFEM coupling of a small-scale melting transport problem in the analysis of the subduction of continental lithosphere.*

Recycling the dynamic lithosphere: the growth of gravitational instability when driven by complex tectonic forcing

Adam Beall,

Monash University

Continental lithosphere typically avoids participation in mantle convection. This boundary layer stability is achieved by means of intrinsic chemical buoyancy, brief thermal buoyancy and, for older and volatile-free lithosphere, a relatively high effective viscosity. However in specific conditions continental mantle lithosphere can be recycled, resulting in crustal deformation and emplacement of new mantle lithosphere. I build upon existing models of active recycling in the form of a lithospheric mantle drip beneath western North Island, New Zealand, which is driven by tectonic juxtaposition of regions of contrasting lithosphere. A particle-in-cell finite element code, Underworld, is used to model the evolution of a lithospheric instability, for the simplified case of tectonically thinned lithosphere with a temperature-dependent visco-plastic rheology and varied thinning style. A parameterisation is used to include the case of active extension during instability growth. By modelling a lithospheric rheology that can evolve dynamically, a range of instability rates and behaviours, as well as a local critical Rayleigh number, are characterised. The relationship between drip growth and dynamic tectonic stress state is studied by quantifying the time-scales of 'natural' and 'tectonically forced' instability in 3D. The mechanical criteria required for the dampening of instability growth-rates are discussed and such criteria may further constrain the processes required for young lithosphere to evolve towards a state of long-term stability.

The thermochemical structure of Precambrian lithosphere from multi-observable probabilistic inversions: a comparative study

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Precambrian lithosphere is typically thought of as cold, strong, and neutrally buoyant (due to depletion) relative to its Phanerozoic counterpart. However, recent seismic and potential field studies of Precambrian domains have highlighted a number of intra-lithospheric complexities/differences that do not conform to the abovementioned simplistic view (e.g. Darbyshire et al., 2013). In addition, there is evidence that the sublithosperic mantle beneath cratons is also heterogeneous in its thermochemical structure (e.g. Lebedev et al., 2009).

To gain insight into the nature of these heterogeneities, we apply a recent multi-observable probabilistic inversion method (Afonso et al., 2013a,b) to 10 reference locations around the world (Archean and Proterozoic), including the Yilgarn Craton in Western Australia. Our main aim is to derive 1D estimates of the thermal and first-order compositional structure of the entire lithosphere and sublithospheric upper mantle at these locations. Radial anisotropy and crustal structure are also obtained from the inversions. Our geophysical dataset includes Rayleigh and Love (phase-velocity) dispersion curves, absolute elevation, geoidal height, and surface heat flow data. Our petrological dataset includes over 2100 natural mantle samples collected from different tectonic settings (xenoliths, abyssal peridotites, ophiolite samples, etc.).

In this presentation, our preliminary results on the similarities and differences of these 10 Precambrian domains will be discussed within the context of their tectonic evolution. Our comparative study reveals a variety of thermochemical structures that warrant more detailed 3D studies and revised interpretations.

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The role of steady-state thermal models in a young volcanic province: The Newer Volcanics Province, southeast Australia

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The Newer Volcanics Province of south-eastern Australia is a Pliocene to recent intraplate basaltic province, which occupies > 20,000km^2. Little is known about the origin and controls of volcanic activity within the province, with processes including mantle plumes, edge-driven convection and asthenospheric shear all suggested. It has been theorised that a shift to east-west compression in the Late Neogene produced trans-tension along parallel fault surfaces allowing seismic-controlled decompression melting and volcanism. To validate this, a 3D model of Victorian crust has been imported into Underworld, a finite element Lagrangian particle-in-cell code, to solve for steady-state heat transfer. Temperatures at the base of the crust are forward modelled against surface heat flow data, with depth-dependent thermal conductivity and heat production accounted for. Impossibly high Moho temperatures (in excess of 900°C) were modelled between Bendigo and Ballarat which means a steady-state approach to crustal heat flow breaks down. The anomalous zone between Bendigo and Ballarat correlates with a region of low teleseismic velocity and high electrical conductivity that intrudes well into the mid crust. This suggests transient heat flow, arising from magma migration, dominates this part of the crust. Finite difference models of thermal diffusion show multiple pulses of magma migration at shallow depth are required to reproduce the heat flow signature observed at the surface. This work demonstrates the value of heat flow data in constraining the transient thermal effects of volcanism. Future work will examine the flow dynamics of magma migration through preferred fault pathways, and coupling this with a convecting upper mantle.

Theoretical analysis of the driving forces of Archean fluid and heat transfer flows.

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Very often, the rocks formed in the deeper crust can be found on the surface along modern and ancient mountain belts and orogenic plateaux. Such movements are usually tectonically activated, requiring space made either through lateral displacements of the upper crust (via extension), downward return flows of the upper crust (sagduction), localized erosion, or a combination of these mechanisms. With these movements, there will usually be transfers of material, fluids, and heat that drive the formation of ore deposits.

For a deeper understanding of the processes associated with the development of these ore deposits and mineral systems, it is critical that we grasp how these fluid and heat transfer forces operate and what activates them. This work is designed as a detailed theoretical evaluation of the forces that drive these fluid and heat transfers. Using powerful numerical codes such as TOUGH2 and SHEMAT, this evaluation endeavours to couple 2D and eventually 3D thermal-mechanical modelling existing output with 3D coupled heat and fluid flow experiments. The outcome of this will help us to understand the formation of such mineralisation patterns.

The successful outcome from this evaluation will also open up new vistas of research, especially in the field of exploration geochemistry and subsurface uncertainty assessments. Industry players will be able to use the newfound findings as an aid to delineate future exploration areas. Apart from being an important contribution to the scientific community, this successful outcome will help maintain Australia's position at the forefront for mineral systems research

Ore deposits of the future - magmatic Ni-Cu-PGE sulphide mineral systems on Mars

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On Earth and Mars, highly siderophile (HSE) and chalcophile elements/metals, such as gold (Au), nickel (Ni), copper (Cu) and the platinum group elements (PGE: Os, Ir, Ru, Rh, Pt, Pd) are strongly partitioned into the metallic core. However, far from being depleted, both planets have elevated (near-chondritic) mantle HSE abundances. Over the long geological history of the Earth, primitive mantle-derived ultramafic magmas sampled these metals and transported them into the lithosphere to form mineralised mafic-ultramafic intrusions and lava flows.

These primitive mantle derived magmas are usually emplaced as layered intrusions at various levels into the crust (e.g. Bushveld - South Africa; Stillwater - USA), or deposited as lava flows at the surface, such as Archean komatiites (e.g. Mount Keith, Australia), Proterozoic ferropicrites (e.g. Pechenga, Russia), and Phanerozoic picrites (e.g. Noril'sk, Russia). These igneous provinces share one common characteristic: they host high-grade (economic) Ni-Cu-PGE sulphide mineralisation. On Earth, igneous complexes associated with impact generated melt sheets also host significant mineralisation, with the Sudbury Igneous Complex containing the largest Ni-Cu-PGE sulphide concentrations on the planet.

Most of what we know from the Martian surface and its interior comes from orbiting satellites and Landers or Rovers equipped with analytical instruments. In addition, the Shergottite-Nakhla-Chassignite-(SNC-) group meteorites, which represent Martian volcanic rocks ejected from Mars at various times by asteroid and/or meteorite impacts, enabled a more detailed insight into the crustal section of Mars. All information gained so far points to a heavily cratered Martian crust/surface, which is dominated by extensive surface volcanism, that show striking mineralogical, petrological and chemical similarities with ultramafic primitive magmas (i.e. komatiites, ferropicrites) extracted from the terrestrial mantle. Consequently, Mars represents a promising target to investigate and explore magmatic Ni-Cu-PGE sulphide mineral systems associated with primitive surface volcanism and layered impact melt sheets.

The main aim of this project is to identify prospective environments for the formation of high-grade polymetallic (Ni-Cu-PGE) sulphide mineralisation, and map areas of interest where mineral exploration on Mars could be focussed in the future. One of the main hypotheses to be tested is whether the integration of available remote sensing data, with (in-situ) analyses of Martian crustal rocks (Lander and Rover landing sites and Martian meteorites), can shed light on the nature and evolution of magmatic sulphide mineral systems on Mars. From a scientific point of view, the outcomes from this study will also result in a better understanding of the temporal and spatial igneous history (e.g. melt S- and PGE-contents as a proxy for the fertility of mantle source rocks and derived source melts) and its influence on the atmosphere (sulphur-degassing). Another outcome is an extension of our current knowledge of the possible environments for the formation of magmatic Ni-Cu-PGE sulphide mineral systems that may be useful for prospective/exploration targeting of our planet.

The 4D crust-mantle evolution and mineral system distribution of the 3.0 Ga Marmion Terrane, Western Superior Province, Canada: Preliminary Observations and Interpretations

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We present the preliminary field-based observations and interpretations of the 4D crust-mantle evolution and mineral system distribution of the Marmion Terrane, Western Superior Province, Canada. This study is part of a core project of the ARC Centre of Excellence for CCFS, which aims to map the lithospheric architecture of the Western Superior Province using U-Pb, Lu-Hf, and O isotope systematics of zircons. Lu and co-workers are currently conducting multi-isotopic study in the Wabigoon Subprovince to define internal terrane boundaries. The 3.0-2.7 Ga Marmion terrane (Tomlinson et al, 2003) within South-central Wabigoon was chosen as a subset of this field area in which to include structural, metamorphic and stratigraphic study of greenstone belts.

Fieldwork in 2013 included regional sampling, belt-scale study of the greenstone belts, and localized study of mineralisation. A total of 222 samples were collected for whole rock analyses and thin sections, and 100 samples will be selected for zircon separation (Fig. 1). Structural observations both at the regional and outcrop scale support final NW-SE compression for the area. Stratigraphic observations support autochthonous development of the greenstone belts. This interpretation will be tested by a spatially constrained multi-isotopic study. In most instances, the contacts between the greenstone belts and the underlying, marginally younger TTG, is intruded by mafic dikes and young tonalite. Deformation is concentrated in these areas. Gold mineralisation occurs near NE-trending structures and contrasting lithology but within a variety of host rocks and with variable alteration mineral assemblages. The 10.7 M oz Hammond Reef gold deposit is located within the 3.0 Ga Marmion Intrusive Complex along intersecting structures. These observations, in addition to isotopic and geochemical analyses, will be used to constrain the crust-mantle evolution of the Marmion Terrane and related mineralization.

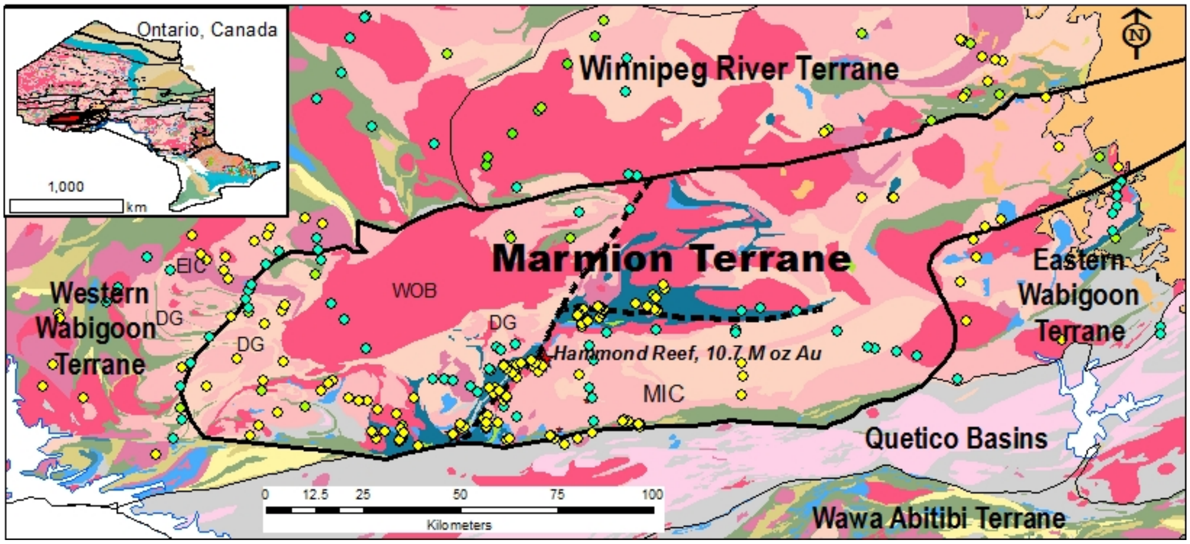

Figure 1: Geological map of the Marmion terrane showing sample distribution: Yellow circles-this study, 2013; blue- Lu (2013), green-Stainton (2013). Intrusions: MIC-Marmion Intrusive Complex; WOB-White Otter Batholith; DG-Dashwa Gneisses; EIC-Entwine Intrusive Complex. Geology is from Ontario Geological Survey (2011), terrane boundaries of Stott et al. (2010). Hatched lines show postulated terrane boundaries.

Tomlinson, K., Davis, D., Stone, D., and Hart, T., 2003, U–Pb age and Nd isotopic evidence for Archean terrane development and crustal recycling in the south-central Wabigoon subprovince, Canada: Contributions to Mineralogy and Petrology, v. 144, no. 6, p. 684-702.

Structure of the Mick Adam Gold Deposit and the Regional Implications: Yilgarn Craton, Western Australia

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The Kunanalling-Zulieka belt has a long history of gold production; the area however remains poorly understood. To date, there has been little integration of the different structural, alteration and mineralisation styles recorded in the various deposits within a regional and camp scale. We present initial structural data collected on the Mick Adam deposit as part of a broader research project documenting the regional structural evolution associated with gold mineralisation within the Coolgardie, Depot and Ora Banda Domains, in the south-eastern Yilgarn Craton, through the integration of the stratigraphic, structural, metamorphic and alteration histories of the region.

At the regional scale as well as the deposit scale, the influence of granitoids on gold mineralisation in the Yilgarn Craton has been hotly debated. Granitoids forming about 80% of the Yilgarn Craton, have been invoked as sources of metals and heat, or locations of local stress heterogeneity for subsequent deformation and mineralisation (eg. Duuring et al., 2001; Ojala et al., 1993). The Mick Adam gold deposit is hosted in the thin, tail-like extension of a tonalite pluton (Kintore Tonalite) located on the Kunanalling Shear Zone in the Kalgoorlie Terrane of the Yilgarn Craton, Western Australia. The deposit and shear zone are contained within a mafic-ultramafic sequence. Preliminary data on the geometric relationship between gold bearing, southwest dipping quartz extension veins and shearing along the tonalite-basalt contact indicates that mineralisation occurred during normal dip-slip shear on the tonalite-basalt contact. The field data is consistent with either a period of extension in the regional deformation sequence, or local dilation resulting from strain heterogeneities due to the rheology and shape of the Kintore tonalite. By deciphering the deformation history of the Kunanalling Shear Zone, and placing gold mineralisation within this framework, we infer that mineralisation at Mick Adam developed within a dilatant accommodation zone facilitated by the heterogeneous distribution of stress around the Kintore Tonalite.

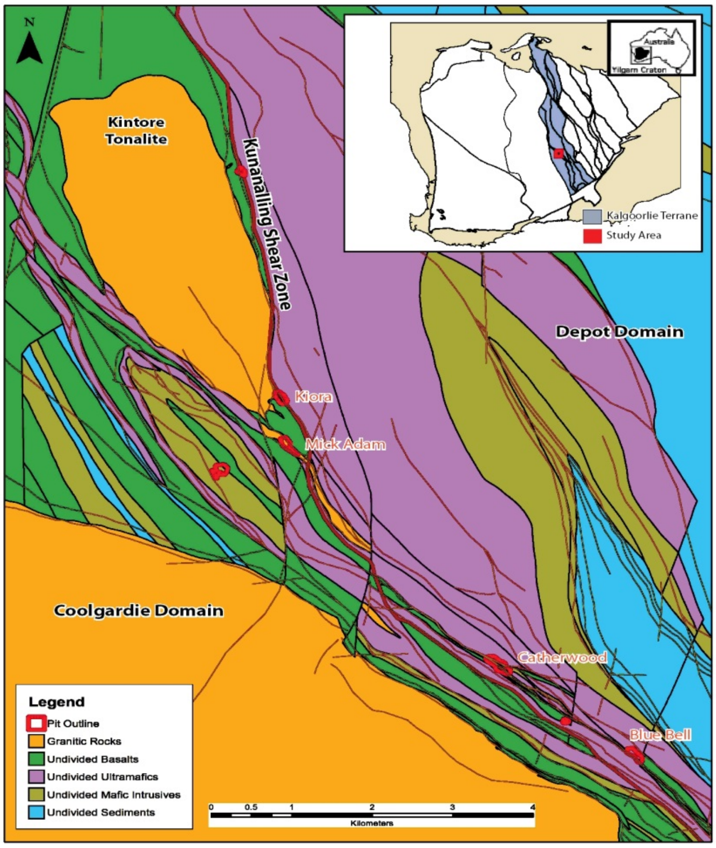

Figure 1: Location geology map of the Kintore Tonalite region

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Structural framework and evolution of the world class Siguiri orogenic gold district (Guinea, West Africa)

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With over 17 deposits, the Siguiri gold district is the only world-class district hosted in the Siguiri Basin (Guinea), one of the vastest basins of the Paleoproterozoic Baoulé-Mossi domain of West Africa. The Siguiri district, spreading north of the Siguiri Basin, is hosted in lower Birimian metasediments of volcaniclastic and granitic origin, intruded by late Eburnean intrusions (Egal et al., 1999, 2002).

At least three main deformation events affect the weakly metamorphosed sediments: D1s is characterised by a N-S compression developing WNW-ESE thrust faults, it is weakly expressed around Siguiri but increases southward; D2s is associated with an E-W compression and develops N-S thrusts and NE-trending dextral shear zones, it is responsible for the bulk of the deformation in the Siguiri Basin; and D3s, a NW-SE compressional event that refolds earlier structures and is linked to a NE- to NNE-trending sub-vertical cleavage (Figure 1).

Mineralisation appears to be mainly developed along the D2s N-S and NE-SW cross-structures. It is associated with localised stockworks of prominently SE-dipping gold-bearing quartz-carbonate veins. NE-SW shear zones are in places accompanied by gold-bearing pyrite and restricted carbonatation of the host rocks.

Based on field observations of mutual cross-cutting relationships of mineralised veins, transient and repetitive stress-switches associated with mineralisation were recognised. Maximum stress orientation associated with mineralisation switches late-D2s and repetitively shifts from a NNW-SSE extensional to a WSW-ENE transtensional setting. Work is currently ongoing to address the question as to why these mineralisation-related transient stress-switches occur regionally and in a short span of time.

This PhD project documents the lithology, structural evolution and the paragenetic sequence of this major gold district and integrates the observations made at the deposit scale within the broader West African Craton architecture.

Keywords: Siguiri, tectonics, stress-switch, orogenic gold, West Africa

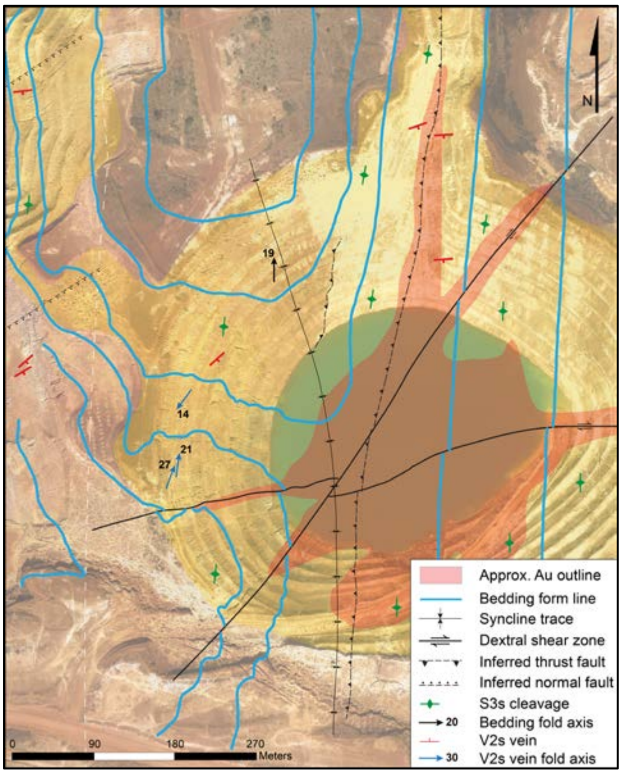

Figure 1: Structural map of Kosise pit showing the N-S thrust and NE-SW dextral shear zones along which stockworks of mineralised quartz-carbonate veins form (V2s). The faults, V2s mineralised veins and S3s cleavage all cut across the F2s fold.

Acknowledgements

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Hydrothermal footprints around magmatic nickel-sulfide deposits: a case study at the Miitel deposit, Yilgarn craton, Western Australia.

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The remobilization of metals during hydrothermal alteration of magmatic nickel-sulfide deposits could result in large geochemical haloes, potentially enlarging the detectable footprint of this ore type. The Miitel komatiite-hosted nickel-sulfide deposit (Western Australia) was used as a case study to investigate the nature and 3D geometry of this footprint. Portable XRF (pXRF) analyses on basalt samples, close to the contact with overlying komatiites, up to 200m away from the mineralization, detected the presence of anomalous Ni concentrations, associated with elevated As, Co, Pt and Pd. A petrographic study of the samples containing anomalous concentrations, combined with SEM-EDS techniques and elemental mapping, associated the elevated Ni concentrations with the presence of Ni-As rich phases. Gersdorfitte, and minor nickeline, are concentrated within small quartz veins within the footwall Lunnon basalt. They are interpreted as forming during the circulation of arsenic-rich hydrothermal fluids through the mineralization and subsequently along the footwall contact into the basalt. Results from in situ LA-ICP-MS analyses on gersdorffite and nickeline also indicate high PGE concentrations (Pt and Pd mainly) within these phases. This PGE enrichment suggests that the massive nickel sulfides from the Miitel ore bodies, rather than the adjacent barren komatiite, are the source of the remobilized Ni. This cryptic Ni-As-PGE signature in immediate footwall rocks could constitute an effective indicator of the presence of massive nickel-sulfides in an As enriched environment.

The Thrym Complex of southeastern Greenland: Evolution of Ni-Cu-sulfide mineralization in the lower crust

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The Thrym Complex of southeastern Greenland forms part of the North Atlantic Craton and is characterized by migmatitic orthogneiss, narrow bands of mafic granulite, ultramafic rocks, paragneiss, and alkaline-carbonatitic intrusive rocks. The narrow bands of mafic granulite are interpreted as tectonically emplaced gabbroic rocks exposed from the lower crust.

The two main styles of mineralization locally observed in the Thrym Complex are: (1) disseminated sulfides associated with mafic and ultramafic locally granoblastic-decussate rocks; and (2) remobilised sulfides concentrated in amphibolite-greenschist facies shear zones. This mineralization observed differs from typical orthomagmatic Ni-Cu-sulfide occurrences common in the upper crust in that there is no evidence for significant contamination by a crustal sulfur source. Furthermore, no trans-lithospheric structure for the emplacement of the mineralization is apparent.

The sulfide mineralization in the Thrym Complex may represent the root of such a system or the result of a similar magma being emplaced in the lower crust in an area lacking such a fluid-pathway. Mantle-sourced magma emplaced at pressure-temperature conditions in the lower crust would maintain or achieve sulfur-saturation more easily than magma emplaced in the upper crust [1]. As such, there may be no need for interaction with crustal material for the formation of sulfide mineralization in lower crustal settings.

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Geology, geochemistry, Sr–Nd and zircon Hf–O isotopic compositions of the Twin Bonanza intrusion-related gold deposit: Implications for a post-collisional lithospheric mantle source for the Granites-Tanami Orogen, North Australian Craton

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The poorly exposed Palaeoproterozoic Granites-Tanami Orogen (GTO) in the North Australian Craton (NAC) straddles the Western Australia and the Northern Territory border. The orogen is positioned between the Halls Creek Orogen to the northwest and the Arunta Orogen to the southeast. The GTO has experienced major tectonic and magmatic events, including: the formation of the Tanami back-arc basin; collision and amalgamation of the GTO with the Arunta Orogen along the Willowra Lineament; convective removal of the thickened lithospheric mantle root and lithosphere extension, collisional to post-collisional mafic to felsic magmatism and greenschist facies metamorphism during ca. 1864–1790 Ma. Several large gold deposits are present in the GTO, which highlight the significant potential for the discovery of economically important mineral occurrences in this gold province. The combined gold reserve in the orogen is over 400 tonnes of gold for predominantly orogenic gold deposits. Twin Bonanza is unique for being the only known intrusion-related gold deposit (IRGD) in the region with a total inferred resource of 127.9 t with a grade of 0.65 g/t Au for 2.67 Moz Au.

Gold at Twin Bonanza is a low grade, large tonnage deposit hosted by mildly to moderately altered monzonite within a composition pluton known at the Buccaneer Porphyry. The mineralisation is in sheeted quartz veins, chalcopyrite-pyrite-arsenopyrite-rich mildly to moderately altered quartz monzonite and associated with highly altered fine arsenopyrite disseminated sheared quartz monzonite. The Buccaneer Porphyry mainly consists of two generations of porphyritic quartz monzonite at the deposit. Also present are mafic microgranular enclaves (MMEs) in both of the quartz monzonite bodies.

The MMEs have a high K calc-alkaline to shoshonite composition and quartz monzonites have a shoshonite composition. Major elements and REEs versus SiO_2 plots for the MMEs and quartz monzonites define tight linear trends. The MMEs have high Cr (up to 920 ppm) and Ni (up to 220 ppm) concentrations. Most of the MMEs and quartz monzonite samples have high Mg#, are highly enriched in LREE and LILE compared with HREE, have pronounced negative Nb, Ta, Ti anomalies, and have high $(La/Yb)_N$, $(Sm/Yb)_N$, consistent $(Dy/Yb)_N$ and low $(^{87}Sr/^{86}Sr)_i$ ratios. The MMEs and quartz monzonites have similar whole-rock $\varepsilon_{Nd}(t)$ (–4.4 to –1.2) and zircon $\varepsilon_{Hf}(t)$ (–5.5 to 0.8) values. The MMEs have very high Nb/Ta ratios between 15.0–28.6 (averaging 21.2), which are higher than those for the continental crust (12–13), bulk-silicate Earth (BSE: ~14), modern MORB (~13–16), ocean-island basalts (15–16) and chondrites (19.9 ± 0.6). Sensitive high-resolution iron microprobe

(SHRIMP) U-Pb zircon dating yielded three indistinguishable weighted average ages for the MMEs (1793 ± 9 Ma), early porphyritic quartz monzonite (1794 ± 7 Ma), and late porphyritic quartz monzonite (1795 ± 10 Ma). The geochemistry, whole rock Sr-Nd and zircon Hf isotopic characteristics and zircon U-Pb geochronology suggest that the two quartz monzonites and MMEs are products of progressive differentiation of a co-magmatic system. The source for this gold-rich intrusion complex is the lithospheric mantle, which had been previously metasomatized by subduction-related material and significant amounts of carbonatite. Zircon $\delta^{18}O$ values of the MMEs (5.58–6.66 ‰) is very similar with those of the late porphyrytic quartz monzonite (5.55–6.68 ‰), but dramatically lower than those of the early quartz monzonite (6.54–7.48 ‰), indicating that crustal assimilation to the magma that forming the early quartz monzonite was significant, but was negligible for the late quartz monzonite and MMEs. Zircon saturation thermometry yielded temperatures of 923°C for the early quartz monzonite and 951°C for the late quartz monzonite, representing the minimum temperature of crystal fractionation within the magma chamber. The corresponding depth and pressure to this temperature is ~37–38 km and 1 GPa, indicative of the upper part of the lower crust in the GTO. The geochemistry of these magmatic units also suggests that partial melting took place in the metasomatized lithospheric mantle underneath the GTO, which was triggered by lithosphere extension and hot mantle flow upwelling after connective removal of the thickened lithospheric mantle root during ca. 1795 Ma immediately following a post-collisional tectonic setting.

Structural setting and controls on ore geometry at the world-class Sadiola gold deposit, Mali, West Africa.

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The West African Craton hosts a number of world-class deposits related to a long-lived period of episodic crustal accretion and deformation referred to as the Eburnean Orogeny (c. 2130 to 1980 Ma) (Abouchami et al. 1990; Liégeois et al. 1991; Hirdes et al. 2002; Pawlig et al. 2006; Gueye et al. 2007). The 10 Moz Sadiola gold mine is located 420 km northwest of Bamako, in the Kédougou-Kénieba Inlier, a window of deformed Birimian volcano-sedimentary rocks along the Mali-Senegal border. The structural framework of the Sadiola deposit concurs with the structural architecture and metamorphic character of the eastern parts of the Kédougou-Kénieba Inlier (Dabo and Aïfa, 2010; Lawrence et al., 2013), and at a larger scale with that of the West African craton i.e. early thrusting tectonics followed by transcurrent tectonics (Liégeois et al. 1991; Milési et al. 1992; Feybesse et al. 2006; Dabo and Aïfa, 2010; Baratoux et al. 2011).

The Sadiola Fracture Zone was the dominant structure active during mineralisation and has therefore focused the greatest amount of dilation and permeability. Combined leapfrog modelling and structural analysis show that mineralisation resulted from the sinistral linkage of the Sadiola Fracture Zone and NE-trending shears. Geometric and kinematic analysis of the deformation defines two local deformation events D1s and D2s. D1s is associated with the formation of recumbent NE-trending folds (F1) and NE-trending thrusts whereas D2s is marked by the refolding of the early recumbent folds by NE-trending upright folds (F2) and the formation of NE-trending high-angle sinistral shears. The D2s local event controlled the ore-body geometry and is compatible with sinistral shearing under stress conditions associated with NW-SE compression. The Sadiola deep sulphide mineralisation is spatially associated with a distinct left hand flexure (dilational) with respect to the overall trend of the Sadiola Fracture Zone. Enhanced dilatation on the steeply-dipping segments of the Sadiola Fracture Zone under dominantly sinistral reactivation with a minor component of normal movement is also proposed to account for the wide mineralised intervals intersected at depth.

Although local complexities account for the Sadiola deposit intricate geometry, our study suggests that the two local deformation events D1s and D2s are related to the evolution of a single regional transpressive deformation event that represents the principal imprint of the Eburnean Orogeny.

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Relationship between microstructures and grain-scale trace element distribution in komatiite-hosted Ni sulphide ores from Flying Fox, Yilgarn Craton

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Komatiite-hosted nickel sulphides from the Flying Fox, Yilgarn Craton (Australia) consist of three main sulphide phases: pyrrhotite (Fe_7S_8), pentlandite ($(Fe,Ni)_9S_8$) and pyrite (FeS_2). Massive sulphide sample has been studied by electron backscatter diffraction and laser ablation inductively coupled plasma mass spectrometry and nano-scale secondary ion mass spectrometry. The trace element composition of pyrrhotite shows significant variation in specific elements (Pb, Bi and Ag). This variation correlates spatially with intragrain pyrrhotite microstructures, such as low angle and twin boundaries. Minor signatures of crystal plasticity in pyrite and pentlandite occur in the form of rare low angle boundaries (pentlandite) and mild lattice misorientation (pyrite). Trace element compositions of pentlandite and pyrite show no correlation with microstructures. Variations in pyrrhotite are interpreted as a result of intragrain diffusion during the syn- and post-deformation history of the deposit. Intragrain diffusion can occur either due to bulk diffusion, dislocation-impurity pair diffusion, or by “pipe diffusion”, i.e. along fast diffusion pathways at high and low angle, and twin boundaries. This contribution examines three different diffusion models and suggests that dislocation-impurity pair diffusion and pipe diffusion are the most likely processes behind increased trace element concentration along the microstructures in pyrrhotite.

Gold remobilization from low-grade sulphide mineralization to gold nuggets? The giant Obuasi gold deposit, Ghana

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Debate surrounds many of the world's largest gold deposits as to whether they benefited from multiple episodes of mineralization. The giant Obuasi gold deposit (62 Moz) in western Africa is hosted at the contact between the Ashanti greenstone belt and the Kumasi volcanosedementary basin, within the major Ashanti thrust fault. The host metasedimentary rocks have been affected by a complex deformation history, with at least three structural stages. The majority of the resource is contained between graphite-rich shears, in two distinct styles. These include gold-bearing disseminated arsenopyrite in sedimentary rocks and visible gold within microfractures in quartz veins as much as 4-m-thick. Microstructural observations demonstrate that the arsenopyrite-hosted ore formed coevally with the second stage of cleavage development. In contrast, the underground/field mapping and the 3D visualization of drill core data indicate that the visible gold ore formed coevally with the latest stage of folding and cleavage development. Our results confirm that the Obuasi gold deposit formed during at least two different structural stages.

The critical question that remains is whether the visible gold is the product of remobilization of gold from the disseminated arsenopyrite ores, or whether the two ore types are genetically unrelated, but spatially overlapping.

Microtextures in arsenopyrites show evidence for microfracturing, fragmentation and significant dissolution. Using a combination of Synchrotron X-ray-fluorescence elemental mapping (XFM beamline, Maia detector) and Secondary Ion Mass Spectrometry (SIMS) to investigate the gold distribution across the sulphide grains, coupled with crystal lattice deformation (EBSD), we find zones in arsenopyrite where gold has been leached and nickel enriched. This may indicate that gold was locally remobilized from arsenopyrite into late-stage microfractures.

Further work will investigate if the two ores styles can be geochemically linked and if the mass balance between the gold dissolved from the sulphide can account for the visible gold in the quartz veins.

Petrogenesis of the plutonic rocks in the Granites-Tanami Orogen

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There is general agreement that the continental crust is the result of the Earth's evolution, but there are various theories on how and when the crust developed. The proposed study will consider the difference between crustal growth and crustal preservation using the poorly studied Paleoproterozoic Granites-Tanami Orogen (GTO) in the North Australian Craton (NAC).
The project's focus is on the development of models for the geodynamics of crustal evolution using state-of-the-art isotope geochemical methods and geophysical data to characterise magmatism and its sources in the GTO through time. The aim is to develop new tools in locating economically important ore systems.

Results of the newly developed in-situ techniques of "forensic zirconology" combined with traditional whole-rock analyses of Sm-Nd, Rb-Sr and Lu-Hf isotopes on igneous rocks, will characterise the source and magmatic processes in the GTO. The results of these techniques will potentially clarify understanding of "crust growth versus crust preservation" during the Paleoproterozoic.
The geochemical results will be integrated with geophysical datasets to build up a comprehensive 4D (3D + time) map of the lithospheric architecture in the GTO. The 4D mapping will be used to solve the evolution of the orogen, refine the poorly constrained tectonic evolution of the NAC, and identify controls on the major mineral endowments, which is of greatest interest for mineral exploration.

$^{40}Ar/^{39}Ar$ thermochronology reveals fast exhumation in the western Albany-Fraser Orogen, Western Australia

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The Albany-Fraser Orogen of southwestern Australia is a Grenville-age orogenic belt that marks the suturing of the Yilgarn Craton of Western Australia to the Mawson Craton of South Australia and Antarctica. The western Albany-Fraser orogen consists of three geological domains: the Nornalup Zone, the Biranup Zone and the Northern Foreland. $^{40}Ar/^{39}Ar$ thermochronology of hornblende, biotite and muscovite grains from a 250 km transect across the western Albany-Fraser Orogen is used to study the exhumation and cooling history of the orogenic root. Previously published geochronological data dates peak amphibolite or granulite facies metamorphism in the Nornalup Zone, Biranup Zone and Northern Foreland at ca. 1170 Ma, ca. 1180 Ma and ca. 1210 – 1180 Ma respectively. All samples reported in this study yielded well defined plateau ages consistent with Stage II of the Albany-Fraser Orogeny (1215 – 1140 Ma). Two hornblendes from the Nornalup and Biranup Zones give cooling ages of 1169 ± 7 Ma and 1169 ± 6 Ma respectively. Four biotites from the Nornalup Zone give cooling ages ranging from 1144 ± 5 Ma to 1168 ± 5 Ma, one biotite from the Biranup Zone gives a cooling age of 1159 ± 5 Ma, and four muscovites from the Northern Foreland give statistically indistinguishable cooling ages ranging from 1157 ± 6 Ma to 1164 ± 5 Ma, with a weighted mean age of 1159 ± 6 Ma ($P = 0.10$). The new cooling ages imply that the three domains were exhumed rapidly after peak metamorphism, had been brought to a similar structural level (12 – 17 km depth) by ca. 1158 Ma, and have shared a common geological history since that time.

Minimum cooling rates of 13°C/Ma for the Nornalup Zone and 12°C/Myr for the Biranup Zone were calculated for cooling from the estimated hornblende closure temperature (ca. 550°C) through the estimated biotite closure temperature (ca. 300°C) within 7 – 10 Ma. This is much faster than the cooling of granulite-facies domains in other Proterozoic orogens, such as ca. 5°C/Ma in the Grenville orogen and 2 - 4°C/Ma in the Sveconorwegian orogen. The tectonic setting and timing of this rapid cooling in the western Albany-Fraser Orogen suggests that exhumation is the result of transpressional tectonic driving forces. This is distinctly different to exhumation models in other Proterozoic orogens, which are typically driven by mechanisms such as post-orogenic extension and gravitational collapse.

The path to peak metamorphism in an ultra hot orogen, South India

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Metamorphic rocks preserve pressure-temperature-time information of tectonic events. The rocks of the Trivandrum Block at the southern tip of India contain zircon and monazite that indicate a metamorphic event that lasted ca. 100 Ma and reflects the amalgamation of India, Madagascar, Sri Lanka, Australia and Antarctica to form the Gondwana Supercontinent.

During the construction of the orogen, the temperature in the lower crust increased to granulite grade (T»800°C), this resulted in partial melting of large volumes of lower crust material. The generated buoyancy of the melt coupled with deformation resulted in the extraction of the melt leaving behind a residual rock composition, the garnet-sillimanite-cordierite khondalites. As the rocks remained at ultra-high temperatures for a protracted period of time elemental diffusion within minerals has reequilibrated the mineral compositions. This leads to an underestimation of the peak metamorphism using traditional mineral thermobarometric techniques. A more robust approach to constrain the peak conditions of this orogenic event is the application of phase diagrams based on the bulk rock composition (pseudosections). However, also the abundance of these minerals is influenced by the occurrence of melt and fluid. Hence, a further method is to consider the presence and assumed behaviour of melt in the calculation to achieve the peak metamorphic condition by reintegration of melt into the thermodynamic model.

Sedimentary and tectonic evolution of a Late Triassic-Early Jurassic intracontinental basin in southeastern South China

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A broad intracontinental basin formed on a young orogenic belt in South China during the Late Triassic to the Early Jurassic. However, details are lacking regarding how the basin evolved, and what controlled the timing and rate of subsidence. Here we examine for the first time outcrop details of sedimentary successions in northern Guangdong Province to document the depositional architecture, basin history and its control factors. Stratigraphic analyses indicate that the basin formed piggy-back on the orogen since the Carnian. It was filled with coal-bearing alluvial-fan, fluvial, lacustrine, shallow-marine and deltaic deposits during the Late Triassic, and these collectively have a retrogradational to progradational (deepening to shallowing) trend. During the Early Jurassic, the basin was filled with shallow-marine to fluvial sediments, which document another deepening-shallowing depositional cycle. Shallowing and uplift, and subsequent changes of the depocentre were followed by the development of a basin-and-range magmatic province between the late Early Jurassic and the Late Jurassic. Eustatic changes played little role on sediment deposition, whereas palaeoclimate had a role on the formation of the coal deposits and on sedimentation (e.g. sediment supply and diagenesis). Instead, regional tectonism played the most important role in the evolution the basin, primarily through an influence on basin subsidence, accommodation creation, sedimentary patterns, and associated volcanism. A tectonic model for the temporal-spatial evolution of the basin involves the gravitational pull of a subducted flat-slab and its subsequent foundering.

From Rodinia to Gondwanaland: A tale of detrital zircon provenance analyses from the southern Nanhua Basin, South China

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The paleogeographic positions of the South China Block (SCB) during the Neoproterozoic and early Paleozoic are important for understanding the transition from the break-up of the supercontinent Rodinia to the formation of Gondwanaland. Integrated *in situ* U-Pb ages and Hf-O isotope analyses of detrital zircons from Cambrian sedimentary rocks in the southwestern SCB reveal major age populations at 2500 Ma, 1100–900 Ma, 850–750 Ma and 650–500 Ma, with a predominant group at ~980 Ma that counts for ~50% of all analyses. Zircon Hf-O isotopic results suggest three Precambrian episodes of juvenile crustal growth for the source area(s) (3.0 Ga, 2.5 Ga and 1.0 Ga), with major crustal reworking at 580–500 Ma. The source provenance as defined by the U-Pb and Hf analyses is distinctly different from the known tectonomagmatic record of the SCB, or that of western Australia or western Laurentia, but matches well with that of the Ediacaran (latest Neoproterozoic)–Cambrian clastic sedimentary rocks and granitic intrusions in the NW Indian Himalaya. The SCB–NW India provenance linkage appears to have started from the Ediacaran. We propose that after breaking away from central Rodinia, the SCB collided with NW India during the Ediacaran–Ordovician time, causing the "Pan-African" Kurgiakh/Bhimphedian orogeny at the northern margin of India as well as the intraplate Wuyi-Yunkai orogeny (>460 Ma to 415 Ma) in South China. The Ediacaran–lower Paleozoic clastic sedimentary rocks in the Nanhua Basin are therefore interpreted to be foreland deposits formed during the collision of the SCB with Gondwanaland.

Rethinking the Columbia supercontinent: new paleomagnetic poles for India from 2.37-1.88 Ga

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Recent advances in paleotectonics and detrital geochronology indicate that Earth's history was punctuated by numerous supercontinental configurations. The geometry of the most recent supercontinent, Pangaea, is well constrained from seafloor magnetic anomaly data, paleomagnetism, geology, and faunal evidence, although there are still vigorous debates regarding the exact configuration. Determining the geometries of earlier supercontinents is far more difficult, and paleomagnetic investigations remain the only quantitative technique for testing these configurations. The geologic record present in Precambrian terranes suggests global orogenesis from 1.9-1.7 Ga, and alignment of these orogenic belts has led some to construct a supercontinent named Columbia. Here we test this supercontinent configuration using well dated paleomagnetic poles at 1.88 Ga, including a new study on mafic dykes from Peninsular India. We report results from 4 separate magmatic events during the Paleoproterozoic, including a ~85,000 km^2 radiating dyke swarm with a fanning angle of 65° at 1.88 Ga. Using well established paleomagnetic poles from available continents we analyse potential cratonic relationships for each magmatic interval, and construct an Apparent Polar Wander Path for Peninsular India from 2.37-1.88 Ga.

The development of plate tectonics caused the demise of BIF.

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Numerous hydrothermal vents are actively depositing large quantities of iron oxides and silicates around the vents and over the deep sea floor at the present time but most of these deposits are destined to be destroyed by the subduction of ocean crust. It is proposed that these deposits are the modern analogues of banded iron formations (BIF) and that they have formed throughout geological history but were only preserved where segments of ocean crust or deep ocean sediments have been incorporated into continental areas.

During the early Archean era the globe was covered by a shallow ocean that increased in depth over time as more water was added from outgassing of volcanic eruptions and also deepened in response to the formation of buoyant continental masses that rose above sea level and restricted the area of oceans. The earliest cratons were formed by partial melting at the base of strongly folded oceanic crust and overlying pelagic sediments producing the sialic granitoids and preserving remnants of ocean floor deposits in the greenstone belts. Ever since the commencement of modern style plate tectonics, oceanic crust has been created at spreading centres and destroyed by subduction at plate margins and the preservation of greenstone belts and BIF was largely supplanted by the accretion of sedimentary orogenic basins.

Early sedimentary basins that formed on the thinner margins of the continents were depressed below the level of the deep sea floor such that hydrothermal plumes and density currents from vents on the ocean floor deposited banded iron formations within the sedimentary piles. Similarly during the Neoproterozoic era, massive ice sheets depressed the continents and marginal sedimentary basins were depressed to the level of deposition of banded iron formations.

Assembly of lithospheric mantle beneath accretionary orogens: the case of the Eastern Mediterranean

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The nature and origin of lithospheric mantle beneath orogenic regions is enigmatic. Severe compression and shortening of the buoyant crust occurs, and the mantle section of the lithosphere is usually thought to be removed and returned to the convecting mantle. In accretionary orogens, a mixture of small continental blocks and oceanic crust are subducted or stacked at convergent margins, leading to the possibility of shallow imbrication of diverse rock packets to form new lithospheric mantle. These processes may be especially relevant for geodynamic processes in the first half of Earth history, when accretionary orogens may have been more common. The smaller number of large continental blocks and the probable formation of new tonalitic continental crust at convergent margins would have led to many small arc-related continental blocks that could become involved in accretionary orogens.

The eastern Mediterranean region has been one of the main accretionary orogens during the last few tens of millions of years: several small oceans have closed and small continental blocks caught up in what has become the western end of the Alpine-Himalayan orogen. We show that during the accretion of oceanic arcs and small continental blocks in the Mediterranean region, the mantle lithosphere is newly created and composed of intimately mixed peridotite and crustal material from the forearc region.

Potassium-rich volcanic rocks emplaced more than 30 Ma after the formation of this lithosphere carry evidence for the presence in it of extremely depleted peridotite in their sources, but also for mica-bearing pyroxenites formed by reaction between subducted continental sediments and peridotite. The rock types in the melt sources can be identified and monitored by the minor and trace element compositions of olivine phenocrysts in the volcanic rocks, thus providing a window into the newly formed lithospheric mantle. These can be compared and contrasted with olivine megacrysts that crystallized within the mantle. Both types of olivine have elevated concentrations of Li and Zn that correlate positively with $^{87}Sr/^{86}Sr$ of the rocks, proving an origin from continental crust-derived sediments.

If much of the continental crust is formed by accretionary orogens of this type, then extensive tracts of the continental lithosphere may contain mixtures of ultra-depleted peridotite and recycled crustal material. In that case much of the subducted sediment is not completely returned to the convecting mantle, but becomes stored within the subcontinental lithospheric mantle, explaining the rarity of geochemical traces of recycled continental crust in the convecting mantle as tapped by ocean island basalts.

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Pre-existing orogenic architecture and the preservation of low metamorphic grade, fluid-bearing sedimentary sequences in the eastern Gawler Craton, South Australia: preparing the ground for Olympic Dam

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Hydrothermal ore deposits result from a number of factors including super-saturated hot metal-bearing fluids, the transport of such fluids via structural pathways and the presence of suitable host lithologies. In the case of the Olympic Dam supergiant iron oxide-copper-gold (IOCG) deposit, multiple fluid sources, sedimentary and magmatic, were particularly important in generating the chemistry suitable to precipitate large quantities of Cu-Au-U-REE-bearing minerals (Haynes et al., 1995; Johnson and McCulloch, 1995). The primary thermal driver for the mineralising event at Olympic Dam was A-type early Mesoproterozoic intrusive and extrusive magmatism; however, magmatism of this age is also present across the central and western Gawler Craton and yet IOCG deposits are apparently restricted to a north-south belt along the eastern margin of the terrane, the so-called Olympic Cu-Au Province (Skirrow et al., 2007). While there are geochemical differences between the early Mesoproterozoic granites in the west versus eastern Gawler Craton (Budd et al., 2001), there are also stark differences in the nature of the crust into which those magmas intruded. In particular, review of the available metamorphic data from the Gawler Craton shows that at c. 1600 Ma – the onset of the magmatism and the start of metallogenesis in the Olympic Cu-Au Province – the eastern Gawler Craton preserved an abundance of essentially unmetamorphosed c. 1750 Ma evaporate-bearing sedimentary sequences (Wallaroo Group; Conor et al., 2010). In contrast, c. 1750 Ma sedimentary rocks across the northern, central and western Gawler Craton were almost universally metamorphosed to amphibolites-granulite facies during a high temperature-moderate to low pressure c. 1730 – 1690 Ma event locally known as the Kimban Orogeny. Intrusion of high-temperature A-type melts into these previously metamorphosed and therefore largely dry sedimentary sequences in the central and western Gawler Craton, was not able to generate the necessary abundance of intra-crustal fluids, particularly saline fluids, that are key ingredients for IOCG deposit formation (Groves et al., 2010). Therefore, the example of the early Mesoproterozoic mineralisation event in Gawler Craton demonstrates a first order lithospheric control on the west to east partitioning of Paleoproterozoic orogenesis effectively prepared the ground for the formation of the Olympic Cu-Au Province through either removing or preserving basinal fluids in supracrustal sequences across the Gawler Craton. Evidently, where such basinal fluids can be preserved subsequent magmatic-related heat and structural processes can force fluid mixing or fluid evolution (e.g. Lester et al., 2012) that leads to the precipitation of metals and the formation of ore deposits.

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3D Fault Network of the Murchison Domain, Yilgarn Craton.

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The architecture of Archean granite-greenstone terranes is often controlled by networks of 10 km to 100 km-scale shear zones that record displacement under amphibolite facies to greenschist facies metamorphic conditions. The geometry of such crustal scale 'fault networks' has been shown to be highly relevant to understand the tectonic and metamorphic history of granite-greenstone terranes, as well as the availability of structural controlled fluid pathways related to magmatic and hydrothermal mineralization.

Here we present a network of the major faults of the NW Yilgarn Craton between the Murchison's NW contact with the Narryer Terrane to the Ida Fault, its boundary with the Eastern Goldfields Superterrane. East of the Ida, the far east of the model, the faults have been integrated with Geoscience Australia's pmd*CRC Eastern Goldfields model. The northern extremity is bounded by the Proterozoic cover and the southern limit has been arbitrarily chosen to include various greenstone belts.

The motivation for the model was the interpretation of the Youanmi, South Carnarvon and Capricorn Deep Seismic Reflection Surveys all of which were processed by Geoscience Australia and interpreted by GSWA and Geoscience Australia down to 20 s TWTT, equivalent to about 60 km depth.

The interpretation of the lines showed a reflective upper crust which could be related to the surface geology. Below this was a non-reflective upper-middle crust which overlay a highly reflective lower-middle crust which had become known as the Yarraquin Seismic Province. The lower crust is bounded by a sharp and a relatively uniform Moho at ca. 33 km depth that drops somewhat across the Ida Fault.

The fault network has been modelled based on the dips and architecture of the seismic interpretations, mapped geology and examination of magnetic anomaly maps.

Taking into account the seismic interpretation, potential field datasets, and field observations, we can correlate two categories of large-scale structures between the reflection survey lines, a shallow west dipping set and a deep east-dipping set. In the west, the major faults in the upper crust, such as the Carbar and Chundaloo Shear Zones, dip steeply towards the west and then flatten off at depth. They form complex branching fault systems that bound the greenstone belts in a series of stacked faults. However, none of these major faults can be followed into the Yarraquin Seismic Province. In the central portion, the major faults such as the Youanmi and Wattle

Creek, dip to the east and can be followed into the fabric of the Yarraquin Seismic Province. The Wattle Creek Shear Zone in particular can be traced on all three of the Youanmi seismic lines. The greenstones are cradled between these major faults and antithetic westward dipping subsidiary faults such as the Edale Shear Zone.

While the Ida Fault cannot be located with great confidence, the slight drop in Moho depth toward the east and the overall change of seismic texture delineate the Youanmi-Eastern Goldfields boundary. The Lawlers Anticline, presumably located in the hanging wall of the Ida Fault, again changes the style of faulting with the Lawler's tonalite forming the core of a 10 km-scale antiform.

The fault network presented here is a milestone to a craton-wide integrated structural model and will hopefully contribute to provide a better spatial context for geological, geochemical and geophysical data in our quest to understand the tectonics and mineral potential of the Yilgarn craton.