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Timescales of Geological Processes

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ABSTRACTS

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INVITED ABSTRACTS

Fluid-Rock Interaction Timescales in Compacting and Anatectic Systems

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A growing body of studies document fluid flow that is highly transient on geological timescales. However, significant questions remain regarding fluid-rock interaction timescales and processes in compacting systems (two-phase flow) and anatectic systems. We present three case studies to examine these types of systems in greater depth. (1) Two-dimensional modeling of a compacting crustal column shows that km-scale, high-permeability conduits can develop in ~10^4 years. These conduits may transport significant thermal energy when fluxes are large; if fluids are anomalously hot (e.g., derived from degassing magma) then thermal perturbations >100 ^oC are possible on multi-km length scales. (2) Two-dimensional modeling of thermo-haline convection demonstrates that convection is heavily damped or eliminated in compacting porous media. During compaction, flow is dominantly upward, and the transition between regimes happens progressively as compaction proceeds. Nonetheless, isolated "compartments" can develop in the crustal column within which localized convection may occur; individual cells have lifetimes of as little as a few thousand years. (3) A field-based study of metamorphic timescales in eclogite from Connecticut, northeastern USA, examines multiple, sharply-bounded compositional zones in garnet. Phase relations and garnet diffusion modeling show that attainment of eclogite facies conditions was due to a ~5 kbar pressure increase which lasted only ~500 years. Local overpressure in response to partial melting in a confined volume (e.g., Vrijmoed et al. 2009) by transient shear heating can account for this ultra-fast compression without requireing burial to great depth. The above three examples highlight transient fluid-related processes that are possible in compacting and anatectic systems.

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Metamorphism at near seismic rate

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Metamorphism is regarded to be a slow process taking place millions of years after tectonic events (Thompson and England 1984). In the case where driven by seismically induced fluids, metamorphism may occur at a near catastrophic rate. We visit metamorphism (eclogite and amphibolite facies) that occurs along pseudotachlyte decorated seismic fault planes from the Bergen Arcs, W-Norway in order to investigate the rate controlling parameters from micro-textures.

Within the pseudotachylyte proper dendritic and spherulitic textures are common and points to a quenching that occurs in seconds after the seismic event. Flow banded pseudotachylytes with dendrite of scapolite and epidote overgrowing the flow banding implies that the melt/gaseous phase contained volatile species like S and H_2O. Sulfide jets refer to trails of micrometer sized sulfide blebs injected into the side wall garnets. Together with splays of hydrous and carbonations minerals emanating from the fault plane this suggest a forceful and rapid metamorphism as fracture propagated and the compressional and dilatational waves from the seismic faulting pasted.

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Three Kinds of Metamorphic Pulses: Cause and Consequence

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Metamorphism is often regarded and modeled as a slow, steady, tectonically paced process. However, new data and observations (from zoned mineral chronology and geospeedometry) have shown that, instead, metamorphism can be punctuated or even dominated by brief pulses. It may be that most of the physical and chemical manifestations of long-lived tectonometamorphic processes were created only during these brief pulses of activity. There are important differences and similarities in how "metamorphic pulses" can be defined, both in terms of how they are caused, and how they are manifested in the rock record. A "pulse" is any process, condition, or manifestation thereof that persists or dramatically accelerates for a brief period of time (relative to the background timescale of tectonic forcing). Metamorphic pulses may be categorized into three groups: geodynamic pulses, thermodynamic pulses, kinetic pulses. A geodynamic pulse results from a rapid tectonic forcing that causes P, T, or X to change rapidly. Advective heat transfer via magma emplacement, or vertical motion near shear zones, or any passage through sharp thermal gradients are examples of scenarios that may create a geodynamic pulse. A thermodynamic pulse results from equilibrium thermodynamic effects when a specific net-transfer reaction is crossed, or if reaction isopleths become narrowly spaced, even with slow and steady P-T evolution. A kinetic pulse can occur if a thermodynamically stable reaction has been overstepped due to some kinetic barrier. Once that barrier is removed or overcome via some kinetic trigger (perhaps the introduction of a catalyzing fluid), a rapid pulse of mineral growth (or breakdown) can result. The apparent discrepancy between lab-based and (time-integrated) field-based measurements of metamorphic reaction rates may be rectified if all the action in nature is confined to brief pulses that encompass just a tiny fraction of the overall long-lived tectonically paced event. Examples of each kind of pulse will be presented.

Timescales of Mantle Metasomatism

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Compositional zoning of minerals is not uncommon in metamorphic and igneous petrology. This zoning, of both major and trace elements, reflects changes in the fluid or melt from which a mineral crystallised, for example, in a magma chamber to which new melt was added periodically. The preservation of these growth zones will depend on the rate at which elements diffuse, the temperature, and the equilibration time. Remarkable examples of oscillatory zoning in zircon, illuminated by cathodoluminescence of the rare earth elements (REE), are preserved because of the extremely slow rates of REE diffusion, even at magmatic temperatures over the timescales of plutons. In contrast minerals in xenoliths of mantle peridotite are almost never zoned. This is usually attributed to the high temperatures and long residence times experienced by the mantle after any perturbation.

Very rare samples of zoned mantle garnet have been reported from the Wesselton Kimberlite in South Africa [1-2; Figure 1]. The outer zone has been interpreted as new garnet that formed during metasomatism of the mantle. Identifying such zones is complicated by the almost ubiquitous presence of kelyphite rims around garnets, which are a breakdown product that forms during ascent in the kimberlite. However, metasomatism is very commonly recorded by mantle garnets through elevated concentrations of elements such as Zr and Ti, and anomalous (sinusoidal) REE patterns [3]. These homogeneous garnets presumably once also had distinct mantle and metasomatic garnet zones, which have now completely equilibrated, with the analysed composition representing a mass-balanced average of the two components.

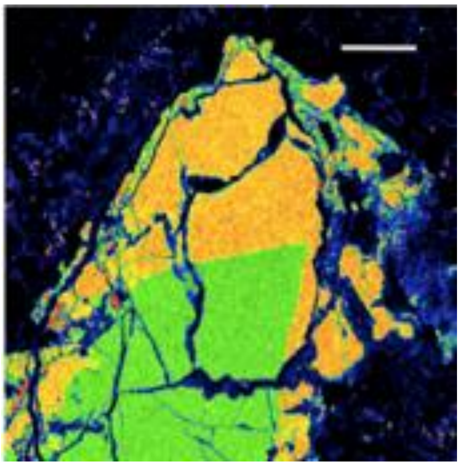

Figure: Distribution of Ca in a compositionally zoned garnet in a sample of garnet peridotite form the Wesselton Kimberlite, South Africa; the scale bar is 100 mm [1].

The width of the boundary defining the compositionally distinct zones was determined for Fe, Ca, and Mg by EPMA and Mn, Ti, Al, Na, Cr and Y by nano-SIMS [4]. The concentration profiles varied for each element indicating that the garnet was in the process of diffusively re-homogenising when it was brought to the surface. By fitting the diffusion profiles, using literature values for the diffusion coefficients and thermobarometry to estimate the temperature at which the garnet equilibrated, it appears that the metasomatic garnet growth occurred only a few years (1-100) prior to eruption in the kimberlite. The metasomatism did not occur during eruption since kimberlites are thought to move from the garent peridotite stability field to the surface in a matter of days. The results also suggest that the event that caused the garnet overgrowth, and hence the timescale of metasomatic events, is only 10s of years.

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From dust to the first rocks: timing of early solar system processes up to planetesimal formation

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Meteorites contain a unique record of solar system formation and early evolution. This record is being revealed thanks to increasingly sophisticated and sensitive techniques. But more recently these data are also being supplemented by other approaches, including dynamical models of solar system evolution and giant planet migration, numerical modelling of dust accretion, and astronomical observations.

Astronomy is now delivering data of sufficient resolution that we can see detail in protoplanetary disks at the scale of ~5AU, allowing us to test models of disk formation and evolution developed from meteorite data. ALMA observations of HL Tauri reveal a complex protoplanetary disk, with a series of light and dark concentric rings [1]. The suggestion is a disk which already has many forming planets – much more evolved than one would expect given the age of the system (luminosity and effective temperature of HL Tauri suggest that its age is <100,000 years, certainly <1 million years).

The general process of disk evolution is also revealed by modern astronomical data. As gas dissipates, and solids accrete, protoplanetary disks evolve to a debris disk. In many cases debris disks are a component of a planetary system. Our solar system has a debris disk which is comprised of the Kuiper belt and the Asteroid belt. Debris disks contain planetesimals (unseen astronomically), and dust produced from collisions (which can be detected optically). Astronomical data indicates that the transition occurs at a few Myr after t=0 to 10Myr after t=0. We can now test whether the evolution of our own planetary system fits the standard galactic timeline, or is anomalous.

It was previously thought that planetesimals form in a hierarchical way, building up from small objects, then accretion of km-sized objects, through to progressively larger planetesimals. New models [2] show that Ceres-class objects can form directly from small particles, following gravitational collapse in a turbulent gas. The process can be highly efficient, with large objects forming in 10-100 orbits. Mapping model constraints on accretion time onto the solar system record found in meteorite is difficult, as there is no chronometer that measures accretion time. One approach is to take the timing of formation of secondary minerals (e.g. Mn-Cr data of carbonates), and integrate that into models of the thermal evolution of planetesimals, to derive a modelled accretion age [3,4].

In this talk I review these and other model and astronomical constraints, and attempt to integrate them with the solar system record in meteorites, including recent data on formation ages for chondritic components such as CAIs and chondrules [5].

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Archean high temperature crustal metamorphism – Contrasting timescales from two cratons

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Attainment of high crustal temperatures and consequent partial melting are critical to the stabilization of continental roots. Understanding the processes and timescales behind partial melting of Archean continental crust is thus paramount for understanding early tectonic modes and processes that led to the formation of stable cratons. Since deviation from a 'normal' crustal geothermal gradient typically reflects dynamic processes associated with advective heat flux, the pressure-temperature-time paths experienced by metamorphic rocks, and particularly the duration of their evolution, can reveal particularly important information about Archean tectonic mechanisms and tempos. Here, we compare results of U-Pb, Sm-Nd and diffusion-based chronology techniques, coupled with estimated metamorphic *P-T* evolution of two Neoarchean terranes in order to begin to characterize the diversity of tectonic style at a crucial period of Earth history, ~ 2.7–2.8 Ga.

The Beartooth Mountains expose rocks of the Wyoming Craton that are dominated by an ~2.8 Ga calc-alkaline granitoid batholith which contains widespread, km-scale, granulite-grade meta-sedimentary roof pendants. The Pikwitonei Granulite Domain (PGD) consists of >15,000 km^2 of high-grade metamorphic rocks in the NW Superior Province. Both terrains have previously been interpreted as reflecting cratonic margins undergoing metamorphism and magmatism at approximately 2.7 Ga. *P-T* paths from each domain appear to record clockwise evolution, reaching temperatures of ~800 and 950˚C, respectively, at ~5–8 kbar. However, metamorphic timescales are dramatically different in each domain. Available data from diffusion modeling and isotopic constraints imply that granulite-grade conditions were achieved in the Beartooth rocks for < 2 Myrs. In contrast, U-Pb and Sm-Nd data suggest maintenance of high-temperatures in the PGD for up to 100 Myrs. Indeed, zoned chronology from a single garnet crystal in a sample that reached ~ 750˚C indicates growth over 60 ± 6 Ma. Zircon and monazite from some of the PGD's hottest rocks suggest growth pulses over durations far briefer than the overall regional-scale high temperature evolution, possibly implying temperature cycling over several tens of millions of years in which rapid and localized phases of > 800˚C metamorphism were superimposed on a much longer duration ~ 700˚C event. Taken together, the depths, temperatures and timescales inferred here imply contrasting processes of Archean crustal heating in the Beartooth and Pikwitonei settings.

What is the source of the heat that leads to the formation of regional scale granulite and UHT metamorphic terranes through Earth history?

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It has been suggested that a major contributor to the generation of regional scale UHT conditions in collisional orogens is the heat produced due to the decay of Heat Producing Elements (HPEs) in thickened crust. A good starting point to test the applicability of this mechanism to the generation of granulite and ultrahigh temperature (G-UHT) terranes through time is to see how it can be related to the observation that G-UHT metamorphism is cyclical in nature, and that there is a first order link between the supercontinent cycle and the generation and preservation of regional scale G-UHT terranes. For this model to be appropriate to the generation of G-UHT conditions in other G-UHT terranes throughout Earth history, a number of conditions must be satisfied.

The primary requirement for radiogenic heat production to be the heat source for the generation of regional-scale G-UHT metamorphic conditions is that there is the requisite concentration of HPEs in the crustal column. The observed link between the occurrence of G-UHT conditions and the terminal stages of supercontinent amalgamation may provide a mechanism for the enrichment of the crustal column in HPEs. It has been proposed that continents reorganize by two contrasting processes, known as extroversion or introversion, or by a combination of both. Extroversion is where a supercontinent rifts apart and then turns inside-out to form a second supercontinent along suture zones that correspond to the margins of the first supercontinent. In contrast, introversion, is where the first supercontinent rifts apart forming an internal ocean and then reassembles through the closure of the newly created ocean forming a second supercontinent. The process of extroversion, which is interpreted to be the driving mechanism for the formation and destruction of several past supercontinents in Earth history such as Vaalbara, Columbia, Rodinia and would have resulted in the development of large passive margins of material derived from the erosive removal of the collisional mountain systems formed during continental collision. The reworking and redistribution of HPE within these collisional orogens, and their erosion and deposition at the margins of a supercontinent where they can be incorporated into the next supercontinent cycle, provides a mechanism for the heat source for the generation of regional scale G-UHT terranes. However, these ideas need to be tested in more detail through studies integrating geochronological and petrological data that focus on the duration and *P–T* conditions of metamorphism in each of these terranes.

Secondly, as partial melting acts as a heat sink during the evolution of a terrane to high temperatures, a requirement for a terrane to attain G-UHT conditions, effectively evolving from a regional scale migmatite terrane into a G-UHT terrane, is that the duration of orogenesis must be long enough (>60 Ma for average crustal heat productions of 3 μWm^{-3}) for the radiogenic heat source to provide the required thermal energy to overcome the thermal buffering effect of partial melting. This means that the orogen must be either large in scale or that erosion rates are slow enough to retard the removal of the HPEs. The observation that the age distribution of metamorphic belts that record regional scale G-UHT metamorphism is not uniform and can be broadly correlated with the amalgamation of the continental lithosphere into supercratons or supercontinents is suggestive of a correlation between the two processes. One school of thought suggests that G-UHT metamorphism is related to the generation of initially high geothermal gradient conditions in continental back-arc regions prior to crustal thickening, we propose that G-UHT conditions actually relate to the final stage of amalgamation (i.e. continent–continent collision). The thickening of the crust during continental collision during the amalgamation of Gondwana has been likened to the generation of a Himalayan-scale continental collision system. This correlation between the terminal phase of collision during supercontinent amalgamation fulfils the requirement that a long-lived collisional system is integral to the cyclic generation of regional scale G-UHT conditions in nature.

While the scenario related to the formation and reorganisation of supercontinents described above fulfils a number of criteria in regard to the apparent cyclicity of G-UHT terranes it should also be noted that continental margins and other thick sedimentary basins on thinned crust and lithosphere, including continental backarcs, are naturally enriched in HPE. Any collision involving a rifted continental margin, or closure of a continental back-arc basin, will result in thickened HPE-enriched sections and lead to the development of elevated geothermal gradients. Provided the crust remains thickened for long enough, there is the potential for the achievement of G-UHT conditions in any orogenic system of this type.

Timescales of Accelerated Weathering in Ultramafic Mine Tailings: Implications for Carbon Mineralization Rates

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Alkaline waste generated from mining of magnesium silicate rocks reacts spontaneously with atmospheric carbon dioxide (CO_2) to precipitate carbon in solid mineral form. The total capacity of these mine tailings to sequester carbon is about ten times greater than greenhouse gas emissions of associated mining and mineral processing. Waste from mining activity globally has capacity to sequester 100-200 Mt of CO_2 per year. However passive, or unintentional, CO_2 mineralization at individual mine sites is modest (1-50 kt/yr), and typically limited by CO_2 supply. Acceleration of these reactions represents an opportunity to generate considerable greenhouse gas offsets for the industry, and to develop expertise in carbon mineralization that is relevant to accelerated weathering at Earth's surface and mineral trapping in low temperature aquifers and reservoirs.

Experimental acceleration of carbon mineralization is readily achieved through enhanced delivery of CO_2, wherein reaction rates are limited by rates of cation (e.g., Mg^{2+}) supply from mineral dissolution. Further acceleration requires optimization of mineral dissolution processes. Continuous-flow dissolution experiments on minerals and mine tailings exhibit rapid, transient cation release rates that decay to slower rates indicative of conventional steady-state bulk mineral dissolution processes (Fig. 1A). The transient initial phase of the experiments can release a significant amount (5-10%) of the total cation content of the material. It reflects the dissolution of highly soluble trace minerals, and surface processes in sheet silicate minerals which together we take to represent the labile cation capacity of the material. Longer-term steady-state cation release is much slower and represents recalcitrant cation capacity indicative of bulk mineral dissolution. The labile cation content represents the carbon mineralization capacity of alkaline mine wastes accessible with existing low-cost technologies while recalcitrant cation content is unlikely to be tapped at existing carbon prices (Fig. 1B). Measured labile cation content of mine tailings varies substantially between and within deposits, with implications for how carbon mineralization capacity should be characterized and how carbonation intervention would be incorporated into mine operations. Specific mines and specific alteration types with high labile cation content, which for some mines is sufficient to offset total mine greenhouse gas emissions, should be the focus of pilot scale carbon mineralization projects.

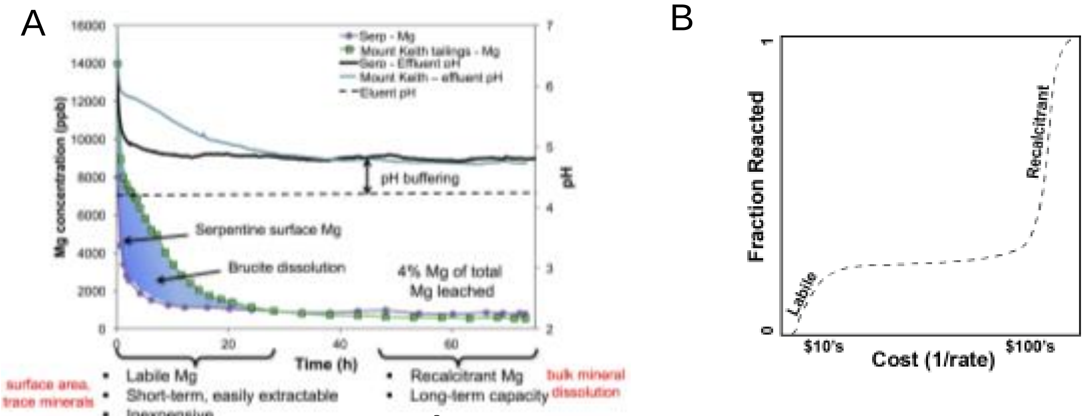

Figure 1: A. Cation release rates (Mg^{2+}) from mineral and tailings dissolution experiments in flow through reactors. Labile cation release rates are defined by transient period of fast release and followed by slow release of recalcitrant cations. B. Labile cation content represents the carbon sequestration capacity of mine tailings easily accessible with existing low-cost technology while recalcitrant cations represent high cost or future sequestration capacity.

What do chemical processes tell us about strain localization ?

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Shear zones are fundamental features that show unequivocally that ductile strain in the lithosphere is strongly heterogeneous and can be localized. Understanding how shear zones nucleate and evolve with time and changing environmental and chemical conditions is crucial for advancing models of the strength of the lithosphere in various tectonic settings.

Strain localization requires strain weakening. Several mechanical processes are proposed such as grain-size reduction and the formation of a fine-grained aggregate responsible for a switch from dislocation-creep to grain-size sensitive creep, or the development of a grain preferred orientation and/or interconnection of an initially dispersed weak phase. All these mechanical processes lead to a change in strength of a deformed rock that in turns controls how shear zone behaves. However, the strength of a rock is not only dependent on the texture but also on its mineralogical composition driven by thermodynamic equilibrium.

In most natural cases, deformation affects rocks that consist in a complex polyphased assemblage that is metastable at the P-T-fluid conditions of the deformation. Because of the deformation, kinetic barriers are overcomed and the actively deformed rock is progressively re-equilibrated into a stable assemblage. This local equilibration process involves a suite of metamorphic reactions that have a strong influence on the strength of the rock. Furthermore, shear zones are characterized by a transient permeability that favors syn-kinematic fluid flow and mass transfer. Metasomatic reactions, that are driven by the change in fluid and bulk chemistry, also contributes to the change in mineralogy in the active shear zone.

To model and understand how strain is localized in the crust, the evolution of the strength of any rock in a shear zone must be calculated taking into account both mechanical and chemical processes. This task is mostly limited by our ability to characterize and predict mineralogical and textural change during deformation in an open-system. In this contribution, we present a collection of data (petrology, geochemistry, microtexture, and thermodynamic modeling) obtained on various shear zones from the Alps. The goal is to highlight how mechanical and chemical processes interact during shear zone development, from its nucleation to its growth and propagation.

Based on these examples, several challenging questions will be explored. (1) One of the main challenge for petrologists is to decipher the time sequence of mineral reaction involved during shear zone development in order to determine the reaction path and the continuous change in viscosity. This task is commonly done by looking at the mineralogical and textural evolution along a finite strain gradient assuming that there is a direct relationship between strain and time. This topic has been initially treated by Means (1995) and will be developed. (2) During shear zone development, the textural evidences of early stages of deformation and the associated chemical processes (fluid-rock interactions) are most commonly overprinted by the deformation. The alternative approach is to look for preserved subtle mineral compositions and zonations (chemical foot-prints) that are related to fluid-rock interactions and not variation in P-T conditions. We will show how phyllosilicates, feldspar and garnet can be used as chemical foot-prints of fluid-rock interactions during the nucleation of a shear zone. (3) The ultimate goal would be to model phase relations as a function of change in P-T-X_{rock}-X_{fluid} conditions in order to predict the continuous evolution in mineralogy during shear zone development. Because the system is open, characterized by multiple local equilibrium and starting conditions which are not stable at the conditions of deformation, conventional phase diagram must be used with great care. We will explore alternative approaches and phase diagrams, using chemical potential of mobile components as variables.

Long-lived thermochemical hot spots

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Generally speaking the duration of thermal events whose thermobarometric character is very different from apparent crustal norms is short lived. Such events are typically driven by transient processes (e.g. magmatism, rapid depth change), and/or are recorded by rocks whose passage through the thermally anomalous region is fast. Where thermobarometrically anomalous conditions persist for extended periods of time, such as in large hot orogens or in long-lived subduction systems, the length scales of the systems are typically large and buffer their thermal evolution.

However there appears to exist a class of long-lived crustal metamorphic systems characterised by high thermal gradients that operated over comparatively small length scales. Such systems are unusual because their comparatively localised nature would appear to preclude longevity, particularly if the heat was supplied by advective processes or if deformation moved rocks out of the high-temperature regions. There are several of these hot spot systems in central and southern Australia with apparent length scale of no more than 50-100km, occurring within both Proterozoic and Palaeozoic rocks systems. Geothermal gradients were sufficiently elevated to stablise andalusite in lower grade areas, and promote low-medium pressure fluid-absent partial melting in high-grade areas. Durations of high thermal gradient metamorphism appear to have been in order of at least 100-150 Ma. Although the thermal durations were long-lived, average strain rates must have been slow in order to preserve low-pressure mineral assemblages.

In at least two of these hot spot systems, the onset of high temperatures appears to form a continuum with preceding basin development, and the structural architecture of the systems still largely reflects the basinal stratigraphic framework. In each case there are no obvious external thermal inputs at the scale necessary to create the thermal record of thermal anomalism. However the rock systems in each region contain elevated concentrations of U-Th compared to global norms. Simple thermal models show that these elevated U-Th concentrations are sufficient to generate high temperature conditions. These thermochemical hot spots will persist until exhumation-driven cooling removes insulating overburden. Provided the hot spots can be mechanically buffered by cooler regionally surrounding lithosphere, they can experience low strain rates, and therefore persist for extended periods of time.

Rates of generation and growth of the continental crust

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It is long accepted that rates of change are key constraints in the development of physically realistic models for natural processes. The geological record provides evidence of processes that range from the extremely slow to the cataclysmic, from for example, the diffusion of ions at rates of a millimetre per million years to earthquakes and catastrophic volcanic eruptions. We evaluate how the rates of generation and the growth of continental crust can be constrained for different periods of Earth history, and how those in turn inform models for the generation and the evolution of the continental crust.

The continental crust provides a record of events that are heterogeneous in time with distinctive peaks and troughs of ages for igneous crystallization, metamorphism, continental margins and mineralization[1-4]. Regionally it can be demonstrated that peaks of crystallization ages are a reasonable proxy for periods of increased magmatism. Yet, for the most part the peaks and troughs of ages are global signatures, and they are unexpected in the context of plate tectonic models in which new continental crust is continuously created and destroyed. An initial question is therefore whether such peaks of ages reflect primary or secondary processes. If they are primary, and the peaks of crystallization ages reflect periods of enhanced crust generation, they are most readily attributed to the emplacement of mantle plumes. Although if the peaks of ages are global in distribution, that implies that the plume activity was also global.

The alternative interpretation, to which we subscribe, is that the peaks and troughs of ages largely reflect the variable preservation potential of rocks generated in different tectonic settings, rather than fundamental pulses of activity, and the peaks of ages are linked to the timing of supercontinent assembly. The peaks of ages are typically linked to increases in the oxygen isotope ratios of zircons, which are taken to reflect increased contributions of upper crustal material in the host magmatic rocks. These are attributed to periods of crustal thickening and reworking associated with compressional tectonics and the development of supercontinents, in which case it is no longer possible to infer periodic changes in the rates of crust generation.

Models built on the detrital zircon and the fine-grained sediment records independently suggest that the continental crust has been generated continuously, and at least 65% of the present volume of continental crust was established by 3 Ga[5]. However there is a marked decrease in the crustal growth rate (crustal addition from the mantle minus recycling of material back into the mantle) at ~3 Ga. The period from >4 Ga to ~3 Ga is characterised by relatively high net rates of continental growth (~ 2.9–3.4 km^3/a), and these are similar to the rates at which new crust is generated (and destroyed) at the present time. Since ~3 Ga the net growth rates have been much lower (0.6–0.9 km^3/a), and this is attributed to higher rates of destruction of continental crust.

There is also increasing evidence that magma types similar to those from recent within-plate and subduction-related settings were generated in different areas at broadly similar times in the early Archaean. At issue therefore is when plate tectonics became the dominant mechanism associated with the generation of continental crust, rather than just when it started. Seismic tomography allows increasingly detailed mapping of the lithosphere, and it provides some evidence that the degree of anisotropy is different in different Archaean terrains.

Structural styles also vary from dome and basisn, attributed to vertical tectonics, as in the Pilbara and southern Africa, to those with more strongly developed regional fabrics and greater seismic anisotropy, as in North America. These terrains tend to be characterized by inferred within-plate and subduction-related magmatism respectively, and there appear to be links between the degree of crustal and mantle anisotropy and the nature of the magmatic record. At least in some areas, terrains with stronger regional fabrics may be younger than those in which such fabrics are less well developed.

The reduction in crustal growth rate at ~3 Ga, is also marked by a change in the average composition of new continental crust. Initial Sr isotope ratios and model Nd ages can be used to estimate the Rb/Sr ratios, and hence the silica content of new continental crust[6]. New continental crust generated before 3 Ga has on average low Rb/Sr, and is mafic, dense, and relatively thin (<20 km). New continental crust formed after 3 Ga gradually is more intermediate in composition, buoyant and thicker, and hence more like the calc-alkaline andesitic crust that dominates the continental record today. The increase in crustal thickness is accompanied by increasing rates of crustal reworking and increasing input of sediment to the ocean. These changes may have been accommodated by a change in lithospheric strength at around 3 Ga, as it became strong enough to support high-relief crust. This time period therefore indicates when significant volumes of continental crust started to become emergent and were available for erosion and weathering, thus impacting on the composition of the atmosphere and the oceans. The reduction in rate of continental growth at ~3 Ga is therefore taken to indicate a global change in the way bulk crust was generated and preserved, and this change can be linked to the development of subduction-driven plate tectonics.

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Microstructural records of intermediate depth Earthquakes

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Fluid-consuming metamorphism is often associated with fluid introduction along zones of localized deformation such as faults and shear zones. In such zones, disequilibrium metamorphism usually produces fine-grained hydrous minerals and/or carbonates which leads to a pronounced reaction-driven weakening (Jamtveit et al., 2016). Continued deformation and reaction at lower stress conditions within faults or shear zones will in most cases obliterate features formed during the earlier stages. Information about the initial stages of coupled deformation and metamorphism is therefore often lost from zones of localized deformation.

Valuable information about these stages can however, be obtain from microstructures recorded by the less deformed wall rocks. Microstructural observations from wall rock minerals surrounding faults formed by deep crustal earthquakes from the Bergen Arcs, Norway (Austrheim et al., 2017) and the HP-LT terrain of Alpine Corsica, record massive fragmentation with a characteristic grain size distribution, a high density of inclusions, and other features previously described from impact related shock metamorphism. This reflects very high stresses during the initial stages of metamorphism. Some of these features are also observed in and near faults and shear zones from localities where no independent evidence for seismic slip (such as pseudotachylites) are observed and may indicate that fluid driven metamorphism along localized deformation zones are often initiated by earthquakes.

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Fast dehydration-related intraslab fluid-flow events: implications for pore fluid pressure fluctuations at the plate interface

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A better understanding of the subduction zone fluid cycle and its mechanical feedback requires in-depth knowledge of how fluids flow within and out of the descending slabs. In order to develop reliable quantitative models of fluid flow, the general relationship between dehydration reactions, fluid pathway formation, and the dimensions and timescales of distinct fluid flow events have to be explored. The high-pressure/low-temperature metamorphic rocks of the Pouébo Eclogite Mélange in New Caledonia provide an excellent opportunity to study the fluid flux in a subduction zone setting. Fluid dynamics are recorded by high-pressure veins that cross-cut eclogite facies mélange blocks from this occurrence. Two types of garnet-quartz-phengite veins can be distinguished. These veins record both synmetamorphic internal fluid release by mineral breakdown reactions (type I veins) as well as infiltration of an external fluid (type II veins) and the associated formation of a reaction halo. The overall dehydration, fluid accumulation and fluid migration documented by the type I veins occurred on a timescale of 10^5-10^6 years that is mainly given by the geometry and convergence rate of the subduction system. In order to quantify the timeframe of fluid-rock interaction between the external fluid and the wall-rock, we have applied Li-isotope chronometry. This approach is based on bulk-diffusion modeling with the advantage that Li represents a trace-element in the solid and the fluid, Li fluid-solid exchange has been controlled by dissolution-precipitation processes, and Li transport occurred exclusively in the fluid. A continuous profile was sampled perpendicular to a type II vein including material from the vein, the reaction selvage and the immediate host rock. Additional drill cores were taken from parts of the outcrop that most likely remained completely unaffected by fluid infiltration-induced alteration. Different Li concentrations in the internal and external fluid reservoirs produced a distinct diffusion profile of decreasing Li concentration and increasing δ^7Li as the reaction front propagated into the host-rock. Li-chronometric constraints indicate that fluid-rock interaction related to the formation of the type II veins and had been completed within *ca.* 3 years. The short-lived, pulse-like character of this process is in accordance with the notion that fluid flow related to oceanic crust dehydration at the blueschist-to-eclogite transition contributes to or even dominates episodic pore fluid pressure increases at the plate interface which may trigger slip events reported from many subduction zones.

Timing of early solar system evolution

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The discovery of numerous exoplanets in the last two decades created renewed interest in a detailed understanding of the process that can lead to the formation of planetary systems consisting of rocky and gas-dominated planets. Exoplanet can only be observed via telescopes and their formation and evolution can only be understood through modelling since in-situ analyses by space crafts is currently not feasible and material for direct study in the laboratory is, and will be for a long time, unavailable. The only planetary system that can be study directly via space missions and meteorites delivered to Earth is our own solar system, which, could serve as a model for other planetary systems. However, a concern is the possibility that it is an unusual or a rare type of planetary systems in the universe.

A key problem towards a robust model for planetary origin and evolution is the combination of physical parameters and chemical evolution of material with the time of important events and processes in the early solar system, starting from the formation of dust to the differentiation of rocky bodies. The different materials from planetary bodies of our solar system available for direct study in the laboratory preserve valuable information on these early processes, their timing and duration. In order to obtain reliable and meaningful time constraints for the sequence of chemical differentiation processes that led to planet formation, high precision and high-resolution ages are crucial. Improvements in analytical techniques in the last decade for the analyses of small variations in isotope abundances generated by short-lived isotopes were essential to obtain precise and accurate ages.

Time constraints can be derived from chemical and isotopic analyses of primitive meteorites and their components using long and short-lived isotope systems. The time line for early solar system processes and events derived from these materials has significantly changed the physical and chemical models describing the evolution of the solar nebula from its formation to the formation of planets. Key findings include the discovery that some planetesimals formed and differentiated into metal cores and silicate mantles within the first Ma of the beginning of the solar system. The observation that chondrites, the chemically and mineralogicaly most primitive materials of the solar system, formed over a time interval of several Ma and after the first highly differentiated planetary bodies had formed. The time needed to form the planets from a cloud of dust and gas was long thought to have taken around 100 Ma, but the new geochronological constraints reveal that the processes involved had a duration that is about one order of magnitude shorter.

Is true polar wander a thermometer?

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Earth was hotter in its early history, though few observations exist on the cooling rate of the bulk Earth. We demonstrate that the speed of true polar wander—wholesale rotation of mantle and crust around the core—have significantly decreased over the past three billion years. As true polar wander is rate-limited by the viscosity structure of the mantle, we interpret the decay to reflect the secular cooling of Earth. The amplitude of the decay indicates that the viscosity of the lower mantle has increased by an order of magnitude, and such a viscosity increase requires a cooling rate of >100 K/Gyr for the lower mantle. This rate is compatible with recent petrological and geochemical estimates on the cooling rate of the upper mantle, suggesting that the mantle as a whole has experienced rapid cooling since at least Neoproterozoic time, and possibly since Archaean time.

Coping with disequilibrium: the key to deciphering orogenic processes

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Our ability to quantify the conditions and rates of geological processes has advanced enormously in the last decades. This is due to improvements in the precision, accuracy and spatial resolution of analytical tools, the increasing database of intensively-studied natural examples, continued refining of key parameters through experimental studies and the further development of powerful programming packages allowing both the determination and modelling of rock histories for different scenarios. However, in order to understand the evolution of an orogenic belt it is most important to identify key samples (or suites of samples) which preserve a segment (or sequence of segments) of the history in the form of e.g., reaction microstructures, compositional zoning (or multiple compositions for a given phase) or contrasting inclusion-matrix relationships. These features are all indicators of disequilibrium typically at the hand specimen to sub-millimetre scale that can be recognised in the microscope, electron microprobe or even directly in the field. The application of equilibrium thermodynamics to ascertain formation conditions for the different stages in the evolution of such samples requires careful determination of the extent of possible local equilibrium domains: a task typically requiring considerable point, line and area analysis of minerals and reaction microstructures. However, once this detailed information is available for natural samples, it is possible to validate thermo-mechanical models by checking the consequences of rates of change of e.g., temperature, pressure, fluid availability, material loss or gain, or deformation in order to validate or refine models. It is the rocks that are reality so models must at least "produce" the right rocks at the right time. For complex orogenic events, however, there are often significant changes in conditions and processes over periods of tens of millions of years leading to overprinting and resetting of the minerals and microstructures of earlier stages. The real art of metamorphic petrology is to decipher a large part of the total evolution path of rock units through recognition and quantification of the consequences of the overprinting and resetting in the resultant mineral assemblages and microstructures.

To illustrate the problems of extracting meaningful information from regional metamorphic rocks I will show a series of examples from the Himalayan and Variscan orogens. In both cases continental crust was subducted deeply into the mantle at an early stage of the orogeny and was rapidly exhumed to then become involved in the subsequent Barrovian-type collision. Also in both cases there was the development of a high-temperature low-pressure event that has overprinted rocks that had experienced the earlier stages. In extreme Variscan examples, eclogites in gneisses preserve prograde zoning in garnet, eclogite facies omphacite partially replaced by diopside-plagioclase symplectites, amphibolite-facies amphibole growth, granulite-facies orthopyroxene in coronas on quartz, pyroxene-hornfels facies olivine (in quartz-bearing samples!) + spinel-bearing symplectites and augite, as well as younger greenschist-facies veins IN A SINGLE THIN SECTION! Gneisses around such eclogites are cordierite + sillimanite + K-Feldspar-bearing migmatites but relict kyanite and rutile point to an earlier higher pressure stage and quartz+/- corundum or spinel or sapphirine as inclusion in garnet reflect unusual high temperature reactions in very local metastable domains. Himalayan and Variscan eclogite garnets preserve sharply bounded overgrowths that allow tight constraints to be set on temperature-time paths via diffusion modelling as well as allowing determination of the reaction history during subduction via garnet growth-step predictions from thermodynamic forward modelling. Most rocks lose their memory of earlier events so such complex rocks, although difficult to study, are a real gold mine for the petrologist trying to reconstruct the whole orogenic cycle.

500 Ma of amagmatic intracontinental reactivation: a case study from the west Musgrave Province, central Australia

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The Musgrave Province is a Mesoproterozoic orogen, exposed at the junction between the North, West, and South Australian Cratons. The province formed during episodic tectonomagmatic events spanning over 600 Ma from at least c. 1650 to 1030 Ma. Currently, the post-Mesoproterozoic amagmatic reactivation of the province is mainly attributed to a 60 Ma long intracontinental orogeny: the 580–520 Ma Petermann Orogeny, the duration of which is primarily constrained by conventional U–Pb and K–Ar dating. In this work we use multi-method thermochronology, along two approximately N–S transects, to demonstrate that intracontinental reactivation was long-lived and extended from the Neoproterozoic to the early Jurassic.

Along the western transect, the thermochronology undertaken is dominantly Ar–Ar and indicates a tectonometamorphic history partly encompassing but largely predating the Petermann Orogeny (Fig. 1). This transect extends from the hinterland of a post-Mesoproterozoic orogen to its core, and near the trace of the 11GA-YO1 deep seismic reflection line. In the southernmost part of the hinterland (in the Talbot Sub-basin), the development of regional-scale open folds and south-directed reverse faults is dated at c. 715 Ma by muscovite Ar–Ar and titanite U–Pb (Fig. 1). The northern part of the hinterland (i.e. the Mitika area) records the development of a west-verging fold and thrust system. The time of peak metamorphism was at c. 630 Ma, given by U–Pb analyses of zircon overgrowths from garnet–kyanite schists (Fig. 1). This was followed by exhumation and cooling below 400 °C at c. 590 Ma (Fig. 1). The lower-grade periphery of the Mitika area cooled below 400 °C between 623 ± 5 Ma in the south and 613 ± 2 Ma in the north (Fig. 1). The gneissic core (i.e. the Wanarn area), a regional-scale antiformal stack bounded to the south by the Mitika Fault and to the north by the Woodroffe Thrust, records the crystallization of pegmatite veins at 592 ± 6 Ma and 545 ± 39 Ma (Fig. 1). The southern Wanarn area cooled below 300 °C at 584 ± 3 Ma, while the northern Wanarn area cooled below 550 °C at 589 ± 4 Ma and then below 400 °C at 567 ± 3 Ma (Fig. 1). This dataset clearly indicates about 150 Ma of pre- to syn-Petermann Orogeny tectonometamorphic history (Fig. 1).

Recent (U–Th)/He thermochronology data, from the eastern transect across the orogenic core into the foreland fold and thrust belt, indicate a tectonometamorphic history that is syn- to post-Petermann Orogeny. While some of the (U–Th)/He data suggest cooling related to the Petermann Orogeny, much of the data show that out-of-sequence thrusting and internal reactivation of this part of the region postdates the Petermann Orogeny. In particular, the orogenic core cooled below 200°C between c. 480 and 400 Ma, indicating post-Petermann Orogeny reactivation of the Woodroffe Thrust. A (U–Th)/He date from zircon shows that internal deformation of the fold and thrust belt occurred at least until c. 200 Ma.

In the absence of extensive magmatism, constraining the evolution of a cold orogen is challenging but can be addressed through multi-method thermochronology, and particularly using mid- to low-closure temperature minerals and systems. This multi-method approach better constrains fault reactivation, post-magmatic fluid mobility, and hence remobilization events. The example from the west Musgrave Province indicates that amagmatic reactivation of a continental interior can be long-lasting and arguably as long as hundreds of millions of years.

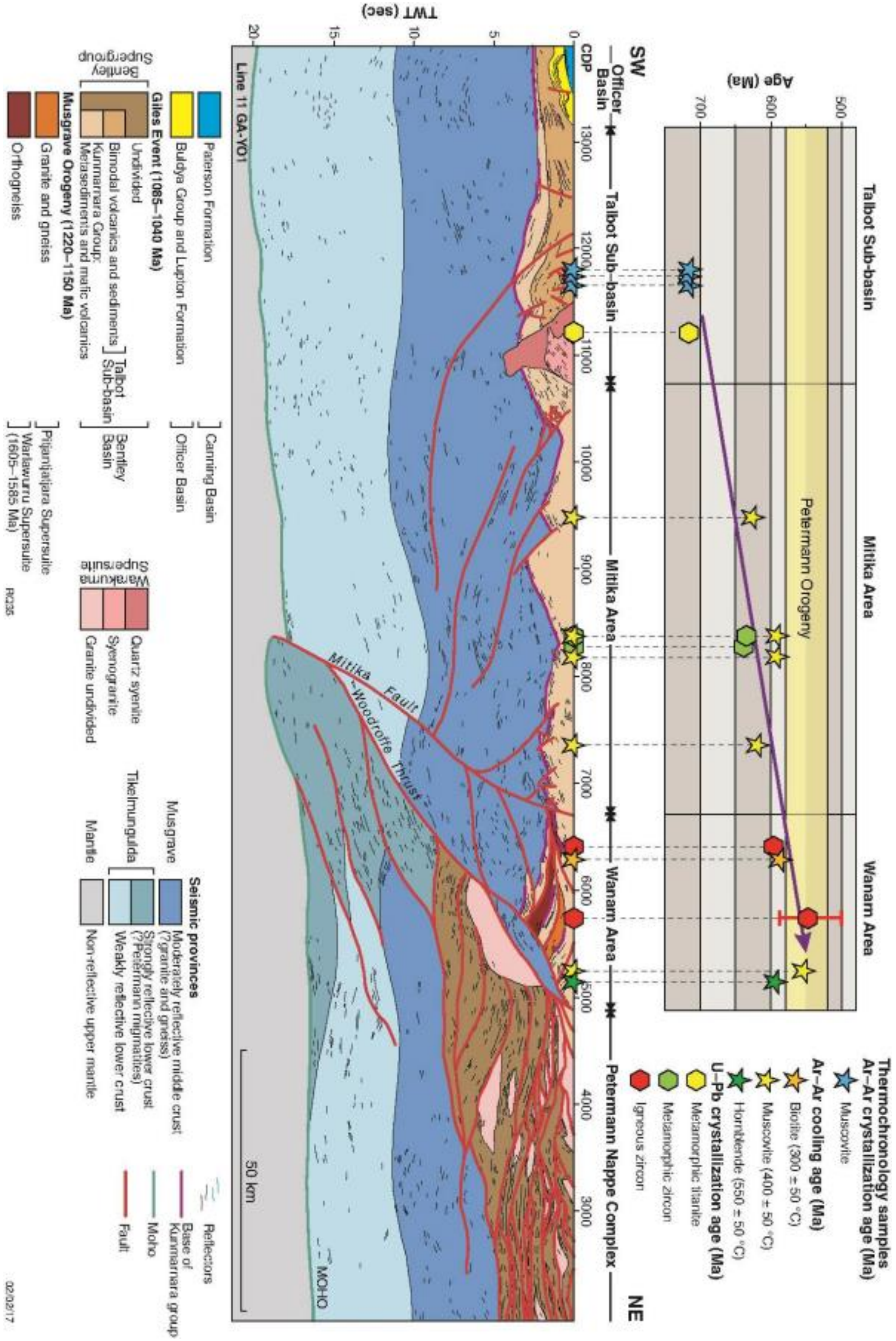

Figure 1. Interpreted seismic section with projected thermochronology samples. The top panel shows a date vs distance plot showing the north-eastward younging of ages mainly predating the Petermann Orogeny. An error bar is shown where the error exceeds the size of the symbol.

The time-scales of a stress-generating retrograde metamorphic reaction revealed by time-resolved in-situ X-ray microtomography

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Several geological systems involve mineral transformations where nominally dry minerals or rocks transform into hydrated phases when left in contact with water. This happens when lower crustal rocks, such as granulite, meet aqueous fluids and transform into eclogites, or when oceanic peridotites transform into serpentinites. In this last case, the reaction induces a volume increase of the solid phase that may lead to large stress increase and fracturing of the surrounding rock (McDonald and Fyfe, 1985; Jamtveit et al., 2008; Kelemen and Hirth, 2012). In the oil and gas industry, cements contain various amounts calcium or magnesium oxide that hydrates with time with large solid volume increase, a property used to efficiently seal boreholes (Wolterbeek et al., 2017). In all these systems, the mineral transformation induces stress if the system is confined, and the new hydrated minerals impose a so-called force of crystallization on their surroundings (Steiger, 2005). Here, we study a model system, the transformation of periclase, MgO, into brucite, $Mg(OH)_2$, in the presence of water, to quantify the coupling between hydration reaction, stress generation, porosity evolution, and deformation of the host rock and the time scales of the entire. These minerals are present in the lower to mid-crust and in industrial cements produced from dolomite. The hydration reaction generates a solid volume increase of 110%, while the density of the solid decreases by 33.8%.

Four centimeter-size core samples of a microporous MgO ceramics were reacted at 170-211°C, 5-80 MPa confining pressure, 6-95 MPa differential stress and 5 MPa pore fluid pressure. The samples were installed into a X-ray transparent triaxial deformation rig, called HADES (Renard et al., 2016), mounted on the rotating microtomography stage at the beamline ID19 of the European Synchrotron Radiation Facility (Grenoble, France). The sample were imaged in 3D and in-situ during the hydration reaction at a voxel size of 6.5 micrometres and an equivalent beam energy of 90 keV. Each experiment lasted between 2 and 5 hours, during which between 35 and 130 images were acquired, allowing to follow in real-time the chemical transformation and the deformation of the sample. Because, periclase, brucite, and porosity have different X-ray adsorption properties, these three phases could be extracted during reaction progress using standard image processing techniques (i.e. segmentation), the challenge being to handle the large volume of data, around 30 TO for the present study.

Two main results were obtained. Below 30 MPa mean pressure, the hydration reaction is coupled to fracturing of the MgO ceramics, and the transformation rate follows a sigmoidal kinetics with a slow initiation, a fast reaction coupled to fracturing, and a slow-down until an almost complete transformation of periclase into brucite. The number of fractures and the surface area increase could be quantified and follow the same sigmoidal curve. Conversely, above 30 MPa, the reaction kinetics was very slow, without fracturing over the time scale of the experiment. The initial MgO microporosity became clogged with brucite. Then, the reaction seemed to stop, or at least slow down dramatically compared to the fracturing case. When considering the driving force of the hydration reaction, stress generation should be several hundreds MPa, whereas data show that fracturing occurred only below 30 MPa. This indicates that the potential energy due to phase transformation generates much lower stress than what is estimated from non-equilibrium thermodynamics. A possible interpretation of this observation is that the stress generated by the reaction may overcome the disjoining pressure at the grain-grain interface, expelling the water film trapped there, and reducing the kinetics of reaction.

The second result is that the time-resolved pore structure evolution shows a sudden increase but short lived porosity generation during the hydration of periclase. The fracturing process is concomitant with this porosity pulse: as fractures are generated, some porosity is created as local pull-aparts, a process which pump more fluid into the sample and accelerates the reaction. After reaction completion, the porosity has disappeared, and we can conclude that porosity generation was transient.

These experimental data show that retrograde metamorphism reactions can generate a force of crystallization of at least 30 MPa during the transformation of periclase into brucite. Under pressure less than 30 MPa, the reaction involves the generation of fractures and a transient porosity pulse that, together, produce new reactive surface area and pump fluid inside the rock, increasing by orders of magnitude the kinetics of the metamorphic reaction and consuming very fast the fluid percolating into the rock.

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Is “nano” beautiful? At which scale should we date?

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The dating of geological events by the radiometric dating of minerals is fundamental to understanding planetary evolution and all the events that have shaped the Earth. However, the dating of minerals (especially zircon and monazite) from old rocks (Hadean, Archaean; 4.4-2.5 Ga) that have undergone multiple geological events (polymetamorphism, deformation, fluid interactions, alteration, impacts) is routinely difficult because these events (and associated reaction processes) lead to very complex age systematics (*Corfu, 2013*). The steady development in micro-sampling methods (SIMS, LA-ICP-MS, EPMA), now routinely applied for *in situ* dating of zircon and monazite, requires clear evaluation of the balance between analytical precision, analytical volume and effective volume of closed system behavior of the isotopic systems (*Corfu, 2013; Nemchin et al., 2013; Schoene et al., 2013*). Any mobility of U, Th or Pb at a significant scale relative to the analytical volume or any overlap of the analytical volume between two volumes characterized by distinct isotopic closure leads to a disturbance, a modification of the initial crystallization age, or an analytically induced mixed age. Nano-petrochronology, is the characterization of samples at different scales, including the nanometer scale (*Kusiak et al., 2015; Seydoux-Guillaume et al., 2012 and 2015; Laurent et al., 2016*) or even atomic scale (*Valley et al., 2014; Valley et al., 2015; Peterman et al., 2016; Piazolo et al., 2016*; *White et al., 2017*) in order to link the mineral properties (nanostructure and nanoscale compositional heterogeneities) with geochronological data. Because Transmission Electron Microscopy (TEM) is the only technique able to combine sub-atomic structural and chemical information, it can provide evidences for the resetting mechanism of geochronological systems by identifying remnant of chemical reactions (e.g. secondary grains products and nano-inclusions; coupled dissolution-precipitation interface; pore filled with fluid/mineral/melt) or structural defects enhancing diffusion and alteration processes (e.g. amorphisation, plastic deformation). Insights from nano-characterization thus help to validate or invalidate the interpretation of an isotopic ratio (a “date”) into a geologically meaningful age. In this presentation, we will focus on zircon and monazite characterization with TEM and how it can sharpen interpretation of U–Th–Pb geochronological data. We will discuss whether or not it is useful to date the rocks down to the atomic scale and the importance of coupling studies from the micro-scale to the atomic-scale to understand processes and thus better interpret the dates.

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Rates of stress-loading and stress-relaxation below the seismogenic zone – evidence from quartz microfabrics in nature and experiment

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Quartz microfabrics from two shear zones in the Alps, the Silvretta basal thrust and the Defereggen-Antholz-Vals (DAV) shear zone, and experimental vein-quartz deformation, record that stress-loading and stress-relaxation rates play an essential role for the localization and accumulation of strain. We consider two stages for the development of localized high-strain zones: (1) stress-loading, where deformation at transient high stresses results not necessarily in a high amount of strain on sample scale, but in localized highly damaged zones enabling grain-size reduction during (2) stress-relaxation, where a high amount of strain can be accumulated, dependent on the rate of stress relaxation.

The quartz microfabrics are analyzed by polarized light and electron microscopy. The microfabrics from both shear zones are characterized by localized strings of new grains cross-cutting strained host grains. The heterogeneous microfabrics record a switch from dislocation glide-controlled deformation at transient high stress to recrystallization at relaxing stresses at greenschist facies conditions. The high-stress glide-controlled deformation at temperatures well above 300°C requires a stage of high stress-loading rates. The subsequent development of new grains during stress relaxation is dominantly by subgrain rotation and strain-induced grain-boundary migration in areas of localized high strain originally formed during initial high-stress deformation. The findings suggest that new grains develop at almost random crystallographic orientations at fast rates of stress relaxation (i.e. at low stress), as indicated by recrystallized quartz zones in the Silvretta fault rocks. In contrast, at slow rates of stress relaxation, new grains develop at moderately high stresses with crystallographic preferred orientation characterized by high Schmid factor for basal <a> glide, as indicated by vein quartz samples from the DAV shear zone. The findings from the two shear zones compare well to results from deformation experiments in a Griggs-type deformation apparatus designed to simulate the natural stress history (Trepmann et al., 2007; Trepmann and Stöckhert, 2013). The experiments indicate that such microfabrics can form within a few thousands years, in accord with the natural observations. The recorded transient peak stresses and different rates of stress relaxation are interpreted to be related to external stress-loading controlled by seismic activity of the fault systems, as opposed to long-term deformation at rather constant stress levels. The difference in stress relaxation rates is suggested to be correlated with the tectonic regime of thrusting for the Silvretta fault rocks and strike-slip faulting for the DAV shear zone. This study demonstrates that characteristic microfabrics provide important information about the deformation and stress history of natural shear zones developed in different tectonic regimes.

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Deformation at low and high stress-loading rates

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Deformation microstructures that are characteristic of low and high stress-loading rates are compared and contrasted. High-pressure low-temperature (HP-LT) metamorphic rocks of the Talea Ori, Crete, show boudins, extensional shear bands and kink bands that are associated with discordant quartz veins. Vein-quartz microstructures with elongate grains grown epitactically from the host rock with abundant fluid inclusion trails parallel to the vein wall indicate vein formation by crack-seal increments. The presence of sutured high-angle grain boundaries and subgrains shows that temperatures were sufficiently high for recovery and strain-induced grain boundary migration, i.e. 350 ± 50 °C. Low stress-loading rates to a few tens of MPa caused by continuous dissolution-precipitation creep are sufficient to cause cyclic crack-seal increments at the given p-T conditions and the indicated high pore fluid pressures. These stress conditions are consistent with the general low amount of strain accumulated by dislocation creep in the quartz veins. Some discordant as well as concordant quartz veins on the other hand can show heterogeneous quartz microstructures with micro-shear zones, sub-basal deformation lamellae and short-wavelength undulatory extinction. These microstructures indicate glide-controlled crystal plasticity at transient high-stresses of a few hundred MPa with subsequent recovery and strain-induced grain boundary migration at relaxing stresses at the same temperatures of 350 ± 50 °C. Such high stresses at the given conditions would require high stress-loading rates, as slow stress-built-up would result in the observed crack-seal microstructures before reaching the stresses of a few hundred of MPa to cause low-temperature plasticity of monophase quartz layers. Therefore, the transient and local high stresses are interpreted to be caused by high stress-loading rates controlled by seismic activity. This study demonstrates that quartz microfabrics can record stress-loading rates that control deformation mechanisms and the strength of the affected rocks, which is relevant for geodynamic interpretations of lithospheric deformation.

Short-duration regional metamorphism: unresolved questions

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Plate tectonics and metamorphism are linked through the metamorphic facies series concept of Miyashiro (1961, 1973); large-scale advection associated with the tectonic processes of subduction, continental collision, extension, etc. produce distinct thermal environments that result in regional metamorphism. Regional metamorphism is considered to record the 'ambient' pressure–temperature (*P*–*T*) conditions that develop from crustal-scale interaction of heat conduction, advection and production within a relatively persistent tectonic setting.

Recent work, has shown that rocks in collisional orogenic and subduction settings (for P < ~2.2 GPa) record significantly higher T than thermal models of tectonism predict (Jamieson et al., 1998; Penniston-Dorland et al., 2015). If the T shortfall in tectonic models relates to localised (sub-crustal-scale) thermal processes, then it may be expected that these 'anomalously hot' examples of regional metamorphism also have 'anomalously short' thermal time scales. Classic examples of Barrovian-type, orogenic metamorphism (e.g., E Alps, New England, Scotland) and high *P*/low *T* (H*P*/L*T*), subduction metamorphism (e.g. Bergen Arcs, Greek Cyclades, W Alps) record regional metamorphic durations that limit length scales of the associated thermal anomaly to significantly less than the continental crust or oceanic lithosphere (i.e. short-duration time scales < 10^7 yr).

Short-duration regional metamorphism records transient, atypical crustal *P*–*T* conditions. The prevalence of short-duration regional metamorphism suggests common crustal *P*–*T* conditions are not commonly recorded (in rocks we see). This is a compelling problem which has associated with it (when one digs!) some unresolved questions.

1. Which time scales are typical? Geospeedometry and geochronology give differing accounts of time scales for short-duration metamorphism; geospeedometry is systematically an order of magnitude (or more) shorter (Fig. 1). Whether this relates to precision-limited temporal resolution in geochronology, or systematic issues in geospeedometry (e.g., fast diffusion pathways, down-*T* extrapolation of experimentally-derived diffusion data) is not known.

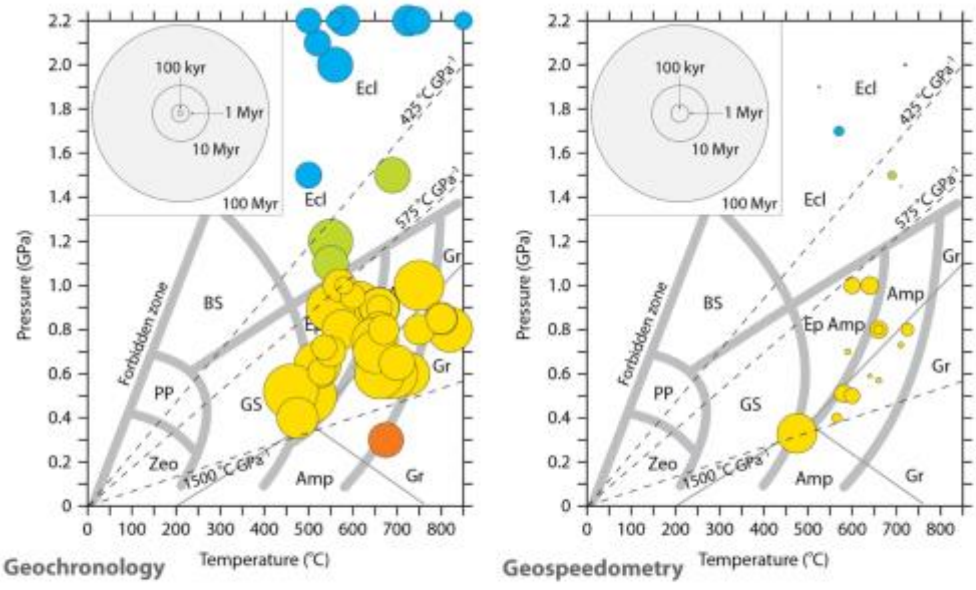

Fig. 1: Compilation of duration and *P*–*T* for short-duration regional metamorphism from geochronology (left) and geospeedometry (right), after Viete & Lister (2017, Fig. 3, p. 384). Area of each balloon gives metamorphic time scale, meaning diameter gives conductive length scale. Blue, green, yellow and orange indicate H*P*/L*T*, intermediate–high *P*/*T*, intermediate *P*/*T* and L*P*/H*T* metamorphic facies series.

2. Is short-duration regional metamorphism a 'recent' trend? Fig. 2 shows geographic distribution and age of examples of short-duration regional metamorphism. In Fig. 2 and the compilations of Viete & Lister (2017)—which only include metamorphism at $T <$ 900 °C—there is not a single Precambrian example of short-duration regional metamorphism. Because precision in geochronology scales with absolute age (e.g., ±2% on a 500 Ma rock yields ±10 Ma), this may be expected. However, temporal resolution in geospeedometry is not limited by absolute age of the rock. Might the lack of Precambrian examples of short-duration metamorphism mark secular change in tectonothermal processes? Or has the community simply not searched widely enough for short-duration thermal signals in these older rocks?

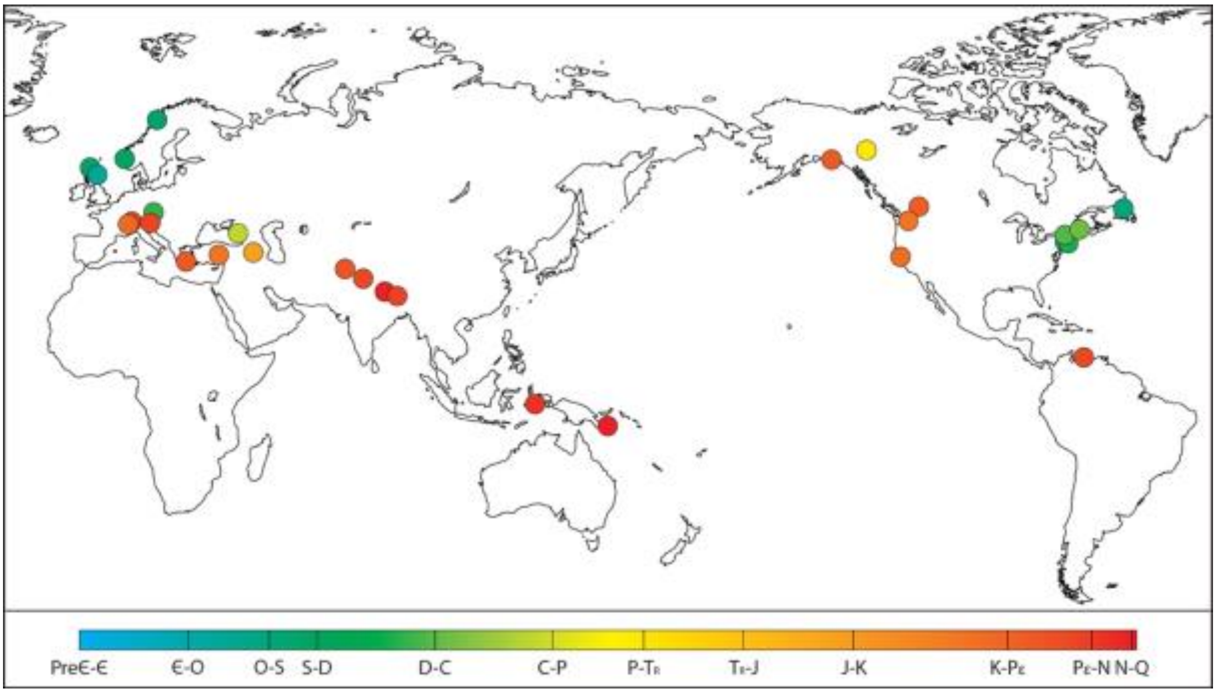

Fig. 2: Locations of short-duration regional metamorphism, coloured according to age, after Viete & Lister (2017, Fig. 2, p. 383). Antarctica removed in the interest of space!

3. Is there a bias in the exposed rock record? Large-scale, regional metamorphic sequences are considered to record typical crustal *P–T* for their tectonic environment. However, the great prevalence of short-duration metamorphism suggests exposed rocks commonly record uncommon, atypical (localised and transient) thermal conditions. So, if rocks that record short-duration regional metamorphism are, by nature, atypical, then where are the metamorphic rocks that record the 'everyday' crustal thermal scenario predicted from thermal models?

The paradox of short-duration regional metamorphism can be accounted for by a bias toward short-duration metamorphism in the exposed rock record; only rocks that have experienced some localised and transient episode of heating are selected (by the Earth system) for exhumation and exposure at the surface (and for study by geologists). Perhaps only specific tectonic environments/settings—associated with short-lived tectonothermal events that produce regional metamorphism—can deliver mid-crustal or subducted rocks to the surface.

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Constraining metamorphic timescales: ages, stages, dates and rates

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The identification of the mechanisms by which crust is buried, deformed, transformed and exhumed is aided by the determination of tectonic rates and timescales. Precise and accurate measurement of radiogenic isotope ratios in minerals used as geological clocks is now routine, providing tightly constrained mineral ages. As spatial precision has increased and the requirement for larger analytical volumes has decreased, protracted geochronometer mineral growth has progressively been shown to be the norm in metamorphic rocks. However it is still unclear whether such a range of dates is due to protracted crystallization of the geochronometer minerals over a range of PT conditions, an artefact due to analytical sampling of multiple growth zones, re-distribution of parent or daughter element after crystallisation or due to some other cause. We have analysed U-Th-Pb monazite dates in six samples collected within a few metres of each other from a layered Grt-Bt-Plag-Qtz±St±Ky±Sill gneiss outcrop in central Bhutan. Taken together, the samples yield dates range from ~32-16 Ma. However monazites in only one of the samples yield dates that span the whole range; other samples contain monazites that yield a much more constricted range of dates that differ subtley from sample to sample. The differences in recorded age across the samples could be due to bulk composition (same reaction at different times or different monazite-forming reactions), reaction kinetics, and/or the effects of fluid circulation. Our dataset show that minor variations in sampling strategy from a single outcrop can have a major effect on the interpreted age and geological evolution of the region, which in turn can have major implications for the tectonic interpretation(s) arising from that dataset. In young orogens such as the Himalaya where events occurring 0.5 Ma apart can now be separated by modern geochronological techniques, it is critical that the geochronometer-forming reactions are tightly tied to the pressure-temperature-deformation evolution of the bulk rock in order to provide a firmer platform for age interpretations. Further research to constrain the PT conditions of different monazite-forming reactions, and to determine the chemical fingerprints that these reactions leave behind in the rock record is the next critical step in tightening the links between age and stage.

CONTRIBUTED ABSTRACTS

Time scales and length scales in magmatic Ni-Cu sulfide mineral systems

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Mineral systems are the product of multi-scale interactions of physical and chemical processes. A goal of exploration geoscientists is to reverse-engineer these systems in order to recognise and detect the critical signals of these processes. Underpinning the science is a very simple principle: in attributing a particular effect to a proximal cause, both must be operating at similar length and time scales. Thinking of mineral systems in this way allows us to arrive at some useful conclusions. We illustrate this principle first in general terms then by specific reference to magmatic Ni-Cu-PGE sulfide mineral systems.

Any major physical system can be represented on a plot of length scale vs time scale (Fig 1). Sets of processes that make up major geological process – e.g. magma flow, tectonic cycles and mineral transformations – plot along linear arrays on this diagram. We apply this principle to magmatic processes in Fig. 1, identifying a range of processes that operate from the scale of LIP-forming mantle plumes to grain-scale processes within the magma or country rock. Processes can be divided broadly into groups controlled by four different properties: chemical and thermal diffusivity, and magma and crust/mantle viscosity. By applying the scale dependence principle, and adding a second principle saying that the fastest process at a given scale wins out in any competition for chemical or thermal components, we can draw some conclusions about the role of various mechanisms in ore formation.

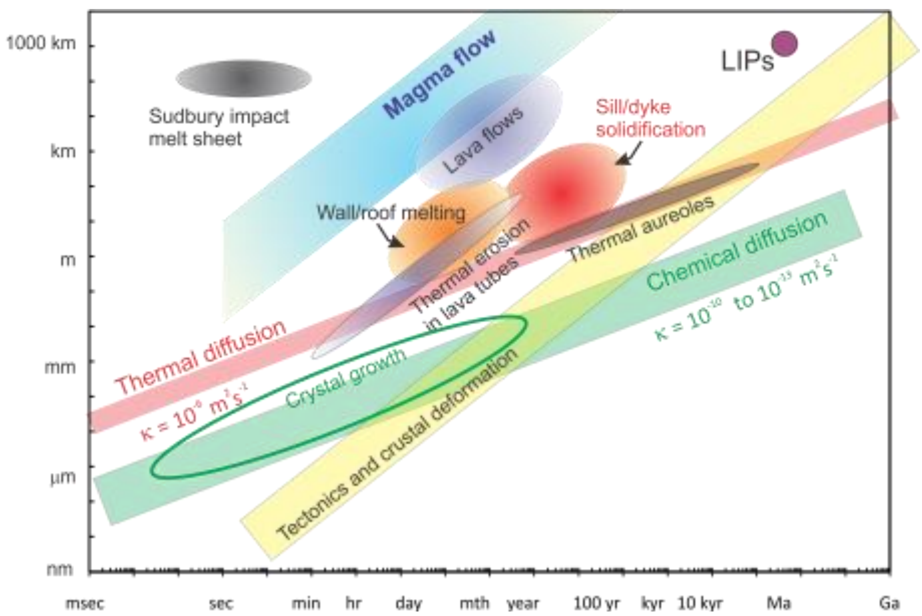

Figure 1 (left). Time scale - length scale plot for generic processes in magmatic systems.

Magmatic Ni sulfide systems require a source of S from country rocks, and a number of mechanisms have been proposed, including volatile transport from pyrite breakdown in thermal aureoles, diffusion of liberated S through country rock, and direct incorporation of sulfide-bearing xenoliths through stoping or wall rock spallation, followed by melting of the xenolith. Following the scaling principle, and referring to specific component ore forming processes in Fig. 2, it is clear that direct melting of xenoliths is by far the fastest process (Robertson et al., 2015), although it overlaps in length-time space with the process of thermomechanical erosion of immediate footwall rocks beneath lava flows (Kauahikaua et al., 1998). Xenolith melting falls on the overlap between the magma viscosity and thermal diffusivity control domains, and consequently is a slower process than the flow of the assimilating magma, which falls entirely within the magma viscosity domain. Hence, it is likely that sulfidic xenoliths are liable to be transported some distance from their site of incorporation before they have time to melt and release all of their sulfides as molten sulfide liquid. A consequence of this is that much of the mass transfer of assimilated sulfide in magmas may be in the form of partially molten and disaggregated xenoliths, rather than purely as suspended droplets as has been commonly assumed (Robertson et al., 2016). This may account for the very common close association between sulfide accumulations and xenoliths in many mafic-intrusion-hosted deposits (Barnes et al., 2017)

Subsequent enrichment of the sulfide liquid depends on processes of chemical diffusion in the magma, one of the slower classes of process (Mungall, 2002). The critical controls here are the diffusivities of chalcophile elements in silicate magma, and the thickness and stability of compositional boundary layers developed around suspended droplets, in relation to the rates of transport and accumulation of sulfide liquid to form ore-grade accumulations. Robertson et al (2016) estimated equilibration times for sulfide droplets undergoing Stokes settling in a basaltic magma of the order of 100 days for mm sized droplets. Assuming typical magma flow rates of the order of 1 ms^{-1} (Fig 2) droplets could be transported many km over this time scale. The implication is that unless flow is turbulent, with resulting rapid breakdown of chemical boundary layers, sulfide droplets or sulfide-silicate aggregates would need to be transported on a scale of km from their source in order to attain high R factors. Turbulent flow is unlikely for mafic magmas. A further implication is that sulfide droplets could be transported considerable distances in sulfide-undersaturated magmas, and are unlikely to equilibrate with their host magmas without some additional mechanism to keep them stirred and entrained on time-scales of months to years.

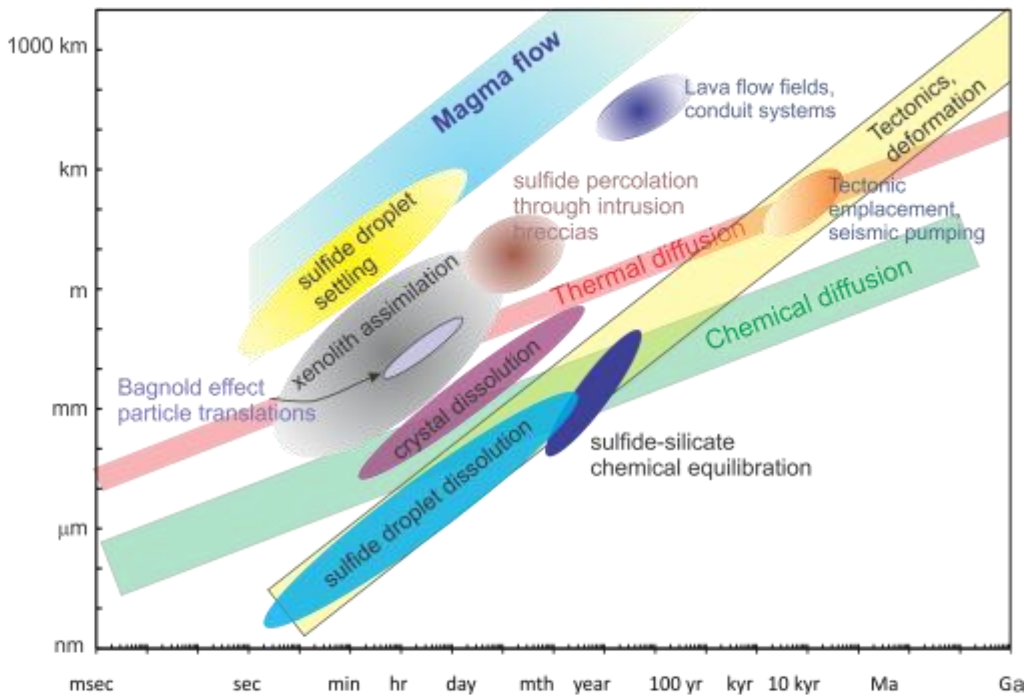

Figure 2. Scales of processes specific to formation of magmatic Ni-Cu sulfide ores.

The time and length scale estimates presented here are in many cases back-of-envelope calculations with very large order-of-magnitude uncertainties. However, it is clear that even at such rough levels of estimation, it is possible to draw some fundamental and in some cases counter-intuitive conclusions about ore forming processes, and to challenge some long-established pieces of received wisdom. The next step is to place some more rigorous and quantitative constraints on some of the arguments above. Much of the work has already been done in the literature of volcanology, intrusion emplacement and terrestrial mass flow and heat flow. Our next challenge as economic geologists is to move from the comfort zone of geochemical modelling into rigorous understanding of the physics of ore forming processes. Computational fluid dynamic codes run on the current generation of supercomputers have enormous potential to generate the next step change in our understanding of the intriguing processes that form some of the world's most valuable metal accumulations.

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Trace elements and Re-Os composition of black shales and pyrite nodules from the Nimbus Deposit, eastern Yilgarn craton, Western Australia.

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The Nimbus Ag-Zn(Au) deposit is located in the Kurnalpi Terrane of the Eastern Goldfields Superterrane in the Yilgarn Craton, WA. The stratigraphy of the deposit consists of bimodal-felsic and mafic package of volcanic rocks with subordinate sedimentary rocks including carbonaceous mudstones and mudstone-rich polymictic conglomerates containing syngenetic to early diagenetic nodular pyrites. Two U-Pb zircon SHRIMP dates of ~2702 Ma for the dacitic host rock to mineralization (Hollis et al., 2017) suggest the Nimbus local stratigraphy is part of the Kambalda Sequence.

Trace elements (TE) analysis for whole-rock lithogeochemistry in black shales and LA-ICP-MS in nodular pyrites from the Nimbus sequence were used to identify samples suitable for Re-Os studies. The aim was to assess whether rock and pyrite chemistry data can be developed into a valid tool for sample selection, and to optimize isotope spiking, to expedite obtaining N-TIMS Re-Os isotope data on sulphides as well as reducing the costs of the analyses.

The use of TE variation in black shales of marine nature as a tool for interpretation of paleo-redox conditions of oceanic environments is well established in the scientific community. TE analysis of sedimentary pyrite as a proxy for seawater chemistry was recently proposed by Large et al. (2014). The correlation of TE and Re-Os isotopic composition allows for interpretation of local marine conditions, as well as the source of metals in these sediments.

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Pressure-Temperature and isotopic constraints on the progressive, fluid-enhanced eclogatisation of granulites in the Bergen Arcs.

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Exhumed eclogitic crust is rare and exposures that preserve both protoliths and altered domains are limited around the world. On Holsnøy Island, western Norway, Neoproterozoic anorthositic granulites are exposed juxtaposing hydrous Ordovicio-Silurian eclogites which formed during well documented progressive fluid infiltration and deformation. Four stages of deformation for the eclogitisation process can be identified based on structural and overprinting relationships: 1) brittle deformation which formed pseudotachylite arrays in the granulite which are now recrystallised to a relatively hydrous metamorphic assemblage consisting of K-feldpar–zoisite–kyanite–plagioclase–clinopyroxene–garnet–quartz–rutile; 2) the development of discrete, small-scale shear zones associated with increased fluid–rock interaction, resulting in the formation of clinopyoxene–zoisite–kynaite–phengite–albitic plagioclase assemblages that partially to completely retrogressed garnets in the granulite protolith 3) the complete replacement of granulite by hydrous eclogite with interpreted peak metamorphic assemblage phengite–zoisite–omphacite–garnet–kyanite–rutile ; and 4) the retrogression of completely eclogitised domains resulting in coarse phengite dominated mineral assemblages (phengite–zoisite–omphacite–garnet–kyanite–amphibole–rutile–quartz), due to a significant availability of fluid. *P*–*T* constraints, determined by phase equilibria forward modelling, indicate that recrystallisation of the pseudotachylite occurred at around 15.5 kbar and 675 °C, peak eclogite assemblages formed at around 21.5 kbar and 680 °C and high-*P* retrogression at 16.5 kbar and 700 °C. As described by a number of workers, the transition from granulite to eclogite was enhanced by fluid but limitations in fluid availability resulted in the recrystallised domains evolving to a fluid absent state, thereby freezing in the mineral assemblage. This helps constraints the different *P*–*T* conditions associated with fluid ingress.

Preliminary isotopic data performed on the fluid-enhanced eclogites and the juxtaposing granulite wall rock show quite significant positive shifts in the δD signatures from the protolith to the eclogite whereas oxygen isotopes show only limited shifts to more positive $\delta^{18}O$ values. Nd data indicate the possibility of two generations of fluid ingress with an evolved source for the peak eclogite and a much more juvenile source for the retrogressed eclogite. Combining the different isotopic signatures result in a metamorphic fluid, conceivably sourced from the dehydration of the Cambrian ophiolite and metasediments that structurally underly the eclogite domains on Holsnøy Island.

Novel methods for constraining the duration of high-temperature metamorphism

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Two unique methods were applied to Rogaland, SW Norway, in an attempt to refine the duration of high- to ultrahigh-temperature metamorphism during regional and subsequent contact metamorphism. Osumilite $[(K, Na)(Fe^{2+}, Mg)_2(Al, Fe^{3+})_3(Si, Al)_{12}O_{30}]$, a K-bearing silicate mineral found in both volcanic and high-temperature metamorphic rocks provides an opportunity to better understand the duration and timing of granulite facies metamorphism via argon dating in conjunction with phase equilibria modelling. Osumilite dated using the $^{40}Ar/^{39}Ar$ method preserves two age populations due to large grain sizes (~1 cm grains) and a high closure temperature (771 ± 11°C for a 175 μm-radius grain and a cooling rate of 10°C/Ma). The two populations are interpreted to relate to prograde growth during regional metamorphism (*ca* 1070–1050 Ma) and later growth and diffusional modification during subsequent contact metamorphism (*ca* 920–880 Ma). These age constraints, combined with phase equilibria modelling, can provide *T*–*t* points along a high–*T* metamorphic path.

A systematic variation in trace element composition of recrystallised zircon was recognised with distance from the Rogaland Igneous Complex (RIC), the driver of contact metamorphism. Recrystallisation of zircon at high temperature within residual rocks is largely controlled by diffusion. The *T*–*t* conditions within a region are of particular importance when assessing elements with low diffusivity, due to the exponential relationship between diffusivity, temperature and the duration of high-grade metamorphism. Using diffusion modelling, the mobility of REE in zircon as a function of temperature and time was assessed. Diffusion profiles were generated for a range of *T*–*t* scenarios and extrapolated to generate modified REE profiles, allowing assessment of the mobility and degree of modification as a function of temperature and/or time.

Microbially Mediated Black Sludge following a Cyclonic Event in Shark Bay, Western Australia and its Link with Cobble Formation

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On the 13th of March 2015 Shark Bay, Western Australia was hit by a category 3 cyclone, "cyclone Olywn", causing destructive wind gusts of up to 140 kilometers per hour and a record total of 122 mm of rain fell in 24 hours. This event caused significant structural changes to a microbial ecosystem found in Hamelin Pool. Immediately after the cyclone, the formation of a black sludge was observed in the impacted area, this black sludge is currently assumed to be a mixture of reconstituted extracellular polymeric substances (EPS) from impacted microbial mats, anoxic sediments containing iron sulfide minerals, marine debris and terrestrial matter (i.e. plant material). Upon returning to the site on the 7th of July 2016 it was found that the black sludge had turned into mud cobbles (Fig. 1).

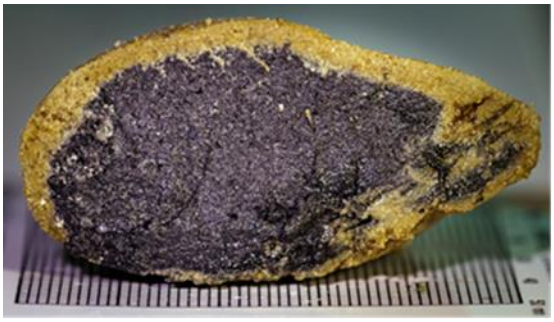

***Figure 1**. Cross-section of mud cobble (photographer: Aditya Chopra)*

These mud cobbles could represent modern analogues of carbonate concretions found throughout the geological record and provide insight into concretion formation. Organic and inorganic geochemical techniques along with genomics will be applied to the black sludge and mud cobbles in order to investigate biomarker and isotopic distributions, variations in sulfur speciation and microbial diversity. This multidisciplinary approach will allow for a greater understanding of how these mud cobbles developed and if they exhibit the necessary conditions and microbial communities such as sulfate-reducing bacteria, for calcium carbonate precipitation. Additionally, sulfurization is recognized as one of the most important diagenetic pathways; Raney nickel desulfurizations will be applied to the black sludge and mud cobbles to establish if biomolecular sulfurization is occurring (Köster et al., 1997).

Current findings indicate that the black sludge and cobbles are from a similar source. The overall molecular and isotopic profiles of the saturated hydrocarbon fractions are almost identical in regards to the distribution and abundance of higher plant, diatom and bacteria biomarkers. These markers and their prominence within the samples are highly common for areas such as Hamelin Pool (Allen et al., 2010). Hopanes, such as the $C_{31\alpha\beta}$ and $C_{31\beta\beta}$ hopanes were present in the free fractions of both samples, $C_{31\beta\beta}$ hopane can indicate the presence of sulfate-reducing bacteria (Pagès et al., 2015). Raney nickel desulfurization of the polar fractions released a series of sulfur bound steranes and hopanes. Two dimensional gas chromatography time of flight mass spectrometry (GCxGC-TOFMS) was used to gain a higher resolution of $C_{27\text{-}29}$ sterane and $C_{27\text{-}34}$ hopane distributions (Fig. 2).

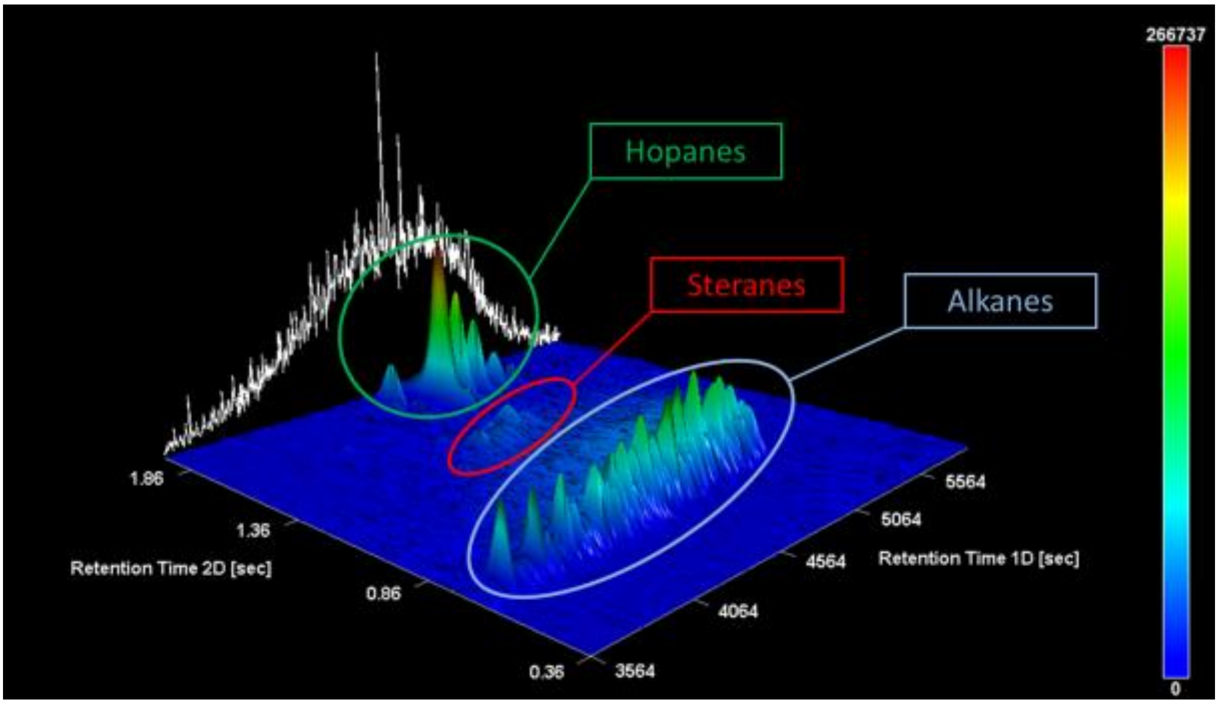

Figure 2. *GCxGC-TOFMS image of a saturate fraction gained from the Raney-Nickel desulfurization of the mud cobble's polar fraction exhibiting high resolution of steranes and hopanes.*

Sulfate-reducing bacteria are known to promote calcium carbonate precipitation within microbial systems and the early stages of biomolecular sulfurization indicates that the mud cobbles have the potential to form into carbonate concretion with the ability to preserve organic material. The further investigation into the microbial taxonomic and functional diversity as well as the inorganic properties of these samples will help to further gain an understanding of how these formations develop and potentially shed light into the major microbial species involved in concretion formation.

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Utilizing microbial genomics and lipid biomarkers to study maturity, provenance, and biodegradation of subsurface petroleum in the North West Shelf, Western Australia

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Western Australia's North West Shelf (NWS) comprises large deposits of crude oil and natural gas, many of which are undeveloped and unexplored due to limitations in exploration technology (1). Maturity and provenance characterizations of known deposits are important factors for exploring prospective reserves, but are disturbed by water-washing, fluid-mixing, and migration patterns across reservoirs (2). Petroleum reservoirs in the deep subsurface are also residence to a variety of bacterial and archaeal communities that are adapted to temperatures up to 80°C and anaerobic and nutrient-depleted conditions (3–5). These microbial communities degrade hydrocarbon compounds as a function of their metabolic processes, and deterioration of hydrocarbons compromises the quality of extracted petroleum (6–8). Because the metabolic characteristics of microbial communities depend on their physicochemical and environmental conditions (9), the expressed genes of hydrocarbon-degrading microbes should be related to their ambient conditions. Furthermore, as reservoir conditions are related to source rock maturity and composition, it should be possible to correlate microbial genes and their corresponding metabolic processes to assess petroleum provenance and maturity.

This project has two key objectives. The first objective is to determine the microbial genes that convey hydrocarbon-deteriorating characteristics and analyse the metabolic and biogeochemical mechanics involved in petroleum biodegradation. The second objective pertains to assessing whether microbial genomics and lipid biomarkers can be utilized as a novel coupled method for determining petroleum maturity and provenance. Formation water and crude oil samples will be obtained from presently active oil wells in the Dampier, Exmouth, and Barrow sub-Basins for lipid biomarker analysis and microbial DNA sequencing. Present advances in metagenomics have allowed microbial DNA to be sequenced directly from their environmental sources, thereby allowing gene material to be analysed for abundance and function (10). Metagenomic and 16S rRNA gene sequencing, as well as extraction, separation, and analyses of relevant lipid biomarkers, will provide an overview of microbial communities in the deep subsurface and the dynamics of hydrocarbon biodegradation. Exploring these methods for deep subsurface microbial ecology and biogeochemistry will also help develop new methods for microbially enhanced oil recovery and gas production.

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Gigayear periodicity of mantle circulation on Earth

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The gigayear periodicity in global radiogenic Hf and Sr isotopic trends is investigated by integrating data from tectonics, geodynamics, and palaeomagnetism, in order to build a holistic geodynamic model linking modes of mantle convection to plate tectonic motions over the last 2,500 Myr. The gigacycle reflects an alternating dominance between degree-2 and degree-1 mantle convective flow, manifest as the presence and absence of a hemispheric subduction girdle, respectively. The girdle is currently represented by the circum-Pacific subduction system and is geologically recorded by Phanerozoic circum-Pacific accretionary orogens. Degree-1 convection resulted in the amalgamation of Columbia ca. 2,000 Myr ago and Gondwana ca. 550 Myr ago accompanied by peaks in crustal reworking ($-\varepsilon$Hf), whereas degree-2 convection produced Nuna ca. 1,600 Myr ago and Pangaea 200 Myr ago accompanied by peaks in mantle input ($+\varepsilon$Hf). The change from degree-2 to degree-1 coincided with Rodinia amalgamation ca. 1,100 Myr ago, when the circum-Nuna subduction girdle collapsed. The gigacycles are rhymthic oscillations of mantle circulation patterns that control plate motion trajectories and contrasting styles of supercontinent amalgamation.

Insights into sulphur cycling at subduction zones from *in-situ* isotopic analysis of sulphides in high-pressure serpentinites and 'hybrid' rocks from Alpine Corsica

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δ^{34}S values of sulphides provide information on sulphur sources and processes subsequent to sulphide crystallisation, such as fluid infiltration or loss, and are sensitive to the redox state of sulphur in the host mineral [1]. Therefore it may be possible to use δ^{34}S to constrain the redox state and fluxes of sulphur. Further, the proximity of serpentinites to ocean crust and metasediments may influence their isotopic signatures during subduction. For example, seafloor serpentinites associated with mafic intrusions have heavier δ^{34}S values [2]. In this study the redox state, the likelihood of sulphur addition to the sub-arc mantle from serpentinite dehydration, and the distribution of sulphur within subducted serpentinites and 'hybrid' mafic/ultramafic rocks from Alpine Corsica is investigated by a combination of petrographic analysis, *in-situ* sulphur isotopic analysis and trace element analyses of sulphides hosted in these rocks. Sulphur-derived from the mantle (δ^{34}S values ~ 0.1‰ [3]) was not the sole sulphur source in these samples with heterogeneous δ^{34}S values of 1.9–15.5‰ for all sulphides, suggesting equilibration on limited length scales. The heaviest values were recorded in pyrites of a hybrid mafic/ultramafic sample. Heavy δ^{34}S is preserved in sulphides attributed to prograde metamorphism, and is most consistent with the retention of isotopic signatures from hydrothermal sulphate reduction on the seafloor. However, a shift towards heavier δ^{34}S from prograde sulphides to sulphides associated with the advanced stages of exhumation suggests that late stage exhumation enhanced access to slab-derived fluids which carry oxidised sulphur (sulphate or SO_2).

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Episodes of hypogene iron enrichment in Neoarchean Banded Iron Formations in the Weld Range district, Yilgarn Craton, Western Australia

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Banded Iron Formations (BIFs) are finely laminated to thinly bedded chert-bearing chemical sedimentary rocks with at least 15 wt.% Fe of sedimentary origin. Primary geological processes are important in controlling the initial thickness of BIFs, the proportion of iron oxide and silica bands, and their chemical composition (e.g. Fe and Si, with trace elements Al, Ti, and P). However, secondary processes involving the interaction between BIFs and large volumes of hydrothermal fluids are required to increase the Fe content in BIFs from <35 wt.% to higher-grade ores containing 57 to 69 wt.% Fe. This typically involves widespread Si removal from BIFs (<99 % removal) and can take place in the near-surface environment as a result of weathering processes, but may also operate below the weathering front due to interaction with ascending deep hypogene fluids (largely magmatic or basinal brines) and/or descending meteoric water (Hagemann et al., 2016). Most world-class iron ore deposits hosted by BIFs (e.g. Mt Tom Price and Mt Whaleback in the Hamersley Province) are a combination of both iron mineralization styles and exhibit near-surface, supergene goethite-hematite orebodies that overlie and partly modify deeper and older hypogene magnetite and crystalline hematite ores.

The Weld Range greenstone belt in the Murchison Domain of the Yilgarn Craton contains the Beebyn and Madoonga high-grade iron deposits hosted by Neoarchean Algoma-type BIFs. Each deposit includes magnetite-rich hypogene ores that are in places overprinted by hypogene crystalline hematite, and by shallower supergene goethite-hematite ores. While the supergene ores are likely the product of Cenozoic weathering, the absolute age of the magnetite- and hematite-rich hypogene ores is unknown. This study is the first to present geochronological data for hypogene iron mineralization events in the Yilgarn Craton. To constrain the age of hypogene magnetite mineralization at Beebyn and Madoonga deposits, 21 polished thin-sections and mounts were inspected for hydrothermal monazite and xenotime using a scanning electron microscope. Phosphates larger than 10 µm were analyzed using the SHRIMP II at the John de Laeter Centre at Curtin University, Western Australia. From the Beebyn deposit, five monazites and three xenotimes were analysed, whereas 27 monazites and 18 xenotimes were analysed from the Madoonga deposit. Monazites are U-poor (<50 ppm) and their ages are constrained using their $^{208}Pb/^{232}Th$ ratios, whereas $^{207}Pb/^{206}Pb$ ages are reported for xenotimes.

At the Beebyn deposit, magnetite-rich orebodies are the product of hydrothermal enrichment of iron in BIF, initially through the replacement of primary quartz bands by hypogene carbonate minerals, followed by the dissolution of carbonates (Duuring and Hagemann, 2013). Eight dated xenotimes and monazites define a weighted mean $^{207}Pb^*/^{206}Pb^*$ age of 2624 ± 6 Ma. In contrast, at the Madoonga deposit, magnetite-talc±chlorite veins record multiple ages: the first at 2863 ± 37 Ma, followed by hydrothermal events at c. 2750 Ma through to 1760 Ma. An age probability plot demonstrates two dominant phosphate growth events at 2200-2000 Ma and 1900-1800 Ma. These ages are from xenotimes and monazites from five samples of magnetite-talc±chlorite veins sampled <2 km apart. Individual hand specimens may also provide large age ranges from dated phosphates (e.g. c. 2604 and 1898 Ma in GSWA sample# 223764). Textural relationships in most samples confirm that there are multiple generations of magnetite formation, such as magnetite cores surrounded by talc or chlorite inclusion-rich magnetite rims. However, it is more difficult to confidently compare mineralizing events between samples because of the mostly monomineralic nature of these magnetite-rich ores. The chemical characteristic of each phosphate age population is presently being examined.

Magnetite-rich orebodies at the Beebyn deposit are likely the result of a multi-kilometre, (magmatic-) hydrothermal fluid system centred beneath BIF and underlying mafic igneous rocks, in shallow areas of the crust that were intermittently accessible by ancient modified seawater (Duuring et al. in review). The timing of this event at c. 2624 Ma post-dates the deposition of dated BIFs in the Weld Range district (<2792 ± 9 Ma, Wingate et al., 2013) and emplacement of nearby 2805 ± 19 Ma (Wingate et al., 2012) Gnanagooragoo mafic-ultramafic country rocks. The relatively precise $^{207}Pb^{*}/^{206}Pb^{*}$ date for the magnetite mineralization event at the Beebyn deposit is treated with caution, considering that there are fewer data available for this deposit compared with Madoonga, and that additional analyses may reveal a larger distribution of ages. Consequently, the c. 2624 Ma date is interpreted to be a minimum age for magnetite mineralization at the Beebyn deposit. In contrast, the 1 billion year time span demonstrated by dated phosphates in magnetite-talc±chlorite veins from the Madoonga deposit, suggests that these rocks have experienced multiple hydrothermal fluids over an extended duration. Each successive fluid evidently resulted in the dissolution-reprecipitation of new monazite and xenotime. Thus, it is likely that the oldest age determined for hydrothermal monazite in the magnetite-talc±chlorite veins at c. 2860 Ma represents the earliest age for alteration of BIFs at Madoonga. This age is older than the depositional age for BIFs located in the centre of the Weld Range district (i.e. c. 2792 Ma) and suggests the presence of older BIFs along the northern margin of the district, with the possibility that the magnetite-talc±chlorite veins represent sub-seafloor alteration and magnetite ore formation in these older BIFs. VMS-style Pb-Zn-Cu mineralization in Madoonga BIFs located within 2 km of the iron deposit (Guilliamse, 2014), is compatible with this interpretation. We correlate the younger hydrothermal events at the Madoonga deposit with episodes of orogenic activity identified in the Capricorn Orogen, namely the 2215-2145 Ma (Ophthalmia Orogeny), 2005-1950 Ma (Glenburgh Orogeny), and 1820-1770 Ma (Capricorn Orogeny) events (Johnson, 2013). Interestingly, these orogenic events coincide with reported ages for hematite mineralization in BIF-hosted iron deposits in the Hamersley Province (Rasmussen et al., 2007) and Pilbara Craton (Sheppard et al., 2017).

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Gold metallogeny of the northern Capricorn Orogen

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Gold deposits commonly have a spatial association with long-lived, crustal-scale faults which act as conduits for mineralizing fluids during hydrothermal activity. However, the precise timing of gold mineralization and the lengthy history of movement on such fundamental structures is often poorly understood. The Proterozoic Capricorn Orogen of Western Australia records the punctuated Proterozoic assembly of the Pilbara and Yilgarn Cratons, and over one billion years of subsequent intracratonic reworking and basin formation. The northern part of the Capricorn Orogen hosts numerous gold deposits that are spatially associated with crustal-scale faults. However, prior to this study, the link between the timing of these gold deposits and (re)activation of these major faults had not been established.

We use in situ SHRIMP U–Th–Pb geochronology of monazite and xenotime from several key gold deposits across the northern Capricorn Orogen to provide precise ages for regional-scale, low-temperature, hydrothermal alteration and associated gold mineralization. Our results demonstrate that mineralization occurred during three discrete periods at c. 2400, c. 1770 and c. 1680 Ma which can be linked to the well-established tectonothermal framework of the Capricorn Orogen. Orogenic gold mineralization dated at c. 2400 Ma does not correspond to any known deformation events along the southern Pilbara margin, however, monazite growth in phyllites across the Pilbara region [1], as well as resetting of high–U zircons in tuffaceous mudstones of the Hamersley Group [2], have been recorded between c. 2430 and 2400 Ma. Carlin-like gold mineralization at c. 1770 Ma and extensive gold remobilization at c. 1680 Ma are synchronous with intracratonic reworking and fault (re)activations during the final stages of the 1820–1770 Ma Capricorn Orogeny and early in the 1680–1620 Ma Mangaroon Orogeny. These results demonstrate multiple gold mineralizing events associated with movement along major faults that act as critical lithospheric-scale deep plumbing systems which concentrate fluids, energy, and metals into the crust.

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Good dates, bad ages – Archean zircon inheritance in Cambrian schist and pegmatite from Madagascar

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Madagascar lies within a wide region of metamorphism in Gondwana reconstructions, widely attributed to collision of the Congo and Dharwar cratons at the close of the Neoproterozoic. More controversial is the location of oceanic sutures in this collision zone, and in particular whether the Antananarivo Block of central Madagascar and Antongil Craton of northeast Madagascar were separated by an ocean basin in the Neoproterozoic or had been together since the Archean. These two models stem from a disputed age for metamorphism in the Ambodiriana Formation, a staurolite–kyanite–biotite±sillimanite schist unit exposed along the northeast edge of the possible suture. Collins *et al.* (2003) argued that 3500–3000, 2700–2500 and 850–700 Ma zircon in the Ambodiriana Formation is detrital while a single zircon rim dated at *c.* 520 Ma grew during peak metamorphism. Conversely, Schofield *et al.* (2010) and Tucker *et al.* (2011) argued that 2700–2500 Ma zircon from pegmatitic leucosome in these same rocks dated peak metamorphism, while 3500–3000 Ma zircon is inherited and 850–700 and 600–500 Ma zircon grew in later metamorphic or hydrothermal events of limited significance. To clarify these age data, we undertook a SHRIMP U–Pb monazite study of the Ambodiriana Formation.

Monazite separates from one sample yield a single population dated at 517 ± 9 Ma while *in situ* analyses of grains in five other samples, including monazite enclosed by kyanite and staurolite, give a date of 521 ± 4 Ma. These data are supported by LA-ICPMS $^{207}Pb/^{206}Pb$ ages of 540 ± 21 Ma for xenotime grains in the same samples. Rare earth element concentrations in these coexisting monazite and xenotime grains are consistent with equilibrium partitioning at upper amphibolite conditions, confirming that peak kyanite-grade metamorphism in the Ambodiriana Formation is Cambrian in age. We interpret 3500–700 Ma zircon in leucosome dated by Schofield *et al.* (2010) and Tucker *et al.* (2011) as detrital grains inherited from host metapelite, and consider a high level of zircon inheritance in such granitoids to be unsurprising given their origin from low-temperature anatexis. Indeed Schofield *et al.* (2010) report a highly peraluminous composition and low Zr concentration (97 ppm) for their leucosome sample, both characteristic features of low-temperature granitoid likely to contain abundant inherited zircon (Miller *et al.* 2003).

Our results show that reliance on zircon crystallisation dates can lead to events being missed or misinterpreted if the rocks are prone to zircon inheritance. In this case, the age of metamorphism has been overestimated by 2 billion years, despite the undoubted high precision and accuracy of the isotopic data.

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Alternative explanations into the initial organic carbon isotope excursion at St. Audrie's Bay during the end-Triassic mass extinction

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Mass extinction events are recognised throughout geological time with all but one associated with large igneous provinces. One of these five mass extinction events associated with intense volcanic activity is the end-Triassic mass extinction (ETE) that occurred ~201 million years ago[1]. St. Audrie's Bay, UK is a focal section in ETE studies. Here, the iconic organic carbon isotope record ($\delta^{13}C_{org}$) exhibits 'initial' and 'main' negative excursions[2], with similar isotopic patterns occurring in other European sections. These 'initial' excursions are typically attributed to the dissociation of methane clathrates that have very low isotopic signatures. This methane rapidly oxidises to CO_2 before subsequently being incorporated into organic matter and thus preserved in the sedimentary record[3–5]. Biomarkers are the fossilised lipids that derive from the 3 domains of life, and are able to serve as import proxies indicating changes in redox, environmental and ecological conditions during mass extinction events[1]. Hopanes (generally derived from bacteria) and steranes (largely derived from eukaryotes) investigated during the 'initial' $\delta^{13}C_{org}$ excursion at St. Audrie's Bay (Figure 1) suggest that the excursion may instead be the result of, or at least influenced by, local biotic community changes as a result of dramatic sea level drop and influx of freshwater evidenced by the presence of freshwater biota and periodic exposure due to the presence of desiccation cracks during the time of the 'initial' organic carbon isotope excursion. Steranes in the C_{26} to C_{30} range indicate that during the 'initial' $\delta^{13}C_{org}$ isotope excursion relative abundances of green algae increase whilst those of prasinophytes, chrysophytes, and red algae decrease. During this time, hopanes indicating redox conditions, unlike those in Canadian sections during the ETE[6], co-vary in opposite directions such that the homohopane index increases whilst the C_{28} 28, 30 bis*nor*hopanes decrease indicating increases in microbial activity and a change in microbial communities as a result of changing water depth respectively[7]. The greater abundances of hopanes compared to steranes during the 'initial' $\delta^{13}C_{org}$ excursion in what has already been determined a sub-oxic to aerobic environment[8] indicates greater bacterial activity in a freshwater to lacustrine environment. Furthermore, biomarkers of methanotrophs also decrease during the initial $\delta^{13}C_{org}$ excursion that may have expected to increase with the dissociation of methane clathrates. Interpretation of this data set suggests the initial $\delta^{13}C_{org}$ excursion results from bacterial community changes and increases in microbial activity due to fractionation differences between bacteria and eukaryotes. This data set also outlines the further need of multi-proxy biomarker investigations during mass extinction events and their recoveries.

Melting Earth's Ancient Mantle

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Recent models suggest Eoarchaean basalts were extracted from mantle with superchondritic Sm/Nd ratios that developed in the Early Hadean. We use a combination of thermodynamic and trace element modelling, to model melting of different mantle compositions.

We show that melts with the Sm/Nd and Lu/Hf ratios of unaltered Eoarchaean tholeiitic basalts from the Isua Supracrustal Belt, West Greenland, cannot be generated from chondritic mantle. In the preferred model, they involve 20–25 % melting of mantle with superchondritic Sm/Nd ratios, with the elevated degrees of mantle melting compared to modern MORB generation reflecting a hotter upper mantle in the Early Archaean.

Quantitative trace-element analysis of gold using LA-ICP-MS and implications for the mechanism of native gold crystallization

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The Geological Survey of Western Australia (GSWA) is undertaking a systematic study of the physical and chemical characteristics of placer and bedrock-hosted gold, to help evaluate the gold prospectivity of Archaean and Proterozoic terranes in Western Australia and thereby determine the potential for the presence of significant undiscovered gold resources. A prerequisite of this project has been the development of a technique for quantitative geochemical analysis of gold using LA-ICP-MS. The technique is calibrated using two certified standards prepared by the London Bullion Metals Association (LBMA) from molten, high-purity gold, doped with small known quantities of 22 other elements (AuRM2 and AuRM2; Murray 2009). The chemical homogeneity of the standards has been tested by measuring the relative trace element abundances (in counts per second, cps) along traverses of several millimetres in length.

While compositional inhomogeneity is evident, possibly due to exsolution and concentration of trace elements within finite areas of the gold crystal lattice or on crystal boundaries, on the gross scale the standards appear uniform in composition. The obvious spikes in the analytical data caused by these impurities/inclusions were removed during data reduction, and residual mean elemental values in cps along the traverses were calibrated against certified values. Repeat analyses of the standards facilitated the calculation of the standard deviation for each analyte in each standard. Calibration graphs have been produced for the analytes in AuRM1 and AuRM2 and, where values are available the graphs have incorporated concentrations for the Perth Mint standard. The graphs indicate excellent correlations for all elements except Pt, hence the LBMA standards are considered suitable for quantitative LA-ICP-MS analysis of trace-elements in native gold.

Chemical inhomogeneity in natural gold grains has been well demonstrated from studies of grain microstructure and distribution of relatively abundant traces determined using SEM-EDS, microprobe, and spectral analyses. However, relatively high detection limits of such techniques inhibits a better understanding of the variability in element distribution, hence of mechanism(s) by which primary gold grains crystallize and chemical inhomogeneities develop. Using quantitative LA-ICP-MS analysis, the distribution and abundances of 23 elements (including mercury) in 56 nuggets from Kurnalpi Goldfield have been determined in an attempt to address these questions. Three 1.3 mm long laser ablation traverses were run across microscopically inclusion-free domains in each nugget. Measured abundances of all analytes are extremely variable, with marked changes in some elements (e.g. Cu, Ag) across structural domains such as recrystallization zones or twin planes. These variations may reflect response to subsequent grain modifying mechanisms, such as recrystallization during deformation or passage of hydrothermal solutions.

There are also transient element compositional variations that show no relationship to any visible microstructural features or polymetallic inclusions. However, given that the laser ablation spot diameter used is 100 µm, it seems likely that these variations represent discrete, micron to sub-micron-scale domains similar to those observed in the certified gold standards. These domains may have been originally-formed nuclei upon which gold grains crystallized from a melt or a solution. It must also be remembered that LA-ICP-MS analysis utilizes a three dimensional sample, and variations throughout the traverse may therefore represent associations of nano-sized areas of relatively high and low analyte composition, which cannot be determined using electron microscopy, but are nonetheless observed when the total volume of ablated sample is ionised in the plasma.

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$\delta^{34}S$ of Organic Sulfur Compounds and the Sulfur Cycle of Petroleum Systems

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The recently invented Compound Specific Sulfur Isotope analysis (CS-S-IA) can help to investigate the incorporation and fate of sulfur in petroleum systems. Sulfur is usually incorporated into fossil fuels via secondary processes (Peters et al., 2005), most significantly by thermochemical sulfate reduction (TSR). The $\delta^{34}S$ of organo sulphur compounds (OSCs) in oils can be significantly influenced by TSR, as well as by other factors such as depositional environment and thermal maturity. Bulk $\delta^{34}S$ values of petroleum can vary over a wide range (8 to 32%; Faure and Mensing, 2005) and have traditionally proved quite useful for oil–oil correlations (see e.g., Gaffney et al.1980). CS-S-IA has already been applied to several S-rich oils from different parts of the world (Amrani et al., 2009; 2012; Greenwood et al., 2014; Li et al., 2015; Cai et al., 2015; Gvirtzman et al., 2015) with the $\delta^{34}S$ values measured ranging from -15 to +40 ‰, and with co-occurring OSCs in a single oil varying by as much as 30 ‰ – reflecting the impact of different controls that would not be resolved by bulk $\delta^{34}S$ analysis. A more sophisticated understanding of the $\delta^{34}S$ relationships of specific S-sources and alteration events requires further CS-S-IA research and application to a variety of petroleum samples.

In a case study demonstrating the contribution of CS-SIA to petroleum characterisation and exploration studies, we will report the analyses of a S-rich condensate oil from a newly drilled well (LS2) in Bachu uplift of the Tarim Basin, China. This petroleum contained high abundances of thiophenic compounds (i.e., alkylated benzothiophenes, BTs; and dibenzothiophenes, DBTs), with lesser abundances of sulfidic (i.e., alkylated thiadiamandoid) compounds. The molecular and isotopic composition of these distinctive organics sulfur compounds (OSCs) will be useful for future oil correlations. A $\delta^{34}S$ distinction between OSCs reflecting a varied sensitivity to TSR (i.e., $\delta^{34}S_{BT\text{-}DBT} \sim 4$ ‰) indicated the condensate had been severely impacted by TSR. This result was consistent with other indicators of TSR including high H_2S concentrations, the formation of thiadiamondoids and the ^{13}C enrichment of gas range hydrocarbons. However, the LS2 reservoir temperatures was too low to have directly supported TSR, implying the presently in place condensate migrated from deeper strata through fracture adjustment of the late Himalayan period. The $\delta^{34}S$ values of the oil and gas are typical of a Cambrian source. Thick evaporites in the middle Cambrian strata and high quality Xiaoerblak ($\in_{1x}$) dolomites in the lower Cambrian experienced geological temperatures greater than 200°C, sufficient for TSR. This discovery suggests the Cambrian salt layers of the Tarim Basin have significant petroleum and gas exploration potential.

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Episodic behaviour of a cooling Earth.

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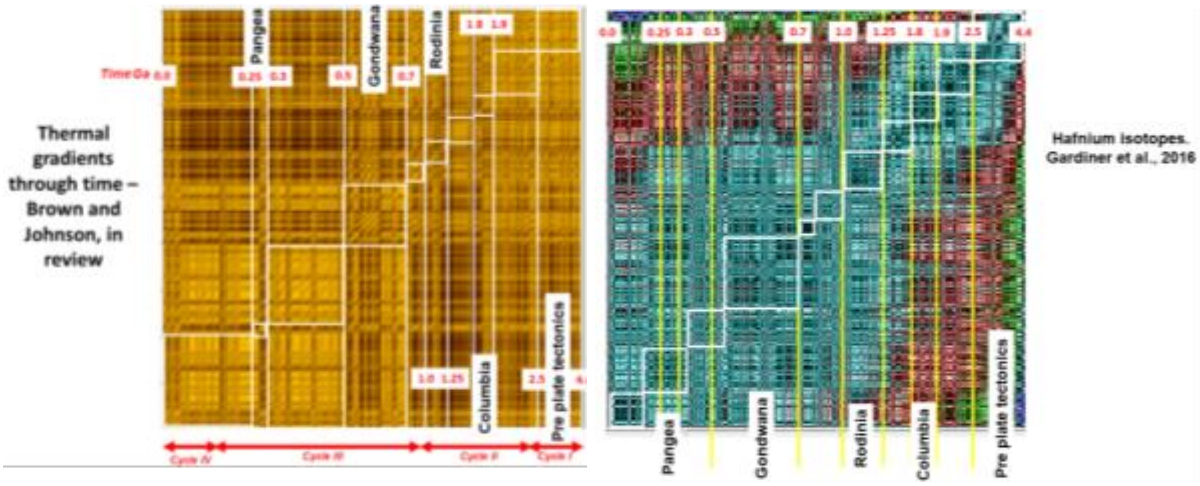
The Earth cools through a series of coupled physical and chemical processes that constitute an energy cascade both in space and time. This cascade ranges from the supercontinent cycle scale to the nanoscale. A direct result of the energy cascade process is the emergence of episodic behaviour. Such behaviour is best analysed and characterised using principles inherent in nonlinear dynamics. One of the most fundamental characteristics of such systems is *recurrence*. We employ recurrence plots (Figure 1), joint recurrence plots and recurrence networks along with quantitative measures of recurrence to examine episodicity through time for the planet Earth. One of the important characteristics of recurrence is *laminarity* which marks transitions between various kinds of episodic behaviour such as transitions between two types of periodic behaviour (period doubling for instance) or between various kinds of chaotic behaviour. Laminarity is expressed as vertical and horizontal bands on recurrence plots (Figure 1). We show that the global histories of metamorphic thermal gradients, granite and pegmatite occurrences, zircon ages and secular hafnium isotopic signatures show strikingly similar patterns of recurrence and laminarity which not only reflect the super-continent cycle (transitions between degree-1 and degree-2 mantle convective systems) but also detail episodicity within and between such cycles. Such episodicity is a characteristic of all tectonic activity at all spatial scales. We speculate on the origin of such detail in terms of the tectonic record and the processes that may have operated including instability and episodicity associated with lithospheric shearing - lithospheric thickening - melting and lithospheric collapse.



Recurrence plots for metamorphic thermal gradients through time (left) and for hafnium isotopes through time (right). The vertical (and horizontal) bands are expressions of laminarity or transitions beteweeen various patterns of episodicity.

Microbial Pb arsenide mineralisation formed during sea-floor hydrothermal chimney growth in the PACMANUS hydrothermal field, Manus Basin, PNG

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Hydrothermal chimneys are widespread on the seafloor along the mid-ocean ridges and back-arc basins (German et al., 2016) and provide habitat for diverse microbes where early life has been suggested to begin (Holden et al., 2012; Takai et al., 2009). It has been widely recognised that microorganisms play an important role in the formation of minerals and the cycling of metals (Holden et al., 2012; Jennifer Lin et al., 2014; Ver Eecke et al., 2009). Microbial organisms can contribute actively to mineralization when utilising trace elements as energy sources or inactively by releasing trace element as metabolic byproducts that are attached to the cell surface (Holden et al., 2012; Templeton and Knowles, 2009). Most previous studies focus on microbial interaction with common metals, such as Fe and Mn (Ver Eecke et al., 2009) on the surface of chimneys. However, the interaction between microbes and some other toxic elements, like As and Pb, or reaction during chimney growth is poorly understood. This study examines the microbe and trace element distribution in hydrothermal chimneys based on petrographic and SEM observations. Chimney samples were collected from seafloor of PACMANUS area in MANUS basin. Microbial colonisation that consists of nano-scale filaments were observed to have been mineralised to dufrenoysite ($Pb_2As_2S_5$) (Figure 1), which is the first observation ever, to our knowledge. Pb-rich filaments also occur within sphalerite that contains pyrite and chalcopyrite zonation as an indication of pulses of hydrothermal fluids during the chimney growth (Figure 2). Filaments around chalcopyrite zoning are characterised as galena (PbS) with minor As, which transform to dufrenoysite with the same morphology at the edge of sphalerite or cluster as dendritic structure outside of sphalerite (Figure 3). Two explanations are proposed. All the filaments may be results of microbial activities, which are associated with Pb mineralization, and are produced during pulses of hot hydrothermal fluids during the growth of this chimney. Alternatively, galena is deposited as a result of rapid cooling down of hydrothermal fluids along with the precipitation of sphalerite and chalcopyrite, and then is utilised by microbes to precipitate dufrenoysite at the edge of sphalerite. This study provides a new understanding of the chimney growth process, and documents a remarkable example of extremophile life associated with high-toxicity elements.

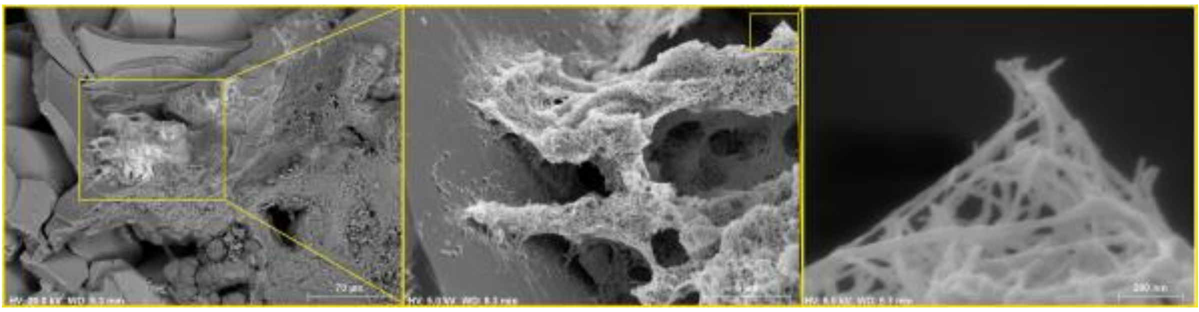

Figure 1 Microbial colonization of mineralized dufrenoysite ($Pb_2As_2S_5$).

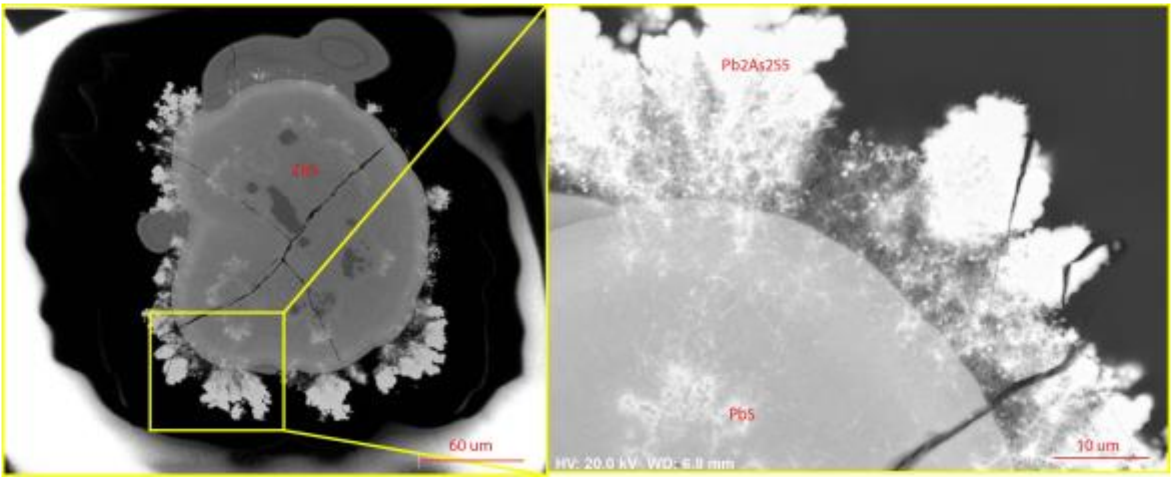

Figure 2 The distribution of Pb-rich sulfides in sphalerite.

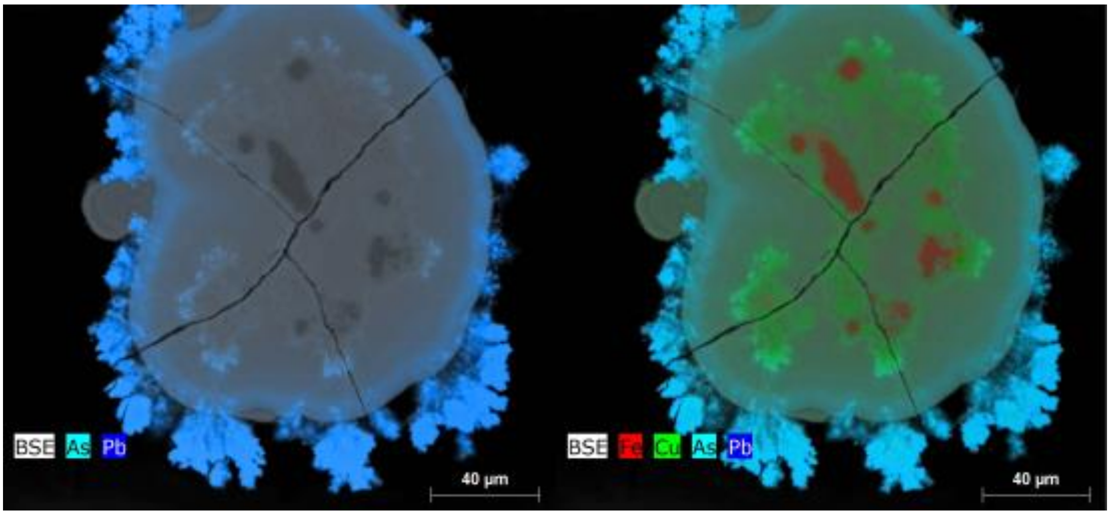

Figure 3 Element mapping of sphalerite.

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Revealing the role of viruses during a petroleum biodegradative experiment, using microbial mats of Shark Bay, WA

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Viruses represent only 5% of total biomass of microbial mats but are significantly more abundant than bacterial and archaeal communities [1]. Viruses play an important role in nutrient cycling and the evolution and genetic and functional diversity of microorganisms [2] [3] [4] [5]. A number of previous studies have demonstrated that bacteria in microbial mats are involved in degradation of petroleum compounds [6] [7] [8], but the role that viruses play in regulating these and other bacteria in microbial mats remains unknown. This study will explore the role of viral communities in microbial mats from a hypersaline environment in Shark Bay (Western Australia), and their potential role in biodegradation of petroleum. Smooth and Pustular microbial mats samples will be collected from Nilemah embayment and will be exposed to petroleum during a time series incubation experiment. Changes in microbial and viral diversity, microbial metabolic potential to degrade petroleum hydrocarbons, and the expression of genes involved in these processes will be monitored using high throughput sequencing of respectively taxonomic marker genes, metagenomes, and metatranscriptomes. Changes in the hydrocarbon profiling and stable isotopic compositions of individual biomarkers associated with microbial decomposition of petroleum will be determined in parallel using state-of-the-art organic and isotope geochemistry tools. The results will then lead to enhance the current knowledge of microbial and viral composition of Shark Bay microbial mats, their susceptibility to petroleum introduced into this ecosystem, provide insights how virus affect or regulate hosts during a petroleum spill experimentation, and evaluate comprehensively hydrocarbon and isotopic composition over time. This research become more relevant due to it is anticipated a 0.5-m sea-level rise for the next decades, and it will lead to a higher probability of petroleum being introduced into the Shark Bay region because of increased shipping and transportation activities.

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What we might learn from strontium in apatite inclusions in zircon that we don't know already

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For decades we have shot holes in zircons for their age information while carefully avoiding hitting any inclusions. Consistently the most abundant primary inclusion in magmatic zircon is apatite. Apatite inclusions have great untapped potential to add to the wealth of geochemical data extracted from zircons if we can apply sufficiently sensitive micro- or nanobeam analytical techniques to their analysis. Because trace element (e.g. Sr, Y, REE) abundances in igneous apatite are more sensitive indicators of magma composition than are those in igneous zircon (e.g. Belousova et al 2002), apatite inclusion analysis could be used to investigate the provenance of detrital zircons, including Hadean zircons. Moreover, having extremely low Rb/Sr, apatite records its initial $^{87}Sr/^{86}Sr$ ratio in the same way that zircon records its initial $^{176}Hf/^{177}Hf$, with the expectation of preservation from subsequent geological disturbances inside the zircon 'time capsule'. This raises the possibility of triple isotope system (Pb–Hf–Sr) geochemistry on comagmatic zircon/apatite pairs. An immediate application would be to be able to estimate the average Rb/Sr ratio of the precursor rocks that melted to produce the zircon/apatite forming magma. This can be used as an index of crustal thickness/differentiation over time (e.g. McDermott F. & Hawkesworth C.J. 1990; Dhuime B. *et al.* 2015), and would be especially valuable to address the temporal evolution of Precambrian crust in which whole rock Sr and Nd isotope ratios are often disturbed and potentially unreliable.

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Visualizing temporal and spatial patterns of U-Pb disturbance

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The zircon U-Pb system is a powerful geochronometer, however disturbance to this system can be widely diagnosed on U-Pb concordia diagrams where it is typically interpreted as a consequence of radiogenic-Pb loss. Pb is incompatible in zircon but is generated by radioactive decay of U in the grain, a process that leads to some degree of radiation damage in the crystal lattice. As a result, Pb is only loosely bound to the zircon crystal lattice, whence U was tightly bound. Hence radiogenic Pb is, in comparison to U, readily mobile, particularly at the margins of the crystal and along any fractures. In many cases, removal of radiogenic-Pb is not complete, and Discordia regressions on concordia diagrams provide a means to track both the original age of crystallization of the rock and the timing of isotopic disturbance. In this talk I will present a new approach to determine the most pervasive time of U-Pb disturbance in a sample. This new statistical approach, the Concordant-Discordant Comparison (CDC) test, evaluates the similarity between a sample's concordant age structure and a modelled age structure, from discordant analyses, over a wide range of potential disturbance times. The closest similarity in concordant and discordant age populations as derived from a specified time of elemental mobility, is interpreted as the best estimate for the time of U-Pb disturbance. The CDC test is appropriate for magmatic as well as detrital samples, and yields dates that can be spatially interpolated to produce regional maps that define spatial domains of temporally similar U-Pb disturbance. A range of case studies using the CDC test will be presented including examples from North Greenland and the Eastern Goldfields Superterrane of the Yilgarn Craton, Western Australia. The CDC test typically captures information on the timing of fluid-rock interaction and has been used to date a wide range of events including mineralization and dyke emplacement. CDC modelling of discordant U-Pb zircon analyses may provide a means to recognize the distal footprint of otherwise difficult to date tectonothermal events and extract useful information from often discarded analyses.

Detrital zircon grain shape analysis in 3D and the effect on preservation bias (Murchison River, Western Australia)

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Detrital zircon geochronology and isotopic signatures are a powerful tool to address questions on provenance, basin dynamics, crustal growth and mantle evolution. However, the relationship between isotopic composition and zircon grain shape is largely unknown. How zircon grain shape is modified during fluvial transport is also poorly quantified. This study presents the first application of X-ray tomography to image and quantify zircon grain shapes in 3D. We combine this imaging method with U-Pb geochronology to quantify how fluvial transport affects zircon shape, age signature and grain density along the Murchison River, whose catchment comprises Eoarchean to Early Paleozoic source rocks in Western Australia. Tomographic volumes and isotopic data from 373 zircon grains were acquired to explore how grain shape, age spectra and zircon density change during fluvial transportation and distance. Results show that grain sphericity and surface roughness in the detrital zircon population clearly depend on transport distance, proximity to new source material and whether this source material contains primary or multi-cycled zircon grains. For an Archean detrital zircon population, which is traceable along the entire channel, grains evolve systematically from 'rough', larger, less dense and less spherical grains in the upstream region to 'smoother', more spherical and more dense grains towards the outlet. A weak positive correlation between surface roughness measures and sphericity values is observed. Variations in grain length (*length3d*) and width (w*idth3d)* reveal that with increasing transport distance, the length (parallel to their crystallographic c-axis) decreases more than their widths (perpendicular to the c-axis). Calculated mean grain density values show a linear trend, which documents the constant loss of metamict grains in the transport direction towards the river mouth. While metamict zircons were preferentially removed during transport, the similarities in grain shape and age distribution suggest that hydraulic sorting did not have a significant effect. The linear change in zircon mean grain density between upstream and outlet regions from moderately dense to highly dense grains indicates a rate of density change of 0.03 g / cm^3 per 100 km channel length. Therefore, apparent density relates to the absolute transport distance and grain shape; particularly sphericity, surface roughness, and grain size can provide valuable information related to the source, the catchment and the transport system. Our conclusion is that 3D shape characteristics provide valuable information on detrital zircon populations, including the interaction between source materials with fluvial transport processes, which significantly affects preservation bias and, by inference, the representativeness of the samples.

Sulfur in sub-volcanic arc ore deposits: A key to deposition rates?

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Volcanic arcs, where continental crust is built, and earthquakes and volcanoes are sourced are the breading grounds for the biggest ore deposits. Despite their immense metal budgets, arcs stand out mostly as sulfur anomalies. More sulfur is erupted from arcs than is thought possible (Oppenheimer et al., 2011) yet magatons remain in the crust. Arc magmas carry sulfur as dissolved sulfide and/or sulfate in silicate melt and excess S as sulfide melt or anhydrite crystals. This mixed valence is both a key complication and a key clue to unravelling sulfur's pathways through arcs. How rapidly porphyry and epithermal ore deposits form is a long-standing question in the Earth Sciences. Radiogenic isotopic analyses suggest a rate of formation within analytical error. Thus, other "speedometers" are needed. Sulfide-sulfate pairs and quenched sulfosalt melts may provide realistic estimates of depositional times. Veins of quenched sulfosalt melt from structural feeder zones in "high-sulfidation" epithermal deposits (Tanner et al., 2015) preserve rapid quench textures and isotopically unusual quartz crystals suggestive of rapid disequilibrium deposition. On the other hand, sulphur isotopic measurements of chalcopyrite-anhydrite veins, which are ubiquitous in porphyry deposits, provide temperatures of deposition that survive subsequent cooling. If local reduction of sulfur at or near the depositional site produces anhydrite plus sulfides in porphyry vein systems, as suggested by Mavrogenes and Blundy (2017), then formation could occur as quickly as minutes. Sulfur isotope thermometers universally yield higher temperatures than fluid inclusions in porphyry deposits. This has led many authors to discount their usefulness due to either partial re-equilibration at low temperatures (Ohmoto and Lasaga, 1982) or dissolution and re-precipitation (Field and Gustafson, 1976). In situ sulfur isotopic analyses of sulfide-sulfate pairs suggest minimal re-equilibration, thus verifying the usefulness of the sulfur isotope thermometer and the implicit rapid deposition sulfide-sulfate pairs.

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Suprasolidus Ediacaran-Cambrian reworking of ultrahigh temperature granulites in the Eastern Ghats Province, India

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The duration and *P–T* conditions of granulite facies metamorphism depends on how burial, heat flux and exhumation occurs during orogenesis. We provide *P–T–t* constraints for two chemically heterogeneous cordierite–spinel bearing granulites from Vizianagaram, Eastern Ghats Province (EGP), India. Their *P–T* evolution is interpreted using domainal pseudosections. U-Pb geochronology and rare earth element (REE) geochemistry of zircon and monazite, and Ti-in-zircon geothermometry provide temporal constraints. The granulites preserve discrete compositional layers containing garnet–sillimanite–spinel and orthopyroxene–sillimanite–spinel – peak assemblages which cannot be resolved by phase equilibria modelling if assuming the rock equilibrated on the scale of a thin section of greater. Calculation and projection of the *P–T* stability fields of five domainal equilibrium assemblages suggests conditions of ~8 kbar, 950 ºC and a clockwise evolution through ~6.0-6.5 kbar, 950–1000 ºC, followed by leucosome crystallization. The spatial arrangement of corona textures likely imply long lived diffusion of relatively immobile components on the modelled *P–T* path. Anatectic zircon crystallisation at temperatures >800 ºC led to a concordant age range ca.1050-800 Ma, attaining ultrahigh temperature (UHT) conditions (>900 ºC) between ca.1000-900 Ma. An age gap in concordant zircon occurs between ca.800-550 Ma with a later concordant population at ca.550-500 at >800 ºC, interpreted to record Pan-African metamorphism. Neoarchean inherited zircon ages ca. 2400-2500 Ma are recorded.

Our results suggest that, between ca.1100-850 Ma, these granulites were exhumed through a UHT clockwise *P–T* path and remained at ~20 km depth at >800 ºC. They are juxtaposed against a crustal block which experienced an anticlockwise *P–T* path but which record similar peak conditions ~8 kbar, 950 ºC and a similar geochronological history. The onset of decompression can be explained by the gravitational collapse of an orogenic plateau, or perhaps partial exhumation via thrusting over a cratonic indentor and the adjacent crustal block with an anticlockwise *P–T–t* evolution. The residual granulites have high heat producing element (HPE) concentrations and likely remained at depths ~20 km during a period of tectonic quiescence ca.800-550 Ma. Minimal additional heat flux generated in the hinterland of the Denman-Pinjarra-Prydz orogen ca.550-500 Ma during convergence of the Eastern Ghats-Rayner terrane and the Crohn craton may have been sufficient to preferentially reheat susceptible HPE enriched crust in the EGP to >800 ºC.

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

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

The time evolution of orogenic gold systems: Deformation, mineral reactions and chaos.

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Episodic excursions in fluid pressure and temperature are characteristic of the behaviour of orogenic gold systems and are commonly attributed to processes *external* to the system such as seismic events and associated fault-valve behaviour. We describe here processes *internal* to the hydrothermal system that lead to episodic behaviour and the deposition of gold. Hydrothermal mineralising systems associated with orogenic gold deposits commonly form during the influx of fluids in the latter part of crustal deformation events and are internally deformed by brecciation and veining that interact with a series of alteration mineral reactions and gold deposition. Importantly the time period for these hydrothermal events appears to be small relative to metamorphic systems with 1-2 million years an upper limit. This has implications for rates of heat production and for the kinetics of mineral reactions during alteration and mineralisation. We explore these systems as nonlinear, non-equilibrium dynamical, open flow systems. The questions we address are: *What is the influence of heat generated by the mineral reactions and deformation on the fluid pressure, temperature and equilibrium solubility of gold? How do these processes couple with the deposition of gold*? A fundamental characteristic of chemical reactions in open flow systems is that the reaction rates are sensitive functions of the supply of both nutrients and heat in incoming fluids. The purpose of this paper is to discuss the feedback relations between these processes. We show that coupling between these thermo-chemical-deformation processes can lead to episodic/chaotic behaviour in temperature and fluid pressure and in the deposition of vein filling materials, pyrite and of gold both in space and time. In particular, coupling of simultaneous endothermic and exothermic reactions with fluid flow leads to highly localised gold deposition. The mechanisms for such episodic and localisation behaviour are recorded in the paragenetic sequence and deformation history.

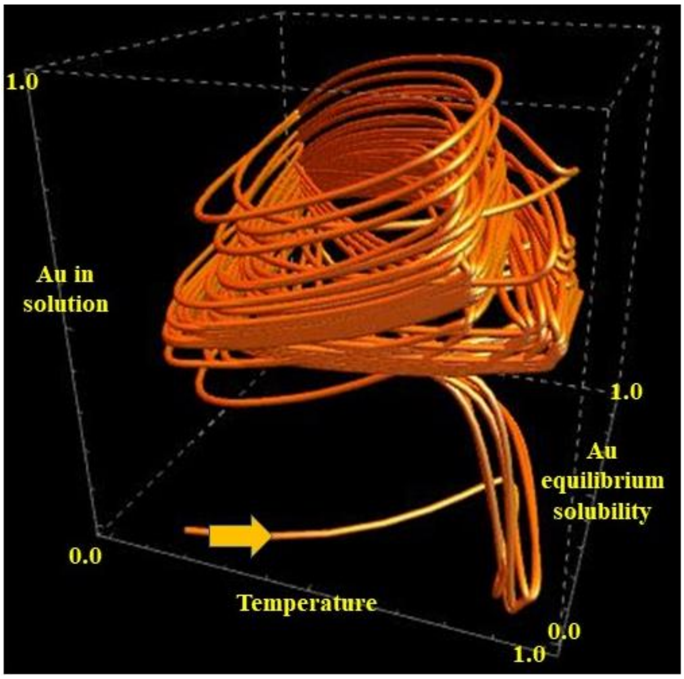

Figure: Chaotic attractor in temperature-gold in solution-gold equilibrium solubility space for an orogenic gold system.

Dating monazite to constrain emplacement ages and melt production rates of leucocratic granites

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Zircon is the most widely used geochronometer in granites but it can be unreliable for low-temeprature, leucocratic crustal melts. For these granites U-Pb dates may reflect just the ages of surviving xenocrystic zircons. In the Capricorn Orogen of Western Australia, leucocratic muscovite-biotite(-tourmaline) granites and barren and rare-element pegmatites crop out over ~420 km^2 in the hanging wall of a major shear zone. Initial SHRIMP U-Pb zircon dating suggested that the granites are Paleoproterozoic in age. However, subsequent dates of 1030–990 Ma for metamorphic monazite in schists intruded by the granites indicates that the main zircon population in the granite is xenocrystic. We used SHRIMP U-Th-Pb monazite geochronology and targeted SHRIMP U-Pb zircon geochronology to obtain reliable igneous crystallisation ages in order to determine the duration of magmatism and the processes responsible for melt generation. Our dating shows that the pegmatites and granites are coeval and were emplaced from c. 1025 to c. 890 Ma. Magmatism outlasted medium-grade (500–550°C and 3–4 kbar) regional metamorphism in the region by ~100 Ma. The long duration of magmatism combined with the relatively small volume of leucocratic granite and pegmatite requires very low melt production rates (~8 km^3/Ma). Field observations of *in situ* melting in older metagranite and the single age (c. 1650 Ma) component of the zircon xenocrysts suggest some of the melt is from an igneous source. However, temperatures attained during regional metamorphism were insufficient to induce dehydration melting reactions. Therefore, an external source of fluid was required to trigger melting, possibly from sedimentary rocks in the footwall of the shear zone. Melt generation appears to have been episodic and may have been related to long-lived, sporadic reactivation along the crustal-scale shear zone.

Rutile isotope and trace element geochemistry through albitite metasomatism of meta-gabbro, Bamble region, southern Norway

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Rutile is an accessory mineral commonly formed at high-grade metamorphic conditions. The incorporation of different trace elements within rutile at the time of formation gives insights into provenance. Ratios and concentrations of Nb and Cr typically indicate felsic vs mafic hostrock source (Zack et al., 2002; Zack et al., 2004a; Triebold et al., 2012), while Zr-in-rutile content is used as a geothermometer (Zack et al., 2004b; Watson et al., 2006; Tomkins et al., 2007). Rutile is also a useful U-Pb geochronometer and has an intermediate closure temperature of approximately 500-600 °C (Cherniak, 2000; Vry and Baker, 2006). Rutile potentially has unique properties to characterise the timeframe of geological processes.

The Bamble sector of southern Norway is dominated by northeast-southwest trending packages of Mesoproterozoic para- and orthogneisses. These rocks underwent granulite to amphibolite-facies metamorphic events caused by the Sveconorwegian orogeny (1.25 – 0.9 Ga). Several episodes of fluid infiltration and veining cross-cut these rocks, causing both scapolitic and albititic metasomatism. In areas where the albitite replacement occurred, the mineralogy is almost entirely of near-endmember composition albite (Engvik et al., 2008). The chemical characteristics of the source fluids during these events are partially attributed to fluid mobilisation through an evaporite sequence (Engvik et al., 2011).

The ages and trace element geochemistry of rutile across a sharp boundary between a meta-gabbro and a completely replaced albitite were studied using SHRIMP and LA-ICPMS. The U-Pb ages for rutile (SHRIMP) in the meta-gabbro and the albitite are statistically the same, at 1079 ± 4 Ma. As rutile underwent significant geochemical change during metasomatism, this implies that metasomatism occurred before 1079 Ma and that the age reflects cooling of the rutile during the later stages of the Sveconorwegian orogeny.

Zr-in-rutile geothermometry (Tomkins et al., 2007) suggests that the rutile formed in the meta-gabbro and the albitite at temperatures above 750 °C. Therefore, it is interpreted the rutile formed or recrystallised in both the meta-gabbro and albitite during granulite-facies conditions. Compatible trace elements were also incorporated under these conditions, prior to cooling below the rutile closure temperature for Pb diffusion.

However, the rutile Cr and V contents differ, with the albitite showing an order of magnitude higher Cr and V contents over its meta-gabbro precursor. The Cr and V source is explained by the breakdown of ilmenite and magnetite in the meta-gabbro, which is absent in the albitite. Some traditional interpretations of rock provenance use the Nb/Cr ratio (Zack et al., 2004a; Meinhold, 2010; Triebold et al., 2012), as high Cr content typically indicates a more mafic source. Given the observed effects of metasomatism, this method should be questioned as it may provide a chemical indicator of metasomatism rather than provenance source.

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Time-resolved, microstructurally-controlled, trace element mobility in deformed Witwatersrand pyrite

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The trace element composition of a mineral is modified through a range of processes as a rock migrates through pressure-temperature space. One potentially important modification process is element migration along fast-diffusion pathways such as low and high-angle boundaries. However, it is often unclear if the localisation of trace elements in such boundaries represents a dynamic process of trace element segregation at the time of boundary formation or later diffusion along a static boundary. Rounded detrital pyrite grains from the Witwatersrand gold province of South Africa contain low and high-angle boundaries, formed by subgrain rotation recrystallization associated with (100){001} slip. Electron microprobe data from these boundaries reveal local enrichment in As, Co and Ni. To investigate the details of this compositional modification in the boundaries, we have used atom probe microscopy (APM) to analyse a low-angle (2°) boundary, a high-angle (12°) boundary, and a pyrrhotite rim surrounding the pyrite. The APM technique allows sub-nanometre, 3D characterisation of atoms within a very small needle-shaped specimen. Atom probe results from the high-angle boundary reveals a heterogeneous distribution of As, Co and Ni on either side of the boundary with the 10nm wide core of the boundary enriched in Sb, Bi and Pb. Pb enrichment is also seen in the region of the low-angle boundary, but in this case the enrichment has a clustered morphology centred on the intersection of two Ni-rich dislocations. The isotopic composition of this Pb cluster is consistent with a 3.0 Ga common Pb component. However, the Pb isotopic composition of the high-angle boundary indicates a 2.0 Ga radiogenic Pb component, consistent with the composition measured in the metamorphic pyrrhotite rim around the grain. These results indicate at least two distinct reservoirs of Pb within the pyrite; the first related to a component of Pb inherited during pyrite growth around 3 Ga ago, the second associated with ingress of a more radiogenic Pb component along a microstructural boundary around 2 Ga ago. These results show the ability of deformation boundaries in pyrite to behave as fast diffusion pathways long after they formed and highlight that the integration of detailed microstructural analysis and site-specific nanoscale analysis of Pb reservoirs can provide a temporal context for understanding trace element mobility in deformed rocks.

Geosphere-biosphere transitions in groundwaters: radiocarbon dating as a tool to unravel stygofaunal trophic relationships

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Groundwater is a fundamental natural resource of national and global importance. The hydrology of Australia's groundwater resources is relatively well studied, but there is scant knowledge of the function of the ecosystems within Australia's aquifers. This issue is not esoteric – subterranean ecosystems are biologically valuable, containing a major component of biodiversity, and as ecosystem service providers maintaining water quality. However, the ecology of these systems is sparsely studied, the emphasis having been on biogeography and phylogenetics rather than abundance and function. One reason for this is that conventional techniques are very hard to employ on micro-fauna – stygofauna – the typical inhabitants of groundwater, and in such cryptic environments which are hard to access.

The occurrence of stygofauna in an aquifer is regarded as being controlled largely by the host geology, the presence of connected voids and groundwater chemistry. The unique environmental conditions shaping these systems – permanent absence of light and low input of carbon inputs – play a major role in the ecological assemblages. The analysis of the energy fluxes within groundwater ecosystems can provide insights into community trophic structure and the biogeochemical transitions between the geosphere and the biosphere.

In a shallow aquifer environment, the basal carbon sources potentially may be derived directly from plant roots, or derived microbially with a chemoautotrophic base or via the recycling of allocthonous particulate or dissoved organic carbon. The quantity and character of available carbon source may also vary with input (e.g. flushes of fresh organic matter during aquifer recharge events). Radiocarbon geochemical analyses have been widely employed to assess the degree of, and changes in, the input of carbon within surface aquatic and non-aquatic environments. However, the technique has not previously been applied in this manner in subsurface environments.

This study aims to measure the radiocarbon in the main potential food sources at the base of the food web and expand the knowledge of carbon flows within two contrasting aquifer sites in Western Australia. The first is a shallow groundwater calcrete aquifer at Sturt Meadows in the Raeside palaeochannel on the Yilgarn craton. The second site is on Rottnest Island offshore of Fremantle, a Class 'A' Reserve comprising Tamala Limestone, an aeolianite, and a tourist destination.

Although geographically and geologically distinct these two sites are similar in having aquifers in the form isolated freshwater lenses formed on an otherwise saline groundwater, formed on Rottnest by seawater intrusion due to historical water extraction, and at Sturt Meadows owing to long term aridification of the climate.

Analyses will be conducted on 72 samples collected using small plankton nets drawn through the water column in bores that provide access to the groundwater. These samples will be selected from a larger sample set based on the taxa avaialble, and their likely trophic position. Additionally, radiocarbon content from plant roots and aquifer sediments will be analysed, in order to establish an idea of the 14C levels in the potential source organic matter.

This project aims to elucidate changes in carbon fluxes and trophic structure in groundwater environments, to provide crucial information and a novel approach for comprehensive environmental impact assessments of subterranean ecosystems. The investigation will provide an essential base-line knowledge of the functional structure, trophic interactions and the source of energy into these complex ecosystems, information that is urgently required to understand the overall functioning and predict the likely impact of species extinctions.

A tale of two humps: using GCxGC-TOFMS to compare Caribbean oil seeps

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Oil oozing from the ground must have fascinated humankind since we first walked the Earth. For thousands of years civilisations made use of oil seeps without understanding what they were. Our understanding of the nature of oil has only taken shape in the last few decades, since mass spectrometry has allowed us to interpret the chemical structures of thousands of compounds present in oil. However, some oil seeps still remain a bit of a mystery.

The vast oil seep known as Pitch Lake in Trinidad has become a tourist destination and, like our early ancestors, we come to gaze at oil emerging from the earth. Pitch Lake is the largest natural deposit of asphalt in the world covering 40ha at La Brea in southwest Trinidad. At the opposite end of the chain of Caribbean islands lies Cuba. Here, oil seeps from mountains, sometimes emerging from rocks not normally associated with oil (Lewis, 1932). The Caribbean islands are thought to be a continuous volcanic arc chain of calc-alkaline composition (Nelson *et al.*, 2011). Although the motion causing the creation of the Caribbean Plate is thought to have begun in the Cenozoic, its formation history is still under debate (Bachmann, 2001). The Greater Antilles group of islands are dated to have initiated volcanic activity in the Early to Late Cretaceous while the Lesser Antilles represent a separate volcanic event beginning in the Oligocene (Bouysse *et al.*, 1990).

Due to the extent of biodegradation and the evaporative processes from the hot Caribbean sunshine on both these seeps, the oils are incredibly difficult to analyse using traditional GC-MS. The unresolved complex mixtures, or 'humps', of hydrocarbons, heterocyclic and polar compounds make producing chromatographic peaks sufficiently resolved to obtain good mass spectra challenging. Using two dimensional gas chromatography with time-of-flight mass spectrometry (GCxGC-TOFMS) the resolution is dramatically improved allowing mass spectra to be obtained.

Biomarkers can be seen as molecular fossils providing us with a view of past climates and sedimentary conditions. By applying GCxGC-TOFMS following minimal sample preparation, we were able to obtain good mass spectra for a range of molecules, including diamondoids, aromatic steroids and age-specific plant biomarkers present in oils from Cuba and Pitch Lake.

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Timescales of hydrocarbon formation: unravelling the sources of oil and gas in the Browse Basin

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The Browse Basin is one of Australia's most prolific petroleum provinces on the North West Shelf hosting vast reserves of gas and condensate (Le Poidevin et al., 2015). In addition, both non-biodegraded (Caswell) and biodegraded (Cornea and Gwydion, Yampi Shelf) oil fields are present. Hydrocarbon accumulations in the Browse Basin originate from multiple petroleum source rock types including fluvio-deltaic and marine-deltaic sedimentary rocks which typically produce a mixture of oil and gas (Pepper and Corvi, 1995). The primary source of gas is thought to be within Lower–Middle Jurassic fluviodeltaic sequences, whereas Upper Jurassic to Lower Cretaceous marine sequences are the most likely source of liquid hydrocarbons (Rollet et al., 2016). Complex fill histories, mixed marine and terrestrial biomarker signatures and, on the Yampi Shelf, the addition of biogenic methane, have made it difficult to understand the charge history of accumulations in the basin.

For this study comprehensive two dimensional gas chromatography coupled to time-of-flight mass spectrometry (GC×GC-TOFMS) and compound specific isotope analyses (CSIA) of *n*-alkanes, isoprenoids, aromatic hydrocarbons and diamondoids were employed to identify the hydrocarbon contributions to the oil and condensate accumulations in the Browse Basin. Diamondoids are source-specific and highly resistant to both thermal maturity and biodegradation (e.g Dahl et al., 1999; Grice et al., 2000; Moldowan et al., 2015), providing an excellent molecular correlation tool for fluids of low and high thermal maturity, as observed in the Browse Basin.

Quantitative diamondoid analysis and routine biomarker analyses reveal that the non-biodegraded oil samples from Caswell consist of a mixture of hydrocarbon sources. Diamondoid concentrations indicate the contribution of a high maturity fluid (wet gas – early dry gas), whereas typical saturated and aromatic hydrocarbon biomarker parameter indicate that this accumulation has been generated from a marine source rock within the oil window. Furthermore, no gas was recovered from this field, which is in disagreement with the high diamondoid concentrations found in the fluids analysed. This indicates that gas has escaped from the structure, leaving behind an accumulation that now consists of a light oil/condensate (47°API gravity).

Additionally, CSIA of isoprenoids and diamondoids, compounds not routinely used for correlation studies, provided further insight into fluid charge history and variations in petroleum source rock facies. This work shows that diamondoid concentrations and CSIA are useful tools to identify the sources of hydrocarbons that are contained within the Browse Basin.

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Magmatic tempo of Earth's youngest exposed plutons in the Hida Mountains of Japan

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Plutons are formed by protracted crystallization of magma bodies several kilometers deep in the crust. The temporal frequency (i.e. episodicity or 'tempo') of pluton formation is often poorly constrained as timescales of pluton formation is largely variable. The Hida Mountains of central Japan host the youngest exposed plutons on Earth and provide a unique opportunity to assess the temporal and spatial characteristics of pluton emplacement at high temporal resolution. Here we apply laser-ablation ICP-MS and ID-TIMS U-Pb geochronology to zircon from the Quaternary Kurobegawa Granite and Takidani Granodiorite in the Hida Mountains of Japan, and from modern river sediments whose fluvial catchments include these plutons in order to reconstruct their formation. The U-Pb data demonstrate that the Kurobegawa pluton experienced two magmatic pulses at ~2.3 Ma and ~0.9 Ma; whereas, to the south, the Takidani pluton experienced only one magmatic pulse at ~1.6 Ma. These data imply that each of these magmatic systems were both spatially and temporally distinct. The apparent ~0.7 Myr age gap between each of the three magmatic pulses potentially constrain the recharge duration of a single pluton within a larger arc plutonic complex.

Long-lived high-pressure metamorphism encodes durations of subduction and slab retreat

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Eclogites and blueschist form along cold geothermal gradients, and hence are important recorders of palaeosubduction. The conventional idea is that these high-pressure rocks are exhumed rapidly to preserve their mineral assemblages. While this may sometimes be the case, a protracted record of high-pressure metamorphism at Port Macquarie in eastern Australia demonstrates that long-lived metamorphism and slow exhumation can preserve ultra-cold mineral assemblages. Pressure-temperature calculations and U–Pb, Lu–Hf, Sm–Nd and Ar–Ar geochronology indicate that blueschist and lawsonite-eclogite remained in their formative environment for more than ca. 45 Ma, while high-pressure material accumulated within the subduction channel. During this interval, palaeogeographic data indicates more than 5000 km of subduction retreat (Cocks and Torsvik, 2002; Matthews et al., 2016), which was accompanied by the development of an extensional upper-plate system (Collins, 2002). This subduction retreat also acted to laterally transport the eclogite and blueschist while they remained trapped in the refrigerated forearc region, eventually locating them within an outboard orogen which formed more than ca. 160 Ma later. This data demonstrates that in oceanic settings, eclogite and blueschist can reside for significant periods of time within forearc regions of retreating subduction systems, and be transported large distances prior to exhumation. Not only does this encode the durations of now extinct subduction, but if these durations of subduction driven metamorphism are understood and coupled with realistic subduction velocities (Schellart et al., 2008), minimum sizes of palaeo-oceanic plates can be estimated.

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Biostratigraphy versus Isotope Geochronology: Testing VHMS models in the Urals

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Introduction

Formation of the Urals Volcanic-Hosted Massive Sulphide (VHMS) deposits is considered to be related with the intra-oceanic stage of island arc(s) development in the Late Ordovician – Middle Devonian (ca. 460 – 385 Ma) based on the biostratigraphic record of ore-hosting sedimentary rocks (Artyushkova and Maslov, 2008; Puchkov, 2010). There are few radiometric ages of ore hosting volcanics and where available they appear to be discordant with known biostratigraphic ages (Ronkin et al., 2016). Moreover, the direct Re-Os dating of four known VHMS system in the Urals gives significantly younger Re-Os isochron ages ranging from 355±15 up to 366±2 (Tessalina et al., 2017; Tessalina et al., 2008; Gannoun et al., 2003). To address this discrepancy, we analysed the U-Pb age of zircons extracted from rhyodacites (biostratigraphic age ca. 395 Ma) situated in a footwall of the Alexandrinka VMS deposit which has a Re-Os isochron age of sulphides of 355±15 Ma) (Tessalina et al., 2008).

Geological setting and sampling

The Urals is considered to be one of the world's largest province of VHMS deposits, second only to the Iberian Pyrite Belt VHMS province (Spain-Portugal) in term of ore reserves. It is orogenic belt of 2,000 km in length, which marks the geographic boundary between Europe and Asia. The structure of Urals is well preserved and formed as a result of intra-oceanic subduction, island arc formation and subsequent collision of the arc with the East European and Kazakhstan continents (e.g., Puchkov, 2010; Herrington et al., 2005).

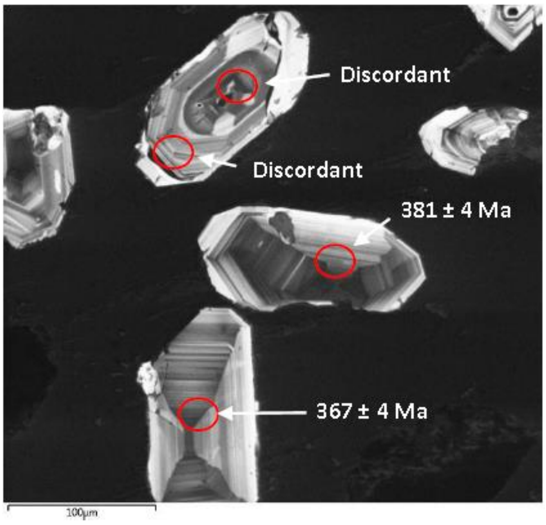
The Alexandrinka deposit is located at 53°31′ N and 59°22′ E and is 25 km northeast of the city of Magnitogorsk within the Middle Devonian East-Magnitogorsk island arc zone. The deposit is hosted by the Eifelian (392-397 Ma) Karamalytash Formation, in which three units are recognised: (1) a sub-ore basaltic unit; (2) an ore-bearing rhyodacite with small phenocrysts; and (3) a supra-ore basalt-rhyolite unit with silicic volcanics rich in large phenocrysts. A representative sample from unit 2 was collected from the open pit for zircon geochronology.

Method

Numerous zircons grains were extracted via conventional heavy liquid and magnetic separation. Zircon grains were handpicked from the zircon concentrate and mounted in an epoxy disc together with zircon standards. The mounted zircons were imaged by Cathodoluminescence imaging on a Mira3 FESEM instrument in the JdLC (John de Laeter Centre). The U-Pb ages were obtained using SHRIMP II at the JdLC using standard methods described in de Laeter and Kennedy (1998).

Results

Zircons studied are subhedral to euhedral and pale pink to colourless with continuous oscillatory zoning typical of igneous zircons (Fig. 1). No inherited cores were found.



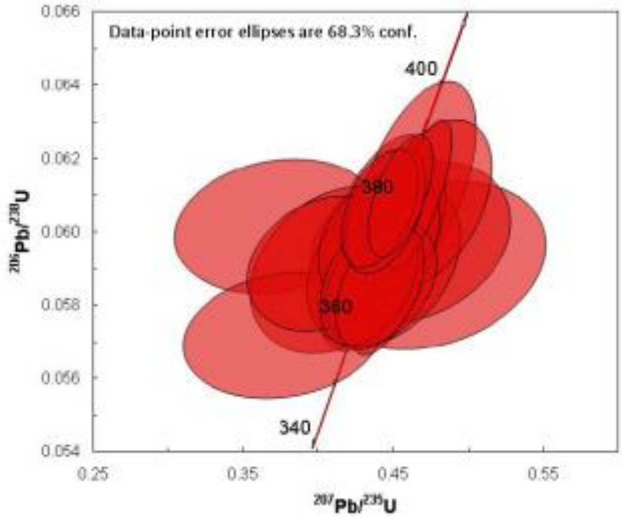


Figure 1. BSE images of zircons studied. Red spots are areas of SHRIMP analysis.

Figure 2. Data Concordia Di uncertainties.

Twenty-one analysis were performed on twenty zircons, nineteen of which yielded concordant dates ranging from 361 Ma to 383 Ma (Fig. 2). Eighteen analyses plot in a single population with a ^{207}Pb corrected $^{206}Pb/^{238}U$ mean age of 374 ± 3 Ma (MSWD = 1.4 and probability 0.11). This age is considered the crystallisation age of this volcanic rock. One younger date at 361 Ma is omitted as a statistical outlier.

Discussion – application for Urals VHMS deposits geodynamic setting

The U-Pb age of zircons from rhyoacite underlying the Alexandrinka orebody (374 ± 3 Ma; this study) is nearly within the error to the Re-Os age of sulphide ores from the same deposit (355 ± 15 Ma; Tessalina et al., 2008), and about 20 Ma younger than the biostratigraphic Eifelian age (392-397 Ma). Based on biostratigraphic ages, it was considered that VHMS deposit formation in Urals had stopped by ca. 385 Ma (e.g. Artyushkova and Maslov, 2008; Puchkov, 2010), and no volcanic activity had been observed during Frasnian time (383 – 372 Ma), with another pick of volcanic activity reappearing at the Frasnian – Famennian boundary (ca. 372-374 Ma). This time is also characterised by the beginning of collision between the volcanic arc and continent(s) (Puchkov 2010, and references therein). Thus, our U-Pb zircon age contradicts the timeframe for the common model of Urals VHMS deposit formation in an intra-oceanic arc setting, and supports the younger Re-Os isochron ages of sulphide mineralisation in the area. Given the significant geodynamic implications for this important metallogenic Province, we encourage further testing of the biostratigraphic geochronology in the Urals using radiometric methods.

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Biomarkers and Stable Isotopes Associated with Major Geological Events across the Cretaceous

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During the Cretaceous, Earth has experienced several mass extinction events and oceanic anoxic events (OAEs), which led to a succession of catastrophic shifts in biogeochemical cycling, climate and biotic evolution (Wolbach et al, 1990). These changes exerted massive impacts on life and the environment-including global warming conditions and sea level rise. The mechanisms, feedback, and temporal relationships between the high latitudes area and the tropics need to be studied for reconstruction of rapid climate change in the past, thus providing predictions for the future.

The Integrated Ocean Drilling Program (IODP) offers a unique opportunity to generate data about the paleoenvironmental and ecological change during the Cretaceous and its subsequent recovery. The analysis of core samples from IODP reveals the potential correlation between the climate changes and extinction as well as the missing information about the paleoenvironmental conditions especially fire history during the End-Cretaceous. Samples collected from the Naturaliste Plateau and Bight Basin by IODP 369 will provide information on the nature and extent of Ocean Anoxia Events (OAEs) led by Cretaceous hothouse in the southern hemisphere (Jenkyns, 2010). Compared to OAEs from the Northern Hemisphere, the results from this study will contribute to establishing the overall mechanisms of OAEs. Organic geochemistry will be conducted on these samples, such as % total organic carbon (TOC), Hydrogen Index (HI), biomarkers, and isotopic analysis (Peters et al., 2004; Grice and Eiserbeck, 2014). The development and timing of photic zone euxinia through the organic-rich black shale intervals will be revealed by analysing the molecular fossils in sedimentary records, for example carotenoids isorenieratene of Chlorobi or their diagenetic alteration products (Grice et al., 2005). Also, the ash layer in the impact crater at Chicxulub from IODP 364 (Yucatan Peninsula, Mexico) that is associated with the mass extinction event during the Cretaceous – Paleogene (K/P) boundary will provide the geochemical records for reconstructing the ecosystem recovery and paleoenvironmental conditions such as combustion history, oceanic conditions and biotic changes. PAHs and δ13C from the ash layers will be analyzed by gas chromatography – mass spectrometry and compound-specific isotopic analyses in order to reveal the severity of post impact wildfires (Grice and Brocks, 2011; Nabbefeld et al., 2010). In addition, core samples collected from IODP 342 at Newfoundland sediment drifts, serving as a high-resolution archive of the Paleocene – Eocene Thermal Maximum (PETM) will further the research of biochemical and ocean geochemical cycles as a result of climatic perturbations (Zachos et al., 2006). A new precise age diagnostic parameter will be developed by calculating the ratio of angiosperm over gymnosperm-derived biomarkers and making comparison with traditional dating methods. By conducting analytical techniques including gas chromatography – mass spectrometry and two-dimensional gas chromatography Time of Flight Mass Spectrometry, gas chromatography – multiple reaction monitoring and compound-specific isotopic analysis (C and H), the measurement and quantification of higher plant biomarkers will be achieved.

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Mineralogy controls colonisation of stony meteorites by environmental microorganisms: An example from the Nullarbor Plain, Australia

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Stony meteorites, such as ordinary chondrites, have well-defined and narrow ranges in mineralogical, elemental and stable isotopic compositions, properties that make them valuable as geochemical standards. Chondritic meteorites are also sterile when they fall to Earth's surface and the surfaces of other planets. We propose that meteorites may be used as "standard" materials for studying first colonisation of sterile rock and preserving information about mineral–microbe–fluid interactions on Earth and potentially Mars.

We have conducted a study of mineral–microbe associations [1] and 16S rRNA gene analysis [2] in meteorites and soil collected from the arid to semi-arid limestone karst of the Nullarbor Plain in southern Australia. Terrestrial endolithic and chasmolithic microorganisms are commonly found in close association with hygroscopic alteration minerals that form veins within cracks that penetrate deep inside these meteorites [1]. The admixture of secondary alteration minerals within these veins consists of Mg-calcite, gypsum, Fe-oxyhydroxides and smectites. Water sorption analyses indicate that this vein material can gain up to 3.0% of its mass in sorbed H_2O under humidity and temperature conditions that prevail at night in the Nullarbor. Our observations indicate that hygroscopic alteration minerals in meteorites act as a "humidity oasis" that can be used by environmental microorganisms to scavenge water, promoting colonisation in this setting. Where microorganisms have colonised grains of silicate minerals and Mg-calcite, the surfaces of these crystals are heavily etched and altered beneath well-developed biofilms. Thus, environmental microorganisms rely on mineral behaviour for humidity and pH regulation within the meteorites.

The results of our 16S rRNA gene analysis show that the microbial community structure of each meteorite bears more resemblance to those of other geochemically similar meteorites than to the community structure of the soil on which each meteorite resided. The meteorites showed poor association with Cyanobacteria and instead were dominated by Actinobacteria, some of which may be able to couple oxidation of trace H_2 with reduction of O_2 in ambient air [3]. Iron/sulfur cycling organisms were also present at lower abundance in meteorites, consistent with our observations of corroded FeNi-alloy minerals and troilite (FeS) as well as the enrichment in ^{34}S observed in secondary sulfate minerals.

Our results show that chondritic meteorites can be used to test ideas about first colonisation of geological substrates by microorganisms. They also demonstrate that atmospheric H_2O vapour can provide a sufficient source of bioavailable water for microbial communities in the presence of hygroscopic minerals. Furthering our understanding of how microorganisms leverage mineral behaviour to colonise sterile rocks not only has fundamental applications to geomicrobiology, but may also have applications to promoting *de novo* formation of soils, bioleaching and enhanced weathering technologies in mafic and ultramafic lithologies, and astrobiological exploration of our solar system.

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Late Jurassic to Early Cretaceous gold mineralization in the West Qinling Orogen (Central China): A link with the subduction of Paleo-Pacific plate?

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Dating of hydrothermal gold mineralization in metamorphic belts is a challenge due to the scarcity of minerals formed during mineralization that are suitable for dating, multiple gold episodes and subsequent hydrothermal alteration (Kazimoto et al., 2015). The West Qinling Orogen (WQO) in the central China hosts numerous orogenic and so-called Carlin-like gold deposits, the timing and genesis of which are the subject of ongoing controversy (Mao et al., 2002). This study reports new geochronology results for the Daqiao gold deposit, a representative world-class gold deposit in the southern domain of the WQO, that constrain the timing of gold mineralization within a regional geological and metallogenic context.

Key results are as follows: (i) The Daqiao gold deposit shows a characteristic low-temperature alteration of silicification-sulfidation-sercization-carbonatation both in the breccia ores and mineralized granodiorite dykes. (ii) LA-ICP-MS zircon U-Pb dating of granodiorite dykes at Daqiao yielded an age between 211.5 ± 1.5 Ma to 215.0 ± 1.1 Ma. This age is consistent with the regional Late Triassic magmatism and within error of several previously reported ages of gold mineralization in the WQO (216–203) (Zeng et al., 2012; Liu et al., 2014; Wang et al., 2014; Hu et al., 2015; Zhang, 2016). (iii) $^{40}Ar/^{39}Ar$ dating of the sericites from the breccia ores and granodiorite dykes generated a weighted plateau age of 144.4 ± 3.1Ma and 128.1 ± 0.9 Ma, respectively. Although similar ages have been occasionally reported in the WQO (142–127 Ma) (Wang, 2000; Lu et al., 2006; Qi et al., 2006; Liu et al., 2015), very little attention have has been paid to this period of hydrothermal-mineralization activity.

A two-stage scenario for the formation of large-scale gold mineralization in the WQO is consistent with the available geochronological evidence. Early stage gold was introduced at ca. 225–195 Ma, and mainly hosted in the ductile zones of Devonian greenshist facies rocks in the northern domain of the WQO. It is regarded to have formed as a response to the tectonic-thermal process during the tectonic transition from syn-collisonal compression to post-collisional extension (Chen et al., 2004). Subsequently, late stage gold mineralization occurred in the shallow Triassic turbidites in the southern domain or as superposition on the early gold deposition, formed at ca. 150–120 Ma during the post-orogenic evolution stage (Dong et al., 2011).

The high-precision geochronology data herein points to a significant Late Jurassic to Early Cretaceous hydrothermal event associated with formation of the Daqiao gold deposit during regional post-orogenic tectonism. This period of magmatism and hydrothermal alteration is prevalent over the whole of East Asia, and is suggested to be triggered by the oblique subduction of Paleo-Pacific plate beneath the Eurasian continent, starting at ca. 160 Ma (Ren, 1992; Niu et al., 2003), and subsequent change of the subduction direction after ca. 135 Ma (Goldfarb et al., 2007; Sun et al., 2007; Mao et al., 2008). The intensity of far-field effect of this subduction shows a gradual decrease from east to west, and has been proposed to be a key factor in the East Qinling gold deposition (Yan et al., 2014). The new geochronology data may provide a link between this far-field effect and the Late Jurassic to Early Cretaceous gold mineralization in the WQO. At a broader scale, this newly identified hydrothermal activity at the Daqiao gold deposit may be part of an orogenwide metallogenic and tectonothermal event in the WQO.

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Environmental drivers shaping flexibility of carbon-utilization of plants in saline environments

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Stress, such as salinity, acts as a selective force in the adjustment of physiological processes in plants to successfully adapt to changing environment. Photosynthesis, the most central and complex physiological process in green plants, is critically affected by environmental stress (e.g. Ashaf and Harris 2013). One possibility to enhance the ability to tolerate elevated ambiental salinity is flexibility of photosynthetic pathways. The C4-carbon fixation pathway in plants is a modified version of the ancestral C3-carbon fixation pathway and has evolved over 60 times in flowering plants (Sage *et al*., 2012), including about 24 times in the grass family (Edwards and Smith, 2010). Plants having C4-pathway increase the efficiency of carbon fixation by reduction of photorespiration, and thus possess higher water use efficiency and enhanced productivity. Obviously, C4 photosynthesis has advantages under environmental conditions that stimulate photorespiration such as heat and salinity (Sage, 2004; Sage *et al*., 2012; Christin *et al*., 2013).

Salt-laden habitats of the Shark Bay region of WA offer a unique model to test the influence of ambiental salinity (and flooding) stress. Besides the high salinity, plants experience re-occurring anoxic stress resulting from repeated flooding events, either as result of tidal regime or temporary (and seasonal) flooding of salt pans by rain. These environmental stress act as filters shaping ecological and evolutionary fitness. As a result, salt-tolerant plant species are along the stress gradients, forming characteristic zonation patterns (Pottier *et al*., 2013). Preliminary analyses revealed ability of some saline plants to switch between C3 and C4 assimilation strategies. We suggest that this switch is driven by (recurrent) changes in the environment, and as such may modify the position of the plants along environmental gradients, reflecting their competitive strength and plant community assembly. In addition, there is emerging evidence that biotic interactions also may play an important role in the plant fitness and community assembly in highly stressed environments. Here root-associated microbiome (algae, fungi and prokaryotes) is thought to play an important, yet poorly understood role (Pellissier *et al.,* 2013).

In this study we investigate saline vegetation and associated microbial soil communities along a saline stress gradient of the Shark Bay region. We try to elucidate the nature of impact of environmental stresses (salinity, flooding) on patterns of C3/C4 carbon-fixation pathway in plants by analysing compound specific stable isotopes. Furthermore we investigate lipid composition in salt-tolerant plants to improve our understanding of the carbon utilization mechanisms. Rhizosphere samples are also analysed to characterize the rhizosphere microbiomes that may shape fitness of salt-tolerant plants, and eventually drive patterns of plant community assembly.

Shark Bay is a natural laboratory for studying saline and flooding stresses in plant communities. This area is characterized by subtropical semi-desert hot and dry climate where water evaporation exceeds greatly the annual precipitation input. Shark Bay is known by extensive sea shallows (showing water salinity up to twice higher than the surrounding ocean), inland salt pans (some with unique current sea connections) and extensive flat coastal salt marshes, supporting mangroves in places.

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Salt pans (dry gypsum lakes) of Shark Bay

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The pathway of mineral replacement of gold tellurides under oxidative hydrothermal conditions investigated by in situ PXRD

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Gold tellurides are a group of gold minerals, including calaverite $AuTe_2$, sylanite $AuAgTe_4$, krennerite Au_3AgTe_3, petzite $AuAg_3Te_2$, montbroyite $(Au,Sb)_2Te_3$, and muthamannite (Ag,Au)Te. In Nature, gold tellurides react with oxidative hydrothermal fluids, forming porous Au or Au-Ag alloy called 'mustard gold', most likely through mineral replacement reactions. Recent mineralogical and microscopic characterization of quenched specimen from hydrothermal experiments suggest a direct replacement of calaverite by Au (Zhao et al., 2009), and krennerite by Au-Ag alloy (Xu et al., 2013), but a complicated multi-step replacement of sylvanite by Au-Ag alloy (Zhao et al., 2013). To further reveal the reaction pathway, this work monitored the same three replacement reactions by synchrotron radiation *in situ* powder X-ray diffraction (PXRD), in which time resolved PXRD patterns were collected over the course of the mineral replacement reactions that were carried out in a quartz glass micro pressure reactor. The results were generally in agreement with the anneal-quench experiments that all the three gold tellurides were eventually replaced by Au or Au-Ag alloy. However, the *in situ* experiments also revealed an intermediate petzite phase in the replacement of krennerite and sylvanite, and the formation of two distinct TeO_2 phases. Hence, the pathways for gold tellurides decomposition under oxidative epithermal condition are: (1) calaverite → Au, (2) krennerite → petzite → Au-Ag alloy, and (3) sylvanite → petzite → Au-Ag alloy.

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Mechanisms of pyrite and marcasite formation during replacement of pyrrhotite: insights from an in-situ synchrotron PXRD study

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Iron sulphides, pyrrhotite, pyrite, and marcasite, are among the most common minerals in the Earth crust particularly in ore deposits (Murowchick, 1992), where they host precious metals such as gold, silver, and platinum group elements (Deditius et al., 2014). Thus, it is crucial to understand the mechanisms of formation and alteration of Fe sulphides to improve mineral exploration, and development of precious metal extraction during in-situ leaching (Sinclair and Thompson, 2015). It has been suggested that replacement of pyrrhotite by pyrite may involve marcasite as an intermediate phase (Murowchick, 1992), which was supported by a crystallographic analysis showing the similarity in crystal structure of pyrrhotite and marcasite (Fleet, 1978). Experimental studies revealed that marcasite is readily transformed to pyrite via a solid-state process (Lennie and Vaughan, 1992). Finally, it has been shown experimentally that replacement of pyrrhotite by pyrite and marcasite is possible under well controlled oxic or anaerobic hydrothermal conditions (Qian et al., 2011). In some cases, a mixture of pyrite and marcasite was formed following the well-known interface-coupled dissolution-reprecipitation mechanism, but it is not clear whether pyrite and marcasite were precipitated independently or marcasite served as an intermediate phase. In this study, we carry out a synchrotron-based in-situ and time resolved powder X-ray diffraction study to gain further insights into the pathways of the formation and transformation of pyrrhotite to pyrite and/or marcasite.

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The replacement of magnetite by hematite under hydrothermal conditions

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The transformation of magnetite to hematite, which is widespread in natural hydrothermal systems, has been extensively studied (Lagoeiro, L.E. 1998, Mücke and Cabral 2005). The transformation from magnetite to hematite is known as martitization, and can be expressed in term of a redox reaction,

e.g., $2Fe_3O_4(mt) + 0.5O_{2(aq)} \leftrightarrow 3Fe_2O_3(hm)$.

Consequently most previous studies have interpreted the interconversion of magnetite and hematite as a near-equilibrium redox reaction, indicating that the fluid was relatively oxidised (e.g., Perry et al. 1973, Taylor et al. 2001); fluctuations in fluid redox state cause either the oxidation of magnetite (Fe^{2+} to Fe^{3+}) or the reduction of hematite (Fe^{3+} to Fe^{2+}). However, Ohmoto (2003) proposed a model whereby the transformation of iron oxides in near-surface environments mostly occurs through non-redox acid-base reactions. In this model, hematite is formed by the preferential removal (leaching) of Fe^{2+} from magnetite; similarly, magnetite forms via the addition of Fe^{2+} to hematite; no reduction or oxidation of Fe is involved in the reactions. The non-redox transformation between the minerals can be written

$Fe_2O_3(hm) + Fe^{2+} + H_2O \leftrightarrow Fe_3O_4(mt) + 2H^+$.

In this study, we conducted a set of experiments on the replacement of magnetite by hematite under mild hydrothermal conditions (140-220 °C, vapour saturated pressures). The main aims of this study were (i) to establish the textures of hematite synthesized by hydrothermal processes, (ii) to establish whether the reaction mechanism is a redox or a non-redox process, and (iii) to decipher whether the redox and non-redox pathways can result in different textures, that can be used to constrain the reaction pathways in natural mineral assemblages. The results indicate that oxygen is not a necessary factor in the replacement reaction of magnetite by hematite, but the addition of excess oxidant does trigger the oxidation reaction, and results in the formation of increased amounts of hematite. However, even under high O_2 environments, some of the replacement of magnetite via hematite occurred via Fe^{2+} leaching.

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Dating basalt by pyroxene $^{40}Ar/^{39}Ar$ with implications for large igneous provinces and correlations of Precambrian basins

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Correlations within and between Precambrian basins are heavily reliant on precise dating of volcanic units (i.e., tuff beds and lava flows) in the absence of biostratigraphy. However, felsic tuffs and lavas are rare or absent in many basins and determining the crystallisation age of basaltic lavas is challenging because uranium-rich phases such as zircon are fine-grained and rare in Si-undersaturated volcanic rocks. $^{40}Ar/^{39}Ar$ isotopic dating of mineral separates has been successfully applied to Phanerozoic flood basalts, but in Precambrian samples plagioclase, the mineral of choice to date mafic rocks with the $^{40}Ar/^{39}Ar$ technique, is invariably compromised by metamorphic overprinting and/or secondary alteration (Verati and Jourdan, 2014).

However, a recent study by Ware and Jourdan (in review) have shown that pyroxene, an abundant phase in mafic rocks that is resistant to both alteration and mid-temperature metamorphism, can now be precisely dated using a new generation of multi-collector noble gas mass spectrometers. Here we report the first successful application of $^{40}Ar/^{39}Ar$ dating to pyroxene from a Neoproterozoic basalt unit, the Keene Basalt in the Officer Basin of central Australia. $^{40}Ar/^{39}Ar$ analyses of igneous pyroxene crystals yield an age of ca. 752 Ma whereas plagioclase separated from the same basalt samples failed to provide any meaningful $^{40}Ar/^{39}Ar$ ages. This age is significant because the Keene Basalt is one of the very few extrusive igneous rocks identified within the Neoproterozoic successions of central Australia (Pirajno et al., 2006), and is potentially an important time marker for correlating the Neoproterozoic stratigraphy within, and beyond, the central Australian basins (Halverson et al., 2005; Swanson-Hysell et al., 2012).

Our geochronological and geochemical data show that the Keene Basalt, which is characterised by enriched elemental and Nd-Pb isotopic signatures, is strikingly similar to, and coeval with, the 755 ± 3 Ma Mundine Well Dolerite Suite in northwestern Australia (Wingate and Giddings, 2000). We suggest that both are part of the same large igneous province (~6.5×10^5 km^2) related to breakup of the supercontinent Rodinia. This study demonstrates the potential of pyroxene $^{40}Ar/^{39}Ar$ geochronology to date ancient flood basalts, and to provide pivotal time-constraints for large igneous provinces and stratigraphic correlations of Precambrian basins.

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Migrating deformation fronts.
An example from the Neoarchean Yilgarn Orogeny

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Deformation fronts can be defined as instantaneous spatial boundaries between undeformed rocks and those undergoing deformation, or between rocks undergoing different stages of deformation (e.g. Gray and Mitra, 1993). A large number of case studies have documented that deformation fronts in many Phanerozoic orogens commonly migrated with time towards the foreland, for example as a consequence of progressive deformation, because of the internal dynamics of the orogenic wedge, or as a result of the interaction between syn-orogenic topography development and climate evolution (e.g. Freeman et al., 1998; Hessami et al., 2001; Norton and Schlunegger, 2011). Recognizing episodes of deformation front migration in Archean orogens is considerably more challenging, because of the more fragmented geological record and the general lack of consensus about Archean geodynamics (Gerya, 2014). In this talk I will discuss an example of multistage migration of a deformation front, recognized in the Archean Yilgarn Craton of Western Australia.

The Yilgarn Craton is a wide granite-greenstone terrain that formed mainly in the 3050–2600 Ma time span. The 2730–2650 Ma Neoarchean Yilgarn Orogeny (Zibra et al., 2017) consists of a craton-wide orogenic cycle that was accompanied by widespread granitic magmatism. Structural studies in the Yilgarn Craton have been traditionally focussed on the better exposed and economically important greenstone belts. The case study presented here provides an example of how structural analysis focussed on large syntectonic plutons represents a fundamental tool for our understanding of large-scale tectonic processes.

The study focuses on three large, adjacent granite plutons that show comparable geometry and structures. In the available literature, the structures associated with these plutons have been assigned to the local D_4, late-orogenic deformation event, associated with north- to north-northeast-trending folds and strike slip shear zones (Van Kranendonk et al., 2013). However, new meso- and microstructural data, supported by geochronological, geochemical and geophysical data document that: (i) the three plutons were sequentially emplaced within the 2730–2660 Ma time span, along crustal-scale, adjacent transpressional shear zones that reflect bulk east–west shortening; (ii) the bulk of the shear fabric in each pluton developed under melt-present to high-temperature solid-state conditions, during pluton emplacement; (iii) syn-emplacement fabrics in the two older plutons are postdated by discordant and undeformed granitic intrusions, which in turn predate the shearing event associated with the emplacement of the younger pluton in the adjacent shear zone. These data indicate that, at the scale of the studied crustal domain, each episode of pluton emplacement induced a deformation event that was mostly localized within the pluton itself and within the crustal-scale channel that allowed its emplacement, leaving only a minor structural signature in the adjacent areas. The overall orogenic cycle produced high-strain, adjacent belts showing comparable geometry and kinematics, but whose ages span from c. 2730 to 2660 Ma, covering most of the duration of the Neoarchean Yilgarn Orogeny. These results have significant implications for our understanding of Archean orogenic processes.

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