Granulites and Granulites 2018

Ullapool, Scotland

10–13th July 2018

Mineralogical Society

Contents

Welcome

Welcome to Ullapool for the fifth Granulites and Granulites (G&G) conference. G&G has existed in its current form since 2006, and was ultimately born out of a major symposium of the same name that ran at a GAC/MAC/CGU Meeting in Ottawa, Canada, in 1986. The inaugural G&G meeting, organised by a joint US–Brazilian team led by Mike Brown, was held at the University of Brasilia, Brazil, in July 2006. The second was held in July 2009 at the Hrubá Skála Chateau, Czech Republic, and was organised by a diverse international team led by Karel Schulmann. The third iteration took place in January 2013 at the National Geophysical Research Institute, Hyderabad, India, and was organised by a joint Indian–Australian team led by Ian Fitzsimons. Most recently, G&G returned south of the equator, to Windhoek, Namibia, in July, 2015, organised by Johann Diener and Dick White.

We are pleased to have attracted around 100 delegates from all corners of the planet to the remote and beautiful fishing town of Ullapool, in the heart of the northwest Highlands of Scotland. It is a fitting location. Less than a kilometre from here are exposed Archaean rocks of the Lewisian Complex, some of the oldest, highest-temperature and longest-studied granulites on Earth. We have a full schedule of talks and posters over the two-and-a-half days, with a selection of internationally renowned keynote speakers and including the 51st Hallimond Lecture of the Mineralogical Society, which will be delivered by Prof. Michael Brown.

On behalf of the convenors and organisers, we hope you enjoy G&G 2018.

Organisers: **Mineralogical Society of Great Britain & Ireland**

Main convenr**: Tim Johnson** (Curtin University, Perth)

Co-convenors: **Chris Clark** (Curtin), **Kathryn Goodenough** (BGS), **Martin Hand** (Adelaide), **Simon Harley** (Edinburgh), **Pete Kinny** (Curtin), **Trond Slagstad** (NGU)

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PRESENTER INDEX

Does the Earth have a Pulse? Constraints from the Geological Record and Implications for Tectonic Processes

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The Earth is a dynamic, evolving system in which the surficial and solid components of the planet interact through a series of cycles and at a variety of scales in response to energy supplied from internal heat and from external sources within the solar system. The grand challenge for the Earth Sciences is to unravel the feedbacks between the deep and surficial Earth, the record of which is preserved in the continental crust. The continental record indicates that the distribution of rock units and events is heterogeneous with distinctive peaks and troughs in the ages of igneous crystallization, metamorphism, continental margins and mineralization, and progressive changes in atmosphere and ocean compositions. For the modern Earth, plate tectonics is the mechanism generating the rock record and controlling feedbacks across the Earth system, but non-plate tectonic processes generally are envisaged as operating on the early Earth.

The nature of changes in the rock record are exemplified by the pattern of metamorphic mineral assemblages, which provide a key archive on the generation and stabilization of the continental crust. Data compilations of temperature, pressure, thermal gradients and age of metamorphism for mineral assemblages by Mike Brown have highlighted a temporally-based tripartite division into high, intermediate and low dT/dP, with the frequency of these thermal gradients also displaying temporally based peaks and troughs. The low dT/dP assemblages are largely restricted to Cryogenian and associated with the initiation of modern cold subduction. The intermediate and high dT/dP gradients represent a temporally paired system that became globally widespread in the Mesoarchaean, which we associate with the transition from a non-plate tectonic to a plate tectonic regime.

Based on the geological record, we recognize 6 stages of Earth evolution: 1) Initial accretion and differentiation of the core/mantle system within the first few 10s of millions of years, on an anoxic prebiotic Earth; 2) Generation of crust prior to 3.2 Ga in a pre-plate tectonic regime associated with the evolution of early life and low oxygen atmosphere; 3) Protracted transition to plate tectonic regime from 3.2 Ga to 2.5 Ga involving development of rigid lithosphere with change from mafic to more felsic composition of continental crust, an increase in crustal thickness and recycling, and the initial emergence of continents with resultant impacts on ocean and atmospheric chemistry; 4) Early sustained plate tectonics involving hot subduction with shallow slab breakoff over the period from 2.5–1.7 Ga, associated with further increases in the proportion of felsic and thick continental crust, along with massive changes in the biosphere, ocean and atmospheric chemistry, and global climate, including the initial rise in atmospheric oxygen and global glaciations; 5) Earth's middle age from 1.8–0.8 Ga, characterized by lithospheric, environmental, and evolutionary stability, and the evolution of early eukaryotes; 6) Initiation of modern cold subduction at ~0.8 Ga, associated with a second rise in atmospheric oxygen, extensive global glaciations, and the radiation of animal life. Supercontinents have operated during the last three stages and their assembly and dispersal require horizontal motion of the lithosphere through plate tectonics. Continental crustal volumes, reflecting the interplay of crustal generation and recycling, increased rapidly on the pre-plate tectonic Earth, then more slowly until the start of middle age, during which crustal volumes were relatively constant, and then for the last 1 Ga they may have been decreasing.

High temperature–pressure Mesoarchaean metamorphism: a new datapoint for early Earth geodynamics

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Modern quantitative metamorphic studies on crustal rocks older than Neoarchean are generally lacking, and filling this knowledge gap is an important step in understanding the evolution of the lithosphere and early Archean geodynamics. Using the limited available data, Brown (2009) argued Paleoarchean–Mesoarchean crust records low-to-moderate-*P*–moderate-to-high-*T* conditions, implying elevated thermal gradients of 850–1350°C/GPa. The limited data also suggests ultrahigh temperature metamorphism was not a feature of pre Neoarchaean crustal regimes.

In this context, granulites on the southwest margin of the Dharwar Craton may be noteworthy. Migmatitic quartz-bearing metapelite contains garnet–kyanite–rutile–K-feldspar–quartz assemblages. Garnet contains inclusions of quartz, sillimanite, biotite, kyanite and rutile. In places garnet has been partially replaced by biotite-kyanite-plagioclase, interpreted to record melt crystallisation, and kyanite forms retrograde coronas on K-feldspar in leucosomes. Migmatitic quartz-bearing mafic rocks contain relic orthopyroxene overgrown by coarse-grained garnet–clinopyroxene–plagioclase followed by retrograde hornblende.

Mineral equilibria modelling using residual rock compositions suggests rocks experienced minimum temperatures of 900°C. Reintegrated rutile Zr concentrations in quartz-zircon bearing metapelite give temperatures of ~925°C, which based on the presence of kyanite in peak assemblages suggests minimum pressures of 1.25 GPa. LA–ICP–MS monazite U–Pb data from metapelite gives ages that range between 3130-3136 ± 15 Ma. The comparatively large uncertainly reflects the effects of Neoproterozoic lead loss or unresolved earlier thermal events. Nonetheless the monazite U–Pb data indicate that metamorphism is Mesoarchaean in age, and is consistent with the existing zircon U–Pb age framework (Santosh et al 2015).

Although inclusion assemblages in compositionally residual rocks need to be interpreted with great caution, the presence of sillimanite in metapelitic garnet and texturally early orthopyroxene in migmatitic garnet-clinopyroxene mafic rocks points to comparatively low-pressure prograde conditions with respect to peak. Furthermore, if it's assumed reaction textures mean anything, the partial replacement of texturally peak garnet by kyanite and biotite in metapelite, and the absence of garnet breakdown in mafic rocks suggests the rocks cooled at depth. In totality, the metamorphic textural evidence points to an anticlockwise *P*–*T* evolution. Such an evolution would seem to negate a transient excursion of these ancient rocks to high pressures. Rather, the apparent anticlockwise *P*–*T* record with deep crustal cooling from UHT conditions is what we expect within long-lived orogenic plateaus.

The inferred *P*–*T* conditions and post-peak history suggest the southern Dharwar Craton may contain the remnants of the world's first orogenic plateau. Geodynamically the notion that long-lived orogenic plateaus may have existed at such an early stage of Earth history is certainly intriguing. It implies that (1) either models for the early thermomechanical Earth are too smooth, and large scale cool lithospheric thermal domains had developed within the first ~billon years of Earth evolution, or (2) that the rocks were thermomechanically supported by bounding continental lithosphere. Of these alternatives, the latter is preferred because density criteria suggest rocks of the type preserved in the southwest margin of the Dharwar Craton would have been lost into an ancient hot mantle.

Namaqualand revisited: new data and regional context for Mesoproterozoic low-pressure granulites

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The Namaqualand sector of the ~1200–1000 Ma Namaqua–Natal tectonic province in South Africa and southern Namibia, one of the major belts involved in the assembly of Rodinia, is noted for a large area of high-grade metamorphic rocks, and the occurrence of mineral associations such as spinel + quartz and osumilite that indicate extreme conditions. The basic tectonic and metamorphic framework was established in the 1980s [1], with metamorphic zones and pressure-temperature conditions defined across parts of the Complex using conventional geothermobarometry [2]. Subsequent studies have defined, and re-defined, a number of distinct terranes, and more precise zircon and monazite chronology has added detail to the history of metamorphism and magmatic activity. Two developments that relate to the Bushmanland (western) and Garies (southern) Terranes seem especially significant: firstly, a strong record of high-temperature metamorphism and associated magmatism peaking at ~1040–1020 Ma, identified with the Klondikean episode of Clifford et al. [3], but largely absent from the eastern Terranes, and secondly, the recognition of younger metasedimentary sequences (Koeris Formation and upper Kamiesberg Subgroup) with a probable age of deposition in the range 1150–1100 Ma, which place a clear hiatus between thermal events at ~1200 Ma and ~1040 Ma in this part of the Complex [4, 5].

This review presents: 1) a refinement of the peak pressure-temperature distribution and P–T paths in the Bushmanland and Garies Terranes using modern datasets, multi-equilibrium and calculated phase diagram approaches; 2) additional data on monazite chemistry and ages that appear to record prograde metamorphism under way at ~1065 Ma in the Garies Terrane, and which confirm the granulite-facies peak, migmatisation and magmatism at 1040–1020 Ma; and 3) a re-consideration of the heat sources and duration of metamorphism that takes into account the crustal structure, the prehistory of the terranes, and the abnormally thorium-rich nature of the granulite-facies region of western Namaqualand [6]. These findings are compared and contrasted with the style and timing of metamorphism in the Kakamas Terrane and its extension into Namibia.

A focus on the thermal evolution of the constituent terranes offers a complementary approach to other recent reviews [7, 8], allowing an assessment of the role and timing of crustal thickening and extension, and of the processes involved in the amalgamation of high-temperature terranes. In the wider context, the terranes that make up the Grenville-age global system occupy a critical period of Earth history before the unambiguous appearance of modern plate tectonic phenomena in the geological record, and modern tectonic analogies should perhaps be applied with caution.

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A new tool to study continental formation: Ti isotope insights

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The extraction of the continental crust from the mantle, and its subsequent maturation, has defined the chemistry of the Earth's surface through the transfer of water and other volatiles from the mantle to the atmosphere and hydrosphere and the release of bio-essential elements into the oceans at the interfaces between continental and oceanic crust, the atmosphere and hydrosphere. Determining how Earth's crust has developed through geological history is therefore essential to understanding how the planet has evolved to its present state. There has been particular debate over the tectonic setting in which continents are formed as a way of determining the onset of plate tectonics. Recent studies have hinted that the mode of continent formation began to transition from oceanic plateau to subduction zone environments at around 3 Ga, although these results still remain heavily debated.

Testing these model is difficult due to the lack of unambiguous geochemical tracers able to directly link continental crust to a specific geodynamic setting. However, little attention has been paid to tracers of rutile (TiO_2) involvement in this process. Ti stable isotopes have been show to be sensitive to oxide-melt equilibrium. Combined with the insolubility of Ti in geological fluids, Ti isotopes therefefore have the potential to bring new insights into this question. Here we investigate the potential of Ti isotopes as tracers of the conditions of formation of juvenile continental crust.

We carried out ultra-high precision (±0.02‰) Ti isotope measurements in modern-day equivalents of the two proposed settings of continent formation (Iceland rhyodacites and adakites for oceanic plateau and subduction zone models, respectively). Results show that all samples are consistenly enriched in heavy isotopes of Ti realtive to the mantle (+0.08‰ < δ^{49}Ti < +0.30‰ vs. +0.005 ± 0.005‰), consistent with a role for rutile in their formation, followed by evolution by fractional crystallisation. Interestingly, adakites and rhyodacites plot along two distinct trends in δ^{49}Ti vs. SiO_2 diagram, with the rhyodacites consistently plotting at lower δ^{49}Ti at a given SiO_2 content, thus outlining a potential discriminating tool between these settings of continent formation.

Application of this method to TTGs from the Pilbara (3.5 to 3.0 Ga), Yilgarn (2.9 to 2.6 Ga), Saglek Hebron (3.7 to 3.3 Ga) and Nuuvuagittuq (3.6 to 3.3 Ga) show that the Pilbara samples systematically plot on the Iceland rhyodacite trend whereas the samples form other cratons plot on the adakitic trend. This result could mean that although the Pilbara formed in an oceanic platea type environment, other cratons may have been formed in environments more akin to subduction zones. This would thus imply that subduction started gradually before 3Ga before becoming global afterwards.

Hot, fast and rich; peering into a mineralized Proterozoic bacK–Arc

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The Albany–Fraser Orogen is located along the southern and eastern margin of the Archean Yilgarn Craton in Western Australia and formed from c. 1810 to 1140 Ma during reworking of the craton. Within this orogen the Fraser Zone is a 430 km long and 50 km wide, geophysically and structurally distinct granulite facies zone, hosting abundant intrusions of c. 1300 Ma gabbroic rocks emplaced into near contemporaneous sedimentary rocks of the upper Arid Basin. The Fraser Zone contains economic nickel sulphide mineralization, related to interaction between cumulate gabbros and sulphur containing metasedimentary rocks (Maier et al., 2016). The Fraser Zone has previously been interpreted as an exhumed block of lower crust, a layered mafic intrusion emplaced into older basement, or multiple accreted oceanic arcs. However, more recent work emphasizes the Fraser Zone as a structurally modified, lower crustal hot-zone where voluminous gabbroic magmas were variably mixed with contemporaneous granites and country-rock melts (Smithies et al., 2013).

P–*T* constraints from pelitic rocks suggests peak metamorphic conditions at c. 1290 Ma were c. 850°C, at pressures of 7–9 kbar. Peak metamorphism was followed by a period of isobaric cooling at pressures of c. 9 kbar (Clark et al., 2014). The recent development of thermodynamic solution models pertaining to high-temperature phase equilibria in mafic systems permits consideration of the crystallisation depths of the mafic magmas, as well as the subsequent metamorphism and partial melting of the crystallised mafic rocks. Pressure constraints from the metagabbros of around 7 kbar are similar to those from the metasedimentary rocks and consistent with depths of around 20–25 km for both, assuming no tectonic overpressure. However, the metagabbros record significantly higher temperatures (~950°C). These data support the view that mafic magmatism was the thermal driver for high–*T*, low–*P* granulite facies metamorphism in the Fraser Zone with auto-metamorphism of the mafic pile. That is, younger mafic rocks in the same magmatic system are essentially unmetamorphosed whereas earlier components of the same system have reached granulite facies.

Magma emplacement was most likely in a dominantly extensional setting, given the rapid sequence of events from deposition of sediments to mafic magma emplacement and granulite facies metamorphism. The primary mafic magma of this zone has ~9% MgO and was derived from a depleted mantle source. This magma was contaminated with small (<10%) amounts of crust that itself has a heritage traced with Hf and Nd isotopes back to the modified Yilgarn Craton, hence excluding an exotic origin for the zone. Zircon Hf isotopic data from granitic rocks across the Albany-Fraser Orogen highlight that even prior to the development of the Fraser Zone this structural domain was already enriched in juvenile input and preconditioned to enhanced mantle flux during later Proterozoic events (Kirkland et al., 2016). Combined, these results emphasize the importance of Archean crustal structure in controlling the location of Proterozoic granulite facies zones on the margins of cratons.

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Granulites, geodynamics and 'accessory terranes'

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Granulite-facies metamorphism in the middle crust has been associated with large-scale advection of mantle heat (emplacement of mantle melts) and subsequent thickening (e.g., Collins, 2002; Hyndman et al., 2005; Brown, 2006), and with internal radiogenic heating of overthickened crust (e.g., Clark et al., 2011, 2015). Granulites produced by these two end-member models are here referred to as Type I and Type II, respectively. The two types predict different geodynamic settings; Type I requires a switch between transient phases of extension and shortening (short-lived geodynamic settings), whereas Type II requires overthickened crust that is geodynamically stable over > 50 Myr. Interestingly, both are associated with periods of supercontinent amalgamation (e.g., Brown, 2007; Clark et al., 2015).

Brown & Johnson (2017) showed that high T/P granulites are a feature of tectonics since c. 3 Ga, and that their abundance and the apparent thermal gradients they record vary with supercontinent cycles. They also suggest that Type I and II granulites should record counter-clockwise and clockwise pressure–temperature (*P–T*) paths, respectively. The problem is that granulites rocks are well known for not recording much; their early history is often overprinted and, having been extensively dehydrated, metamorphism often ignores much of their exhumation history. Studies using notoriously difficult accessory phases to investigate tectonothermal/geodynamic histories of granulites may be complemented by the use of 'accessory terranes'.

Brown (2006, 2007) and Brown & Johnson (2017) showed that low T/P (blueschist) metamorphism started with an apparent switch to modern tectonics (steep subduction) in the Cryogenian (c. 720 Ma). Viete & Lister (2017) showed that short-duration 'regional' metamorphism has only been recognized for the Phanerozoic. Age-dependent temporal resolution in geochronology makes recognition of short thermal time scales difficult in Precambrian rocks; however, thermal length scales can be used as a proxy for thermal history in the same way diffusion length scales are. Intense metamorphic field gradients may signify short-duration thermal settings expected for accretionary orogenesis typified by rapidly switching/evolving geodynamic settings (cf. Collins, 2002). Where terranes preserve low T/P (blueschist) conditions and/or intense metamorphic field gradients, one may expect Type I granulites. Orogens for which such associations are not apparent may perhaps have had a geodynamic style more likely to produce Type II granulites.

Intense Barrovian metamorphic field gradients are rare or absent through most of the Precambrian. However, they are relatively common and widespread at 1.9–1.8 Ga, during the late Paleoproterozoic, including in association with the Penokean (Vallini et al., 2007; Rasmussen et al., 2016), Trans-North China (Huang et al., 2016) and Wopmay (St Onge, 1987; St Onge & Davis, 2017) Orogens. This 1.9–1.8 Ga period also saw the only two examples of blueschist T/P prior to the late Tonian (cf. Glassley et al., 2014; Weller & St Onge, 2017). Brown & Johnson (2017) argued that the Paleoproterozoic low T/P rocks may represent a thermal anomaly restricted to the 'Laurentian realm'. The recognition of associated and more widespread examples of short length scale (and therefore time scale) thermal settings may suggest that 1.9–1.8 Ga saw a more global episode of anomalous 'Phanerozoic-style' (accretionary) tectonics, involving steep subduction, and during which one may expect Type I granulites to have been dominant.

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Conservation of deep crustal heat production

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Partial melting of continental crust is generally considered to produce granitic rocks that have high radiogenic heat production rates when compared to their inferred source regions and average continental crust. If this idea is correct then residual granulite facies rocks, which are the source regions for crustally-derived melt and comprise the residual material left behind after melt loss, should have depleted heat production rates with respect to crustally-derived granites. However, there are cases where residual crustal granulites retain high radiogenic heat production. These examples from the Eastern Ghats Belt and Southern Granulite Terrane, India (Kumar et al. 2007, Ray et al. 2008), the Namaqualand Complex, South Africa (Andreoli et al. 2006), and the Jequié Terrane, Brazil (Alexandrino and Hamza 2008) demonstrate that the deep/lower crust is not necessarily always depleted in radiogenic heat production during partial melt extraction.

In this study, K–U–Th measurements were collected from metapelitic compositions in five different metamorphic terranes: Reynolds Range and Mt Stafford in the Arunta Complex in central Australia; Broken Hill in the Curnamona Province in southern Australia; the Ivrea–Verbano Zone in northern Italy and Sierra De Quilmes in north-west Argentina. These data show that crustal heat production rates do not change significantly between subsolidus regions and their suprasolidus equivalents that have undergone extensive fluid-absent partial melting and experienced significant melt loss. In some cases, crustal heat production rates increase in the residual granulite facies rocks. This suggests fluid-absent partial melting does not deplete concentrations of heat producing elements in residual metapelitic-derived granulites. Consequently, basement terranes may retain comparatively elevated concentrations of heat producing elements and therefore be more susceptible to thermo-mechanical reactivation than typically expected.

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Rapid exhumation of Miocene UHT granulites in eastern Indonesia

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The island of Seram, eastern Indonesia, incorporates Miocene ultrahigh-temperature (UHT) garnet–sillimanite granulites in close association with spinel lherzolites (Pownall *et al.*, 2014). UHT conditions were attained by extreme lithospheric extension behind rolling-back Banda Arc in response to Australia–SE Asia collision, which initiated at *c.* 23 Ma (Spakman & Hall, 2010). Slab rollback exhumed subcontinental lithospheric mantle to shallow depths, driving short-lived UHT metamorphism in the overriding Australian continental crust. The resulting UHT complex, which at 16 Ma is the youngest so far identified, provides a rare opportunity to study how the Modern Earth is able to produce extreme thermal metamorphic conditions.

Several geochronological (U–Pb zircon, U–Pb monazite, Lu–Hf garnet, Sm–Nd garnet, $^{40}Ar/^{39}Ar$ biotite, $^{40}Ar/^{39}Ar$ white mica, and $^{40}Ar/^{39}Ar$ K-feldspar), microchemical (REE analysis of zircon and garnet), and thermobarometry techniques have now been applied to these UHT migmatites exposed on the island of Seram (Pownall *et al.*, 2014, 2018). The U–Pb zircon, U–Pb monazite, and $^{40}Ar/^{39}Ar$ (furnace step heating) biotite ages that relate to the UHT metamorphic event are all identical within error (15.9 ± 0.2 Ma). Furthermore, pairs of U–Pb zircon and $^{40}Ar/^{39}Ar$ biotite ages obtained for a suite of migmatites that are also related to the UHT complex similarly record identical ages, within uncertainty. These findings challenge conventional interpretations of high-grade migmatites experiencing long-lived metamorphic histories culminating in slow/moderate cooling, when distinct ages are expected to be recorded sequentially by isotopic systems of decreasing closure temperatures. We argue the tight synchroneity in this instance is accounted for by (1) the zircon having crystallised *not* under peak conditions but late on the decompression path (controlled by breakdown of garnet; Fig. 1); (2) the complex having been exhumed stepwise, as thin fault-bound slices; and (3), exhumation having been rapid, driven by Banda slab rollback.

In addition, the Seram UHT granulites demonstrate that: (1) Zircon grains in shielded microtextural sites (in this instance as inclusions within garnet) may be subjected to an entire UHT metamorphic cycle without crystallizing new rims and therefore without recording the UHT event; and (2) Short-lived UHT metamorphic events are sometimes unable to reset the Lu–Hf system in garnet. In such instances, Hf retention from a previous metamorphic event may lead to a mixed Lu–Hf age even for garnets that no longer preserve major element zonation (Pownall *et al.*, 2018).

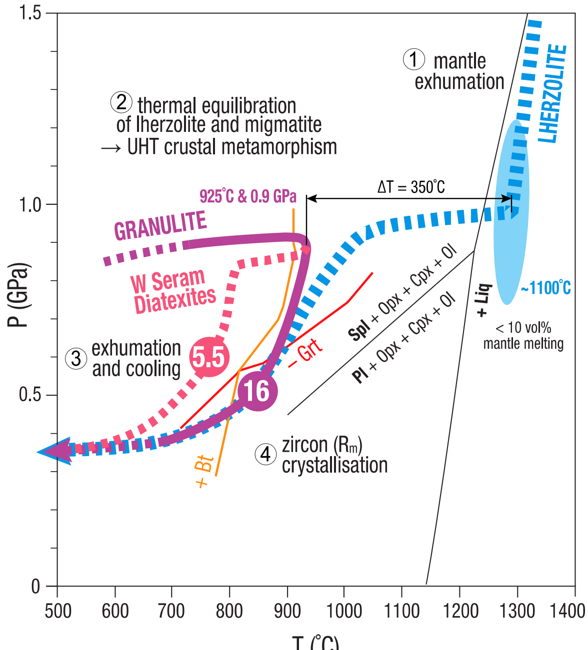

Fig. 1: UHT metamorphism driven by hot mantle exhumation. 16 Ma zircon formed during decompression through ~6 kbar, not under peak conditions.

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Thermal buffering in the orogenic crust

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Metamorphic rocks evolve through chemical reactions that consume energy in order to advance. Melting reactions in particular are strongly endothermic and may consume substantial portions of the orogenic heat budget. The effects of this process are qualitatively established, but modern thermodynamic data sets now allow quantification of the thermal consequences for real rocks. We calculate the heat consumption of melting reactions, and its effect on the temperature attained during high grade metamorphism, for two compositional end-members that commonly constitute orogenic crust. Fertile metapelites are volumetrically minor but petrologically significant, as *P*–*T*–*t*–(d) constraints and burial-exhumation paths are preferentially derived from this lithology, whereas refractory granites comprise the bulk of orogenic crust. We show that metapelites may maintain a near-isothermal state as melting reactions advance, effectively forming a thermal barrier to regional heat flow. By contrast, granites experience a linear heating path, as they produce negligible amounts of melt at typical orogenic temperatures. Lithology can therefore exert a control on the attainable metamorphic temperature and may lead to a similarity of peak temperatures attained over a depth profile, as has been suggested for orogenic crust. Conversely, lithological layering may lead to a thermally-stratified orogenic crust during partial melting. Furthermore, our modelling confirms that thermal buffering may prevent the attainment of ultrahigh-temperature (UHT) conditions in excess of 900 ºC in fertile bulk compositions, even as these temperatures may be reflected in coexisting, more refractory lithologies.

Considerations on zircon, monazite and garnet geochemistry and geochronology in high-grade rocks

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Geochronology of granulite-facies metamorphism is best achieved with U–Pb dating of zircon and monazite, and Lu–Hf dating of garnet. The high temperature, possible long duration and common presence of melt in granulites presents specific challenges to each of this method.

For zircon and monazite geochronology, the use of other chemical and isotopic indicators to aid the interpretation of U–Pb dates has become routine. In granulites, the extreme temperatures and possibly the long duration of metamorphism can lead to decoupling of different isotopic and geochemical systematics.

Examples from granulites of the Greater Himalayan Crystalline illustrate how monazite and zircon (U,Th)–Pb ages of specific growth zones can be related to specific conditions of mineral growth on the basis of textural relationships with co-existing minerals, zoning patterns, trace element signatures, and index mineral inclusions. The results show that inherited domains are preserved in monazite even at granulite-facies conditions. Metamorphic zircon and monazite can form during prograde melting. Most monazite and zircon grains crystallized from melt during decompression and are chemically related to garnet breakdown reactions. Monazite grown at final melt crystallization is homogeneous in composition. In this example, the correlation between accessory mineral chemistry and age is maintained even after a protracted high temperature evolution. In other granulite facies rocks, however decoupling induces lack of correlation between different isotopic and chemical signatures as for example age and trace elements. The possible conditions leading to such decoupling will be discussed.

While trace element geochemistry and U–Pb ages are commonly combined, less is know about the significance and variability of oxygen isotopes in zircon (or monazite) during high-grade metamorphism and anatexis. Preliminary studies suggest that, in some cases, melting may produce a heterogeneous oxygen isotope signature in anatectic zircon.

Garnet has the advantage that *P*–*T* conditions can be retrieved from thermobarometry or thermodynamic modeling involving garnet. For correct age interpretation however, the distribution of trace elements and particularly Sm and Lu have to be investigated to distinguish growth zoning from diffusional re-equilibration. Novel REE element mapping of garnet produced by LA–ICP–TOFMS compared to major element zoning give insight into partial diffusional equilibration and matrix controlled zoning in granulites.

Due to its large stability field, garnet is also an ideal target for oxygen isotope investigation to trace fluid-rock interaction. Diffusional re-equilibration of oxygen isotope in garnet has been investigated experimentally at 1-atmosphere and at high-pressure in piston cylinders. The recovered crystals were analyzed in step-scanning and depth profiling mode by SHRIMP ion microprobe and nanoSIMS. Results, independently of pressure and garnet composition, define an Arrhenius relationship that returns a diffusion coefficient that is faster than any previous calibration.

The retentivity of oxygen isotopes in granulite facies rocks is investigated in a sample from East Antarctica. Garnet preserves step-wise zoning between garnet core and rim in phosphorus, whereas microscale oxygen isotope analysis shows a gradual transition. Fitting of the data to the diffusion equation provide constraints on the residence time of sample at high temperature.

Rutile: A window into the lower crust

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Rutile is a robust accessory mineral that is stable over a large *P–T* range and found within a wide variety of high-grade metamorphic assemblages. It is a major host of HFSE (e.g. Nb, Ta and Cr), which can be used to discriminate between source rock lithology, and temperatures can be obtained using the Zr-in-rutile geothermometer. It has also recently been shown that metamorphic rutile is an excellent container of mineral inclusions, due to properties which promote the preservation of mineral inclusions, such as being resistant to fracturing and fluid infiltration.

Although rutile has the potential to identify and investigate UHT metamorphic terranes, the prograde history of UHT rocks is poorly preserved owing to rapid diffusion and reaction rates, and whilst Zr-in-rutile thermometry is a powerful tool when investigating metamorphic terranes, its application to granulites can be difficult owing to diffusional resetting of Zr concentrations during cooling and decompression. To resolve these issues and further utilise rutile as a tool to identify and investigate UHT terranes, rutile from the granulite-facies paragneisses of the Napier Complex and the Rauer Group, Antarctica have been investigated for trace element composition and mineral inclusions/intergrowths.

In this contribution, textural observations and Zr-in-rutile temperatures show that unlike the large proportion of rutiles grains in the matrix, rutile grains that are shielded by phases with low Zr-diffusivities (e.g. orthopyroxene) and/or are in chemical isolation from zircon, have the potential to retain Zr concentrations that correspond to ultrahigh-temperatures. Furthermore, rutile from the Napier Complex granulites is found to contain inclusions and intergrowths of aluminium silicate, quartz, corundum and feldspar, including the first reported occurrence of prograde kyanite, which suggests that the Napier Complex experienced a typical clockwise *P–T* evolution. These findings highlight the importance of rutile in UHT terranes and may profoundly change how we investigate and recover evidence of high-temperature events.

Zircon and rutile *in extremis*: lessons from 1200°C sanidinite facies partial melting of a sapphirine–enstatite granulite

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Natural tests of Ti-in-zircon and Zr-in-rutile thermometers to ultrahigh temperature (UHT) conditions are important for validating the experimental calibrations, understanding the mechanisms of trace element incorporation into and expulsion from UHT minerals, and assessing the length- and timescales of post-UHT resetting of trace element chemistries and hence thermometry. Here we report and evaluate the Ti contents in zircons and Zr concentrations in rutiles that formed during extreme, and essentially instantaneous, sanidinite facies partial melting and melt crystallization of a pre-existing highly-magnesian (X_{Mg}99) sapphirine-enstatite granulite. The precursor granulite formed in an end-Archaean (2520-2480 Ma) regional metamorphic event (5-7 kbar, 860°C) that affected the basement gneisses of the Vestfold Hills, Antarctica [1]. Fragments of this granulite uniquely occur as xenoliths hosted within a significantly younger (2240 Ma) norite igneous body that intruded the older basement gneisses some 250 million years after the regional metamorphism. Millimetre-scale former partial melt pockets and stringers in this xenolith contain Ti-bearing sapphirine and enstatite, spinel, feldspar, zircon, monazite, zirconolite, rutile and rare perrierite [2]. Phase equilibria modelling of this xenolith in the KMASH system and independent near-liquidus modelling of the host norite constrain the sanidinite facies partial melting and consequent zircon, rutile and zirconolite accessory mineral crystallisation to 1170-1210°C at 2.5 kbar [3,4]. The age of this sanidinite facies event is corroborated as c. 2240 Ma by in situ SIMS U–Pb dating of zircon and zirconolite in the former melt pools.

Melt-crystallised zircons are interstital between spinels, have euhedral to hopper and stellate shapes, and show minor zoning parallel to their tetrad axes. They have high MREE–HREE (Gd_N = 1000; $(Yb/Gd)_N$ = 4) and strong negative Eu anomalies (Eu* = 0.2). The Ti contents of these zircons, determined by SIMS and 'high beam current' EPMA, are 329 ± 47 ppm (range: 250–440 ppm) - the highest recorded from any non-shocked terrestrial zircons. The resultant pressure-corrected Ti-in-zircon temperatures [5] of 1190 ± 29°C are consistent with earlier independent estimates and hence support the experimental calibration of this thermometer in rutile-saturated systems. Melt-crystallised rutiles display complex textures, from spindle and euhedral shapes to rounded and amoeboid grains intergrown with Ti-bearing sapphirine. The rutiles show exsolution/decomposition into intricate two- or three-phase intergrowths dominated by micron-scale zircon granules and lamellae, with three directions of lamalle growth dicated by the rutile lattice. These granule networks are reorganised into stringers and grains along fractures and grain boundaries within rutile, leaving granule-depleted marginal zones. Rutile grain boundaries exhibit dissolution-reprecipitation leading to boundary-parallel rutile-sapphirine intergrowths lacking zircon granules / lamellae exterior to zircon granule 'fronts'.

The trace element and Zr contents of the rutiles have been determined by SIMS, high beam current EPMA, and femtosecond LA-ICPMS. SIMS and EPMA yield re-integrated Zr contents of 2.75 ± 0.90 wt%, requiring *minimum* temperatures [6] of 1168 ± 80°C at 2.5 kbar. Whilst these overlap with the Ti-in-zircon temperatures, the high Zr contents in the rutile are only retrieved by integration of area analyses (EMPA) and multiple SIMS spots – granule-free rutile contains only 9000–3000 ppm Zr, indicating rutile rapid re-equilibration to 950-800°C on expulsion of granules, even in the extremely short timespan (less than years!) available for cooling of the xenolith to ambient temperatures (c. 200°C). Notably, whilst Zr contents mostly correlate strongly with Si, indicating zircon as the exsolving phase, a second analytical population show no Zr-Si correlation, pointing to the presence of baddelyite. This suggests that the rutile has been open to Si once exsolution-decomposition is initiated through formation of baddelyite, a process evaluated on the using TEM imaging coupled with the Zr-Si chemical data.

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Interpreting titanite U–Pb dates and Zr temperatures in granulites: Empirical estimates of elemental diffusivities

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We measured the length scales of compositional heterogeneity in titanite to provide empirical constraints on elemental diffusivities. The titanite grains are from 800–1000°C metamorphic rocks from southern Madagascar; previous empirical studies have been limited to ~750–800°C rocks. Pb diffusivity is comparable to experimental estimates of Sr diffusivity; in rocks that reached peak temperatures as high as 850°C, U–Pb dates should be interpreted as (re)crystallization ages. Grain-boundary conditions—grain-boundary diffusivities or which phases are adjacent to titanite—may limit the rate at which Pb (and other elements) can diffuse out of titanite, allowing preservation of U–Pb dates at temperatures even greater than predicted by intracrystalline diffusivity. Zr diffuses slowly and its concentrations likely reflect the conditions of (re)crystallization even at temperatures >900°C. Coupled U–Pb dates and Zr-in-titanite thermometry—measured from the same volumes of material by LA–ICP–MS—can be used to construct *P–T–t* paths of granulites, contrary to the wide-held paradigm that U–Pb titanite dates are cooling ages.

Recognizing melt pathways in the crust: nature and experiments

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Geochemical signatures throughout the layered Earth require significant mass transfer through the crust, yet pathways for melt are under-recognized in the geological record. Field studies in different geotectonic environments show that melt pathways other than those seen in dykes are commonly delineated by the signatures of melt-rock interaction. Such melt-rock interaction is triggered by the fact that a fluxing melt, which is external to the rock that it transgresses, is likely to be in chemical disequilibrium with the surrounding through which it passes. Hence, reaction and dissolution features delineate such melt pathways[1] along with distinct REE patterns of newly grown phases[2].

Our studies show that melt can migrate through a rock by a variety of mechanisms that are linked to porous melt flow. During diffuse porous melt flow the fluxing melt migrates along grain boundaries and reacts with unstable phases of the host rock. The migration of the melt is thought to be aided by the pre-existing presence of a melt film network within the host rock. Typical signatures are asymmetry corona replacement textures and trace element variations at a subgrain scale[1,2,3]. Such diffuse porous melt flow can develop into channelized melt flow, where melt flux channels are characterized by high metasomatism, low phase numbers, and on an outcrop and thin section scale diffuse boundaries between melt channels and microstructures indicative for dissolution of an anhydrous phase (e.g. quartz or plagioclase) and precipitation of a hydrous phase (e.g. amphibole, biotite)[3]. Within the highly metasomatised zones, microstructures typically associated with the former presence of melt (e.g. low dihedral angles) are common[2,3]. The development of diffuse to channelized porous melt flow is directly associated with melt flux in a static or dynamic environment, i.e. without or with contemporaneous deformation, respectively. Static melt flux styles are inferred to involve diffuse porous melt flow with low melt flux occurring at the kilometre scale[3] while channelled high melt-flux is associated with high melt flux volumes occurring at the metre to 100s of meter scale, leading to generation of distinct bodies such as an ultrabasic "layer"[2] and/or local migmatisation through significant melt induced hydration[4].

In addition, in high strain zones active at mid crustal levels, syntectonic melt flux can be recognized not only by extensive metasomatism but also by "floating" Kfsp phenocrysts and slivers of the fluxing melt interpreted to represent parts of the fluxing melt that were trapped at the late stages of melt flux. In an extensional regime, where partially molten rock may be ubiquitous, melt flux of externally derived melt through migmatites can be substantial.

Preliminary data from experiments where shards of anhydrous gabbro are reacted with a hydrous gabbroic melt show that within very short periods (12 hrs) dissolution-precipitation reactions results in dissolution of feldspar and pyroxene and precipitation of hornblende at the melt-shard interfaces.

Identification of such melt flux zones is not only important in understanding the chemical evolution of Earth in space and time, but also for the assessment of rheological properties of the investigated area. Areas of high melt flux are rheologically very weak at the time of melt migration; hence these areas will localize strain from the meter to 100s of kilometer scale.

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Why are granulites dry? An alternative model based on Coincident Site Lattice Theory

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Quartzofeldspathic rocks metamorphosed under granulite facies conditions, such as charnockites and enderbites, are believed to form under low water activity conditions in the lower crust, and their presence on the present-day surface of the Earth indicates that they remained dry during ascent and exhumation. However, felsic granulite terranes are commonly intruded by mafic dykes that in turn are metamorphosed to amphibolites. Stabilization of metamorphic amphibole-plagioclase assemblages in these dykes (now amphibolites) indicates that hydrous fluids did infiltrate the terrane following granulite facies metamorphism and dyke intrusion, but preferentially hydrated only the mafic dykes. The host felsic granulite, in contrast, preserves only limited evidence of retrogression suggesting sustained impermeability to fluid infiltration following granulite facies metamorphism. This suggests that some underlying fundamental causative mechanism inhibits fluid percolation into felsic granulite facies rocks.

The dark history of charnockite

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Charnockite is defined as orthopyroxene-bearing granite but is also distinguished by the dark colour of its quartz and feldspar. This latter characteristic is most obvious in so-called "incipient" charnockites, which comprise dark patches of coarse-grained orthopyroxene-bearing felsic rock within a finer-grained biotite- and or hornblende-bearing gneissic host. Such patches always contain variably retrogressed orthopyroxene and markedly reduced biotite and/or hornblende contents compared to the orthopyroxene-absent host. These differences in mineral mode imply that the orthopyroxene in charnockite patches grew at the expense of biotite and/or hornblende, and this is often ascribed to influx of low-a_{H2O} fluid based on (1) the shape and distribution of the dark patches around orthopyroxene grains; and (2) an apparent increase in CO_2 fluid inclusions in dark patches compared to the host. This led to suggestions that such fluids are responsible more generally for dehydration of the lower crust, conflicting with traditional petrological wisdom that anhydrous lower crust forms by melt extraction in the absence of volatile fluid.

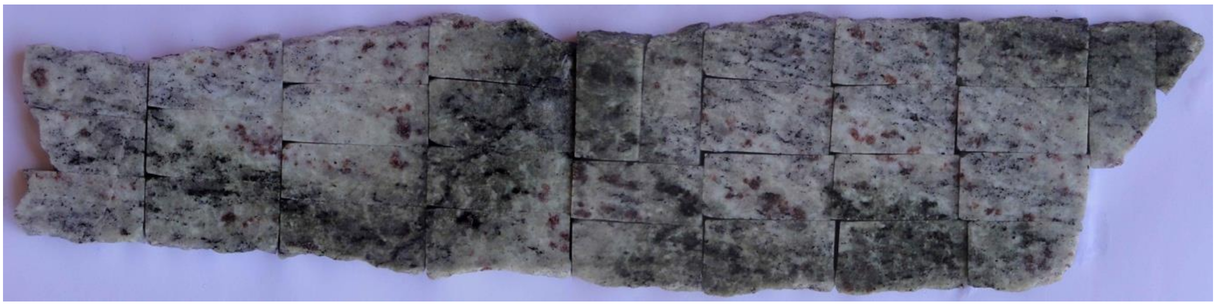

Figure 1. Incipient charnockite comprising dark orthopyroxene-bearing patches in garnet-bearing migmatite.

There are several overlooked features of incipient charnockite that complicate this story. Firstly, it has long been known that the dark hue around orthopyroxene reflects fine-grained chlorite and other iron-rich hydrous minerals. This low-temperature alteration must post-date orthopyroxene and the shape and distribution of the dark patches will therefore mark the passage of late hydrothermal fluids and need not reflect any fluid present during orthopyroxene growth. Secondly, the host gneissic rock is migmatite that contains garnet-bearing leucosome with similar grain sizes and shapes to the charnockite patches. There is also some indication that garnet leucosome has the same increased abundance of CO_2 fluid inclusions seen in charnockite, weakening the link between low-a_{H2O} fluid and orthopyroxene growth. These observations are more consistent with orthopyroxene forming in leucosome as a peritectic product of dehydration melting in bulk compositions with lower Al or Fe^{2+} than those that stabilised garnet. In this model the low-a_{H2O} inclusions are residual fluids left after extraction of H_2O-rich melt from both garnet- and orthopyroxene-bearing leucosome.

This model does not explain the spatial link between orthopyroxene growth and hydrothermal retrogression. Why is the dark alteration always present around orthopyroxene but never seen away from orthopyroxene? Perhaps the hydrothermal fluid passed through all rock types, but only caused visible alteration if it intersected orthopyroxene causing retrogression and release of FeO and other components into adjacent rock. If so, the dark patches that dominate incipient charnockite are linked to low-temperature hydration of pre-existing orthopyroxene rather than high-temperature dehydration that stabilises orthopyroxene. This model has no need for substantial flux of externally derived low-a_{H2O} fluid, and instead requires influx of retrograde hydrothermal fluids that could be provided by granite plutons crystallising at depth.

Interplay between chemical diffusion and deformation

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In the classical view of metamorphic zoning, fast viscous relaxation (and therefore constant pressure) across the microstructure is assumed, with chemical diffusion being the limiting factor in equilibration. Recently, we have focused on the other possible scenario – fast diffusion and slow viscous relaxation – which brings an alternative interpretation of chemical zoning found in high-grade rocks. The aim has been to provide insight into the role of mechanically maintained pressure variations on multi-component chemical zoning in minerals.

Our effort is inspired by several specialized analyses of species segregation in biotechnology, chemical engineering and deep-oil reservoir modelling that use an equilibrium formulation for calculating compositional gradients under external forces. These forces are then responsible for a maintenance of a compositional gradient. In these analyses, the principles of energy, momentum and mass conservation are followed. A geologically relevant application of the aforementioned approach is the calculation of mineral equilibria under mechanically-imposed grain-scale pressure variations. Similarly to the centrifugation effects mentioned above, a mechanically–maintained pressure variation in space is likely to cause a redistribution of components in minerals, with higher density minerals and mineral compositions developing towards the higher pressure part of the microstructure. Therefore, a chemical zonation can occur as a result of spatial pressure variation under thermodynamic equilibrium.

In this contribution, the appropriate modification of a macroscopic flux for a system with a pressure variation is derived and a consequence of using mass or molar units in diffusional fluxes is discussed. The use of appropriate units in the equations for fluxes for a system under pressure variation is essential because the sign of the molar volume and the density difference can be opposite, which can significantly influence the trend of chemical zoning.

Additionally, a coupled model for chemical diffusion and mechanical deformation has been developed and applied to the chemically zoned binary plagioclase. The theory of coupling these two processes is developed in analogy to the studies of poroelasticity and thermoelasticity by considering the conservation of mass, momentum and energy and the constitutive relations derived from fundamental thermodynamic relations. Dimensional analysis and numerical results suggest the presence of two different mechanisms that can be responsible for the maintenance of the chemical zonation in minerals, the diffusion-controlled and the mechanically-controlled mechanisms.

Tracking the anatectic record of aluminous granulites: new approaches and limitations, with examples from the Grenville orogen

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Large hot orogens are characterized by widespread granulite-facies metamorphism and constitute first-rate natural laboratories for investigating partial melting of the middle to lower crust in dynamic settings. In addition, developments in imaging techniques and microanalysis has opened new avenues for the interpretation of metamorphic rocks, with potential implications for assessing the anatectic record in high-T environments. Here we document the case of aluminous granulites from contrasting crustal panels in the central part of the Mesoproterozoic Grenville Province (Quebec, Canada): high-P crust with kyanite stable in the Parautochthonous belt and the overlying hinterland, and structurally higher, mid-P crustal with sillimanite stable in the orogenic hinterland.

Rocks in all structural levels show evidence for anatexis by breakdown of micas, and melt escape with retention of some melt (6 to 8% predicted by phase equilibria modeling). SEM–MLA false-color mineral maps of thin sections conveniently show the general distribution of former melt sites, and of retrograde domains inferred to have developed during melt crystallization. Hence, they provide a context for finer scale features typically observed by optical microscopy, such as former melt pseudomorphs. In addition, quartz and kyanite rims (in the high-P rocks), produced during melt crystallisation are revealed by cathodoluminescence (Cl) imaging in microstructures not identifiable by optical means (Fig. 1a,b) and highlight the potential to recalculate on microstructural grounds the proportion of former melt in the rock, based on the amount of phases produced during melt crystallisation. Microstructural data in conjunction with mineral chemistry and phase equilibria modeling suggest contrasting P–T patterns in the three granulite-facies segments of the central Grenville that, together with monazite metamorphic ages have implications on the tectonic interpretation of the orogen.

The data also highlight several limitations. A common difficulty is to obtain peak metamorphic T above the P–T field of biotite melting in mid to high-P rocks. Ti in quartz and Zr in rutile thermobarometry are attractive alternatives. However, application of these methods in the samples from the central Grenville, yielded dispersed and generally lower P–T conditions than expected, despite coexistence of the phases of interest, and suggests that the interpretation of these type of data is not straightforward. Furthermore, for apatite-bearing aluminous granulites, which are relatively common, modeling of metamorphic pressures in CKNFMASTHO system gives unrealistic results. This is attributed to dissolution of apatite in the anatectic melt coupled with Ca transfer to garnet, and is consistent with textures revealed by CL in apatite (Fig. 1c) and REE patterns of high Ca garnet inferred to have grown in sites of apatite dissolution.

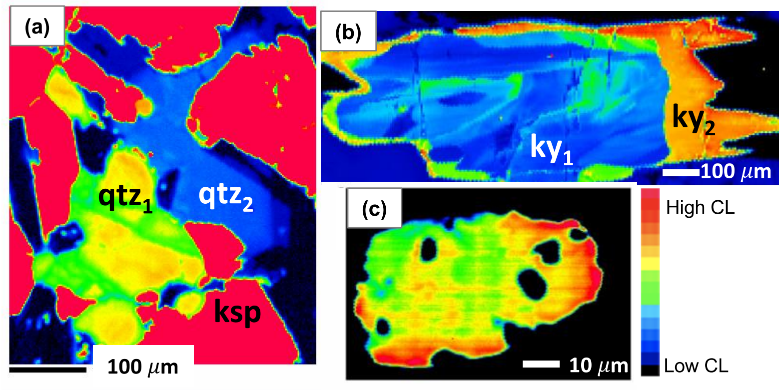

Figure 1: Examples of false color CL maps of (a) quartz; (b) kyanite; and (c) resorbed apatite; qtz$_2$ and ky$_2$: quartz and kyanite crystallized from melt; host rocks: anatectic aluminous gneisses from the central Grenville Province.

Progress and pitfalls in metamorphic phase petrology

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Over the last 20 years the use of quantitative phase petrology to understand metamorphic rocks and processes has increased substantially. Much of this has been driven by the ongoing development of endmember thermodynamic data and activity–composition relationships for complex solid-solution minerals and for silicate melt. These developments have resulted in the ability to undertake calculations in geologically-realistic chemical systems involving ten or more components. This has seen the relatively successful adaptation of calculated phase petrology methods as a directly applicable tool to better understand metamorphic rocks and processes, especially so in granulite faces rocks. However, such apparent sophistication must be considered in the context of the errors involved in the thermodynamic calculations and the inherent differences between models and geological reality.

Equilibrium thermodynamics provides an idealized view, but an incomplete one. However, it's very success in explaining many features of metamorphic rocks has led to an increasing tendency to describe metamorphic features or interpretation of observations in terms of thermodynamic rather than descriptive geological terminology (e.g. equilibrium metamorphism, disequilibrium textures etc). However, it should be used with caution in metamorphic research and clearly distinguished from features and inferred processes based on observations or analytical data.

Of particular concern is the recent tendency to treat processes that are not equilibrium-thermodynamic features, such as nucleation, in terms of equilibrium thermodynamic calculations. Approaches such as setting Gibbs energy differences as criteria for nucleation or even the thermodynamic adjustment of phase diagrams to meet personal bias on the nucleation kinetics of particular phases have been suggested by some workers. While such an approach may have a simplistic appeal it is nonetheless provably incorrect and thermodynamically misleading.

Despite the current shortcomings of the approach, equilibrium thermodynamic methods still have substantial relevance for metamorphic research. Improvements in thermodynamic models for minerals and melt and extension of chemical systems for calculations are ongoing, allowing new applications. Increased computational power is now allowing a much more direct integration of thermodynamic calculations with sophisticated thermo-mechanical simulation to allow a much more complete and robust framework for large-scale geodynamic models and allows geodynamic simulations to be rendered in terms of petrographic observables.

Phase equilibria modeling of residual migmatites and granulites

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Suprasolidus continental crust is prone to loss and redistribution of anatectic melt to shallow crustal levels. These processes ultimately lead to differentiation of the continental crust. The majority of granulite facies rocks worldwide has experienced melt loss and the reintegration of melt is becoming an increasingly popular approach to reconstruct the prograde history of melt-depleted rocks by means of phase equilibria modelling. It involves the stepwise down-temperature reintegration of a certain amount of melt into the residual bulk composition along an inferred *P*–*T* path, and various ways of calculating and reintegrating melt compositions have been developed and applied.

In this contribution, the different melt-reintegration approaches proposed in the literature are, firstly, reviewed. Then, they are tested using El Hoyazo granulitic enclaves (SE Spain) and Mt. Stafford residual migmatites (central Australia). These two case studies present different advantages and limitations. Melt-reintegration was done following one-step and multi-step procedures proposed in the literature. For El Hoyazo granulites, modelling was also performed reintegrating the measured melt inclusions and matrix glass compositions and considering the melt amounts inferred by mass–balance calculations. Various sets of *P*–*T* pseudosections will be presented and discussed.

Forward modelling of accessory minerals in migmatites: insights and limitations

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Accessory minerals are important chronometers and hosts of trace elements in migmatites and granulites. Ages retrieved from accessory minerals are commonly linked to the growth and breakdown of major minerals via trace element concentrations. This is commonly done using an inverse approach where measured trace element compositions of accessory minerals are linked to the growth and breakdown of the major *P*–*T*-sensitive minerals[1]. An alternative approach is forward modelling. This allows investigation into the *P*–*T*–*X* controls on accessory mineral behaviour and provides a general framework in which to interpret the geological significance of accessory mineral ages. Here, trace element partition coefficients are coupled with the results of phase equilibria modelling to examine how the trace element compositions of accessory and major minerals can change along a *P*–*T* evolution and examine the trace element budgets of migmatites.

Zircon is one of the most commonly used metamorphic chronometers. The suprasolidus behaviour of zircon is modelled by combining experimentally-derived solubility expressions[2] with the predictions of phase equilibria modelling[3]. This information is then combined with trace element partition coefficients of major and accessory minerals. Modelled Th/U ratios of equilibrated anatectic zircon are expected to increase during prograde metamorphism if Th-rich accessory minerals are consumed. In metapelites, the breakdown of Th-rich monazite will contribute to higher Th/U ratios in zircon4. In metabasites, the breakdown of Th-rich allanite is predicted to generate high Th/U ratios in equilibrated zircon (Figure 1). At the solidus, allanite is expected to be the main repository for Th in metabasites whereas the U budget is shared by the accessory and major minerals (Figure 1). Most Th and U is predicted to remain in the residue at $T < 900°C$.

Forward modelling of accessory minerals and trace element budgets in migmatites assumes equilibrium between major and accessory minerals and no substitution of the essential structural constituents of accessory minerals into major minerals. The preservation of trace element zoning in accessory minerals indicates that equilibrium is not always achieved. The substitution of the essential structural constituents of accessory minerals (e.g. Zr in zircon) into major minerals is important in some high-temperature assemblages (e.g. Zr in garnet). Nonetheless, this modelling approach provides a general framework in which to link trace element compositions of accessory minerals to the growth and breakdown of major minerals in migmatites for a variety of *P*–*T* paths and bulk rock compositions.

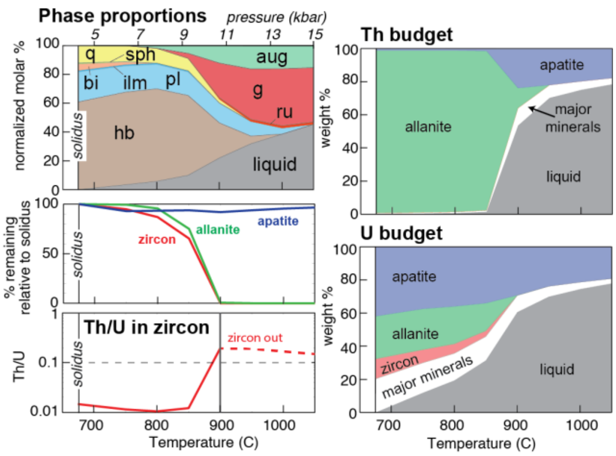

Figure 1. Phase equilibria modelling of an average MORB[5] along a prograde *P*–*T* path. Zircon and allanite are expected to break down during prograde metamorphism and are completely consumed by ~900°C. The Th/U ratio of equilibrated zircon increases with temperature. The Th budget is mostly hosted by allanite at low temperatures and by liquid at high temperatures. Most of the U budget is shared between the accessory minerals at the solidus. Apatite is generally expected to be unreactive during prograde metamorphism. Most Th and U remains in the residue at $T < 900°C$.

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High-pressure granulite facies equilibration in the eclogite facies orogenic root (Western Gneiss Region, Norway)

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Garnet-clinopyroxene-dominated mafic rocks have been investigated in the outer coastal area of the northwestern-most part of the Western Gneiss Region, South Norway. The garnet-clinopyroxene rocks occur as lenses with amphibolitised and deformed margins ranging in size from 1 m^2 up to 2–3 km^2. They are regionally widespread and included in migmatitic gneisses, mica schists and amphibolites. The mafic lenses vary from fine- to coarse-grained with a strain variation from massive to strongly foliated and lineated. Garnet is $Alm_{42\text{-}53}Prp_{17\text{-}35}Grs_{20\text{-}33}Sps_{0\text{-}3}$. Clinopyroxene is a Na–Al diopside ($En_{34\text{-}43}Fs_{8\text{-}17}Wo_{48\text{-}52}$) with Al up to 0.50 a.p.f.u. and Na-content up to Ac_{18}. Garnet and clinopyroxene occur in assemblage with edenitic-pargasitic amphibole (Ti < 0.32 a.p.f.u.), plagioclase ($An_{16\text{-}43}Ab_{57\text{-}71}$), quartz, locally biotite (Mg#=0.46–0.56; Ti = 0.51–0.59 a.p.f.u.), calcite and epidote, and accessoric rutile, ilmenite, zircon and apatite. Garnet porphyroblasts occur commonly as euhedral crystals and locally with corroded rims surrounded by a corona of plagioclase or amphibole-plagioclase. Clinopyroxene occurs as elongated subhedral crystals forming a strong fabric, or as a coarse symplectite with plagioclase. Amphibole is present as matrix grains in the garnet-clinopyroxene assemblage, but occurs also in coronas on garnet as symplectite with plagioclase, or as replacement textures on clinopyroxene. Titanite is produced secondary on rutile, and spinel + plagioclase on ilmenite.

The *P*–*T* evolution is modeled by *P*–*T* pseudosections (TheriakDomino software), thermobaromtry and by mapping of garnet chemistry. Garnet porphyroblasts show a decrease in CaO and MnO, an increase in MgO and variable FeO with resulting increasing Mg# from core to rim, indicating growth under increasing temperatures and decompression. Calculation of garnet + clinopyroxene + plagioclase + quartz + rutile stability combined with garnet and clinopyroxene isopleths of grossular and Mg# composition, yields peak metamorphism of P = 1.4–1.8 GPa and T > 900°C. The *P*–*T* modeling supports high-pressure granulite facies condition for the peak equilibration of the garnet-clinopyroxene-dominated mafic lenses. The peak metamorphism is associated with partial melting. Thermobarometric calculation of host migmatitic gneisses reveal 1.34 ± 0.13 GPa and 824 ± 43°C based on the garnet + muscovite + biotite + plagioclase + quartz-assemblage. In addition, an outermost small Mn-increase, and local reversal of the Mg# ratio and CaO flattening in garnet of the mafic lenses is interpreted as a retrogression into amphibolites facies. This is in accordance of mineral replacement of clinopyroxene to amphibole and titanite growth on rutile.

The data support an evolution where the eclogite facies crust in the northwestern-most coastal part of Western Gneiss Region underwent decompression during heating into high-pressure granulite facies conditions. The host gneisses underwent migmatitisation, followed by amphibolitisation. Our investigation gives a regional petrological documentation and illustrates an extensive high-temperature equilibration in the Caledonian root zone subsequent to the deep crustal burial.

Unravelling the tectonometamorphic history of Meta Incognita, Arctic Canada, using integrated LA–ICP–MS monazite mapping and phase equilibria modelling

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The Meta Incognita Peninsula, located on south-east Baffin Island, Canada, exposes upper plate, supracrustal rocks metamorphosed at granulite-facies conditions during the Himalayan-scale Paleoproterozoic Trans-Hudson Orogen (St-Onge *et al.* 2007; Weller & St-Onge, 2017). A suite of migmatitic metasedimentary and metabasic rocks from the region were selected for integrated thermobarometric and geochronogical analysis to further understand metamorphic processes operating at mid-crustal levels during orogenesis. Equilibrium phase diagrams were constructed using the latest activity–composition relations for metabasic (Green *et al.,* 2016) and pelitic assemblages (White *et al.,* 2014), indicating that the region was characterised by peak pressure–temperature conditions of ~7 kbar and 850°C. *In situ* sensitive high-resolution ion microprobe (SHRIMP) analysis was performed on monazite contained in four of the metasedimentary samples, revealing a complex history of crystallization from *ca.* 1870–1740 Ma. To interpret this dataset, follow-up laser ablation inductively coupled plasma mass spectrometry (LA–ICP–MS) raster mapping of a sub-set of the analysed monazite grains was applied to quantitatively determine the spatial variation in trace element signatures (with a pixel size of 4 μm, e.g. Fig. 1). These maps complement qualitative electron microprobe maps made of all grains prior to SHRIMP analysis. In tandem with the petrographic context of the monazite grains afforded by the *in situ* analysis, and the insights given by the phase equilibria models as to the modal history of influential trace element hosts such as garnet and plagioclase, the complex U–Pb dataset was effectively disentangled to provide temporal constraints on the prograde, peak, and retrograde evolution of Meta Incognita. The results highlight the usefulness of quantitative LA–ICP–MS mapping of monazite grains to interpret complex supra-solidus monazite behaviour in granulite facies terranes.

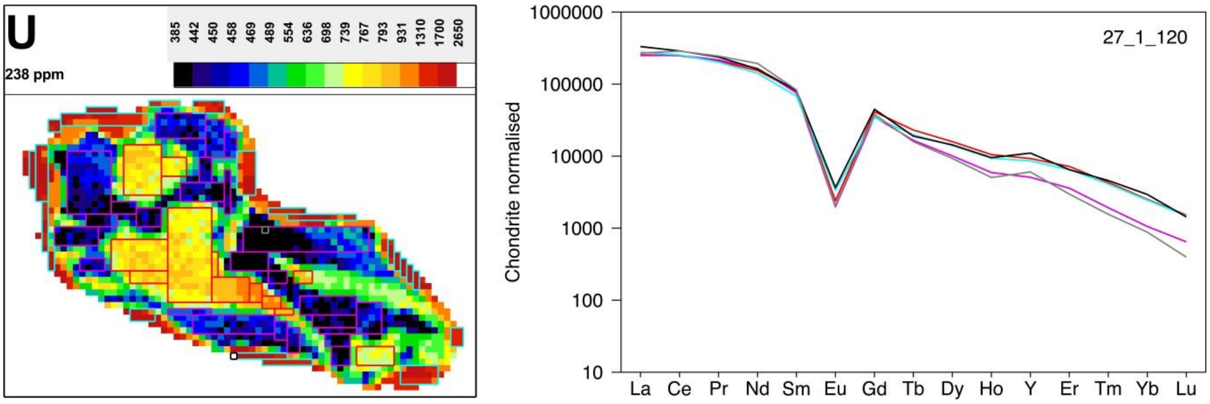

Fig. 1. An example of a LA–ICP–MS map of a monazite grain from a granulite-facies pelite from Meta Incognita exhibiting a complex crystallisation history. Pixel sizes are 4 μm for scale.

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Re-evaluation of *P–T* estimates and reaction textures in the In Ouzzal UHT terrane, northwestern Hoggar, Algeria, through mineral equilibrium modelling and calculated chemical potentials

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Mg–Al-rich orthopyroxene–sillimanite-bearing granulites from the In Hihaou locality of the In Ouzzal terrane of northwest Hoggar were previously determined to have experienced ultrahigh-temperature metamorphism at 1050 ºC and 10 kbar. Multi-layer corona and symplectite reaction textures that pervasively replace peak metamorphic porphyroblasts were interpreted to have formed by near-isothermal decompression during terrane exhumation. Pseudosection calculations using new and realistic activity–composition models revise near-peak estimates to 900 ± 20 ºC and 8 ± 0.5 kbar. Calculated chemical potential relations show that reaction textures formed due to very minor decompression at near-peak conditions, when the removal of intracrystalline melt led to the development of local equilibrium domains around the porphyroblasts. The growth of initial monomineralic coronas further isolated the porphyroblasts from the matrix, leading to the later development of the symplectites. These results indicate that the derivation and interpretation of UHT condition using the occurrence of diagnostic assemblages on classic petrogenetic grids can over-estimate temperatures by 150 ºC or more. Similarly, the interpretation of reaction textures to derive retrograde conditions and *P–T* paths without considering their spatial development is unlikely to be reliable, as textures do not typically form in this way and therefore do not routinely record this information.

Granites and crustal heat budget

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The origin of large I-type batholiths remains a disputed topic. One model (probably favored in the granulite and crustal melting community) states that I-type granites form by partial melting of older crustal lithologies (amphibolites or intermediate igneous rocks). On the other hand, the arc community regards granites as trapped rhyolitic liquids occurring at the end of fractionation trends defining a basalt–andesite–dacite–rhyolite series.

Field, petrological and geochemical evidence are ambiguous at best, and it is hard to find criteria that rule out either alternative. In this talk, I explore the thermal implications of both models. I build a heat balance model that abstracts the heat production and consumption during crustal melting. Heat is consumed by melting and by losses through the surface (conductive or advective, as a result of eruption). It is supplied as a basal conductive heat flux, as internal heat production, or as advective heat carried by an influx of hot basalt into the crust. In the latter case however, the basalts may differentiate into felsic liquids (granites) and therefore large amounts of “fractionated” granites will form, possibly volumetrically more important than intra-crustal melts.

Using this abstract approach, it is possible to explore the role different parameters have on the balance of granites formed by differentiation of basalts or by crustal melting. Two end-member situations appear equally favorable to generate large volumes of granites: (i) short-lived environments dominated by high basaltic flux. The mafic magmas carry important amounts of heat to the crust, but also generate large amounts of residual melts, that end up dominating the granite balance. These systems cannot be long-lived, as the high basaltic flux required cannot be sustained for long periods of time (the crust would be unrealistically thickened). (ii) long-lived systems with no or minimal basalt flux. These can be sustained for protracted periods of time, and radiogenic heat accumulation will promote crustal melting. The granites there are mostly crustal melts.

The two end-member situations correspond to arc (or bacK–Arc) and orogenic environments, and they echo the opposition between “long-lived” and “short lived” granulitic provinces (Kelsey & Hand 2015). They also reflect the two main sites in which granites can be formed on Earth.

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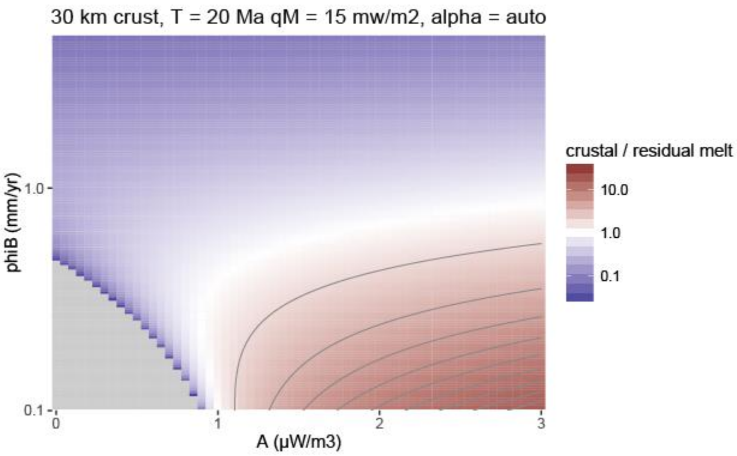

Figure 1: The balance of crustal melts vs. residual melts formed after 20 MYr of evolution of a 30 km thick crust with moderate basalt heat flux (15 mW/m²), as a function of the heat production (A, in µW/m³) and the basaltic influx (phiB, in mm of basalt per year). Two main regimes are evident, basalt-dominated for high phiB and melting dominated for high A and low to moderate phiB. The transition between the two regimes is sharp and does not allow much hybrid situations. Also note that 20 Myr of a basaltic flux of 1 mm/yr results in a 20 km thick layer of basalt, probably an extreme situation – basalt dominated systems are hard to sustain for long periods in a given crustal segment.

51st Hallimond Lecture
Time's arrow, time's cycle: Granulite metamorphism and geodynamics

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Metamorphism of crustal rocks is due to heat generated by radioactive decay and viscous dissipation, and the heat flux from the mantle. Earth's radiogenic heat production has declined by >75% since the Hadean and mantle potential temperature (T_P) has declined by ~200–300°C since *c.* 3.0 Ga. However, the ΔT_P at the start of mantle convection after crystallization of the last magma ocean is poorly constrained and the thermal evolution of the mantle until *c.* 3.0 Ga remains unclear. By contrast, the thermal history of the crust is preserved in the record of metamorphism. At the present day, different plate tectonic settings exhibit contrasts in heat flow that are registered as differing metamorphic facies series in distinct crustal terranes. However, how far back in time these relationships are reliable is unclear, the thermal effects of the formation and breakup of supercontinents are poorly characterized and the geodynamic regime operating in the Archean is controversial. Although reliable data are sparse before the Neoarchean, we use a dataset of temperature (T), pressure (P) and thermal gradient (T/P at the metamorphic 'peak'), and age of metamorphism (timing of the metamorphic 'peak') for 564 localities (~25% increase from the 456 localities used in Brown and Johnson, 2018) from the Cenozoic to the Eoarchean Eras to interrogate the crustal record of metamorphism as a proxy for the heat budget of the crust through time. Based on T/P, metamorphic rocks are classified into three natural groups: high dT/dP type (>775 °C/GPa, mean ~1105 °C/GPa), including common and UHT granulites, intermediate dT/dP type (775–375 °C/GPa, mean ~575 °C/GPa), including HP granulites and eclogites, and low dT/dP type (<375 °C/GPa, mean ~255 °C/GPa), including blueschists, low-T eclogites and UHP rocks. Plots of T, T/P and number of localities against age show that since *c.* 3.0 Ga cyclic variations in the heat budget of the crust have been superimposed on secular cooling.

A first cycle is marked by the widespread occurrence of two contrasting types of metamorphism—high dT/dP and intermediate dT/dP— in the rock record, associated with the amalgamation of dispersed blocks of lithosphere into protocontinents (supercratons) during the Mesoarchean–Neoarchean. Paired metamorphic belts with different heat budgets are characteristic of convergent plate margins and subduction of ocean lithosphere, suggesting the existence of a mobile lid tectonic regime. The transition to a second cycle is marked by the fragmentation of the protocontinents into cratons and their subsequent accretion into the supercontinent Columbia during the Paleoproterozoic. Moving means of both T and T/P of high dT/dP metamorphism exceed the arithmetic means of T and T/P during most of the Proterozoic, reflecting insulation of the mantle beneath the quasi-integrated lithosphere of Columbia and then, after a limited geographical reorganization, Rodinia. The start of the third cycle was synchronous with the breakup of Rodinia and the appearance of low dT/dP metamorphism in the rock record at the end of the Tonian, registering a change to deeper, colder subduction and the modern plate tectonic regime. Both T and T/P of high dT/dP metamorphism were relatively high from the Ediacaran to the Silurian, reflecting insulation of the mantle beneath Gondwana during the Pan-African thermal event before Gondwana sutured with Laurussia to form the short-lived Pangea. The decline in T and T/P of high dT/dP metamorphism from the Devonian to the Jurassic and the breakup of Pangea may indicate a transition to a fourth cycle.

The limited occurrence of high dT/dP metamorphism and absence of eclogite before the late Mesoarchean suggest that suitable tectonic environments to generate these types of metamorphism were not widely available before then. Stable subduction and the generation of a network of plate boundaries in a mobile-lid tectonics regime became possible after the balance between heat production and heat loss changed in favor of secular cooling, possibly as early as *c.* 3.0 Ga in some areas. Whether this was a globally linked system or remained continuous to the present is unknown. The Proterozoic was characterized by stability from the formation of Columbia to the breakup of Rodinia, generating higher than average T and T/P of high dT/dP metamorphism. The colder, deeper subduction characteristic of modern plate tectonics became possible once the ΔT_P of ambient mantle had decreased to <100 °C after *c.* 1.0 Ga.

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Ten years of research on nanogranitoids

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The discovery of crystallized melt inclusions in peritectic garnet from the granulites of the Kerala Khondalite Belt (Cesare et al., 2009) and the optimization of an experimental protocol for their rehomogenization to an analyzable glass (Bartoli et al., 2013) have opened new perspectives in crustal petrology by allowing direct measurement of the composition of anatectic melts.

Less than ten years after, nanogranitoids (after Cesare et al., 2015) are accepted by the petrological community as a valuable microstructural criterion to infer the partial melting of a rock, and as a tool for constraining *in situ* the chemical aspects of anatexis.

Although garnet is by far the most common host, melt inclusions have been observed in numerous other minerals, including e.g., zircon, ilmenite, and sapphirine.

Nanogranitoids, initially found and studied in metasedimentary migmatites from low- to medium-pressure terrains, have recently been discovered in mafic and ultramafic rocks (Ferrero et al., 2018), and are increasingly reported in metapelites and metabasites partially melted at HP and UHP conditions (Ferrero et al., 2015; Gao et al., 2017).

The composition of anatectic melts can be analyzed by a combination of EMP, LA–ICP–MS and (nano)SIMS techniques for a full characterization of major, traces and volatile elements. The spectrum of observed compositions is relatively large, and even if peraluminous leucogranites are the most common terms, tonalites and trachytes are also observed. Up to now, more mafic compositions have not been detected. In addition, systematic differences occur between samples (Bartoli et al., 2016), and also within the same sample (Acosta-Vigil et al., 2016).

The coexistence in the same array of nanogranitoids and fluid or multiphase inclusions allows to highlight the occurrence of fluid-melt imiscibility phenomena during anatexis. CO_2-rich inclusions trapped in garnet at UHT condidions appear to interact with the host on cooling, forming carbonates and metastable quartz + corundum (Tacchetto et al., 2018). The widespread occurrence of the metastable polymorphs kokchetavite ($KAlSi_3O_8$), kumdykolite ($NaAlSi_3O_8$) and cristobalite within inclusions appears to be an indication of preservation of the inclusions' content after entrapment (Ferrero et al., 2016).

In this presentation I will review the main outcomes of recent research on nanogranitoids, and highlight some of the possible directions for future studies.

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Nanogranitoids in orogenic peridotite and UHP eclogite of the Bohemian Massif

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Former melt inclusions have been identified in orogenic peridotite from two different localities of the Granulitgebirge and in UHP eclogite of the Erzgebirge, Bohemian Massif. In the Granulitgebirge the samples derive from single layers of garnet-clinopyroxenite enclosed in the orogenic peridotite. The inclusions, from 5-20 µm in diameter, occur in clusters in the inner part of the garnet and they are both polycrystalline, i.e. nanogranitoids, and glassy. When crystallized, the phases present are kumdykolite/albite, phlogopite, osumilite, kokchetavite and quartz as identified by Raman spectroscopy and EDS mapping. Microstructural and microchemical features suggest that they were former droplets of melt trapped while the garnet was growing as a peritectic phase along with clinopyroxene. Thus the melt is genetically connected with the formation of the whole pyroxenite. Nanogranitoids have been re-homogenized to a hydrous glass trondhjemitic to granitic in composition using a piston cylinder apparatus. The re-homogenization conditions are 1000-1050ºC and 22–15 kbar and correspond to those expected for the formation of the garnet and thus of melt entrapment. The melt is enriched in Li, B and in mantle incompatible elements as Cs, Rb, Ba and Pb and with negative anomalies in Nb, Ta and Sr. The trends are consistent with the involvement of a crustal component, i.e. white mica/phengite, in the melting producing reaction. The presence of a melt with a granitic composition in garnet clinopyroxenite enclosed in orogenic peridotite can be the results of two different scenarios: (1) localized partial melting of a phengite-bearing rock with the simultaneous production of melt, garnet and clinopyroxene or (2) infiltration of an external melt which generates the pyroxenite via metasomatic interaction with the peridotite.

The other case study involves a preliminary investigation of the UHP eclogite of the Erzgebirge. Those rocks occur in lenses and blocks in diamond-bearing gneisses. The inclusions, from 5–25 µm in diameter, occur in the inner part of the garnet and are polycrystalline but in some cases also with glass. The minerals present are biotite, quartz/cristobalite, white mica, kumdykolite/albite with varied amounts of kokchetavite, carbonate and graphite. The detailed study of those samples will allow us to better understand the processes related with the melt production in the continental crust at mantle depths and in general to better constrain the processes that involve melt and high grade mafic rocks in the Bohemian Massif.

Melt and fluid inclusions in metapelitic migmatites from Ivrea Zone: anatexis and fluid regime of a high-grade terrane

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Peritectic minerals form as result of incongruent melting reactions, and in some cases, they can trap droplets of the coexisting anatectic melt (Cesare et al. 2015) and of the fluid immiscible with it, if present. These inclusions provide the best window to investigate the starting composition of the anatectic melt and fluid regime during crustal melting (e.g. Bartoli et al., 2013).

The Ivrea Zone (IZ), NW Italy, is a section of mid to lower Permian crust. Metapelites of the Kinzigite Formation have experienced extensive partial melting and melt loss and can be divided in three main zones: i) metatexites with isolated leucosomes (upper amphibolite facies), ii) stromatic metatexites (transition zone), and iii) residual diatexites (granulite facies). According to Redler et al. (2012) *P–T* estimates vary from 3.5–6.5 kbar at 650°C to 10–12 kbar at 900°C.

In this study, we investigate the inclusions hosted in garnet from metapelitic migmatites of Val Strona di Omegna (IZ) to evaluate the composition of the anatectic melt and fluid regime of the migmatites throughout the three zones mentioned above. Inclusions have oval to negative crystal shapes, size from 2–10 μm and they are regularly distributed in the core of the garnet. Micro-Raman investigation has shown the presence of two types of inclusions: crystallized silicate melt inclusions (i.e. nanogranitoid inclusions, hereafter NI) and fluid inclusions (FI). Microstructural evidence suggests that FI and NI coexist in the same cluster and are primary (i.e. trapped simultaneously during garnet growth). Although FI are more abundant in metatexites from amphibolite facies, they are similar in the three zones and comprise CO_2, CH_4, N_2, commonly with siderite and pyrophyllite, and in a few cases calcite, magnesite, graphite and chlorite. Mineral assemblage in the NI is mainly composed of K-feldspar, plagioclase, quartz, biotite, muscovite, chlorite, graphite and, sometimes, calcite. Polymorphs such as kumdykolite, cristobalite, tridymite, and, less frequently, kokchetavite (e.g. Ferrero et al. 2016) were also found. In samples from transition zone and granulite facies, few NI also contain CO_2, N_2 and CH_4, and likely represent mixed inclusions of silicate melt and fluid.

Piston cylinder apparatus was used to re-homogenize NI from the different zones at 820°C, 850°C and 900°C, and 1.2 GPa. Preliminary data show that the melts are granitic, leucocratic and peraluminous but have slightly different compositions. In samples from the transition zone melts are more peraluminous (ASI ~1.1-1.9), have lower Na_2O/K_2O (0.14–0.42 wt. %), variable contents of H_2O (3–12 wt.%) and reach higher maficity (FeO + MgO = 2.3–3.9 wt.%). In contrast in the upper amphibolite facies, melts have higher Na_2O/K_2O (0.55-0.89 wt.%), are relatively less peraluminous (ASI = 1.08–1.28), less mafic (FeO + MgO = 2–2.7 wt.%) and contain 5–9 wt.% H_2O.

Our data suggests that anatexis of these metapelites occurred through muscovite and biotite melting but always in the presence of a COH fluid, possibly produced initially by devolatilization of hydrous silicates in the graphitic protolith (before amphibolite facies), then as result of oxidation of carbon after melting of Fe^{3+}-bearing biotite. Phases observed within the FI are interpreted as post-entrainment reaction between host garnet and a COH fluid during the cooling path of the migmatites.

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Zircon U–Pb dates in granulite facies rocks: decoupling from geochemistry above 850°C?

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Many granulite facies terranes show a large spread in their U–Pb zircon dates, raising the questions: Do the dates reflect real ages or several growth episodes? Or has the isotopic system been disturbed? By what process(es) and conditions did the alteration occur? Furthermore, under some circumstances of (ultra)high-temperature metamorphism, decoupling of zircon U–Pb dates from their trace element geochemistry has been reported. Understanding these processes is crucial to help interpret such dates in the context of the *P–T* history. Decoupling has been previously described, but only for zircon from Proterozoic rocks and was tentatively linked to Pb mobility during (U)HT metamorphism. The present study is the first work reporting decoupling in young (~280 Ma) non-metamict (average α-dose 0.4×10^{15} α/mg) zircon from a HT (>850°C) metamorphic terrain.

We present results from zircon from a continuous high-temperature metamorphic field gradient in the Ivrea Zone (NW Italy). These rocks represent a well-characterised segment of lower continental crust with an apparent protracted high-temperature history during the Permian. CL-images reveal that zircon in the mid amphibolite facies preserve mainly detrital cores with narrow overgrowths. In the upper amphibolite and granulite facies, preserved detrital cores decrease and metamorphic zircon increase in quantity. Across all samples we document a sequence of four rim generations based on textures. U–Pb dates, Th/U ratios and Ti-in-zircon concentrations show an essentially continuous evolution with increasing metamorphic grade, except in the samples from the granulite facies, which display significant scatter in age and chemistry.

We associate the observed decoupling of zircon systematics in high-grade non-metamict zircon with disturbance processes related to differences in behaviour of non-formula elements (i.e. Pb, Th, U, Ti) at high-temperature conditions, notably differences in compatibility within the crystal structure. However details of the process(es) that caused this disturbance remain uncertain; since lower grade samples were not affected, HT processes are inferred. Such decoupling hampers the ability to link and interpret the observed scatter in these data to different stages along the metamorphic evolution of the samples. Therefore it is important to study and understand the circumstances under which zircon ages are decoupled from their geochemistry.

Overprinting Metamorphic Events During Continental Collision: Insight From Geodynamic Modeling

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The development of numerical modeling methods has made it possible to compare pressure–temperature–time (*P*–*T*–*t*) paths retrieved from metamorphic rocks with those predicted by geodynamic models. Metamorphic rocks with high and intermediate thermal gradients (dT/dP) have been preserved in the rock record since the Eoarchean up to the present day, but most probably under different geodynamic regimes (Brown and Johnson, 2018). The modern style of continental collision creates thickened lithosphere with low and intermediate dT/dP metamorphism in the suture and orogen, and high dT/dP metamorphism in the orogenic hinterland. Some rocks that record intermediate dT/dP gradients preserve relict minerals indicating a previous (ultra)high-pressure metamorphic stage with low thermal gradients. Although it remains a petrological challenge to fully determine the tectonic events that led to such a two-stage *P*–*T*–*t* evolution, we may use geodynamic modeling to test how these overprinting metamorphic events might be developed. Based on the results of experiments using a 2D coupled petrological–thermomechanical tectono-magmatic numerical model, we propose one possible sequence of tectonic stages that will lead to overprinting metamorphic events along an orogenic *P*–*T*–*t* path. These stages include subduction and exhumation of the continental crust, following slab retreat that leads to extension and subsequent mantle melting. During the last stage the deeply subducted crustal material may be exhumed back to lower crustal depths, where it undergoes heating due to the proximity of the underlying melt-bearing mantle. Thus, the (ultra)high-pressure metamorphic rocks with pressures up to 4.5 GPa are overprinted by high-temperature metamorphism with temperatures up to 900 ºC. Overprinting metamorphic events generated along orogenic *P*–*T*–*t* paths have been reported from many Phanerozoic collisional orogens, such as the Variscan Bohemian Massif, the Triassic Dabie Shan, the Cenozoic north-west Himalaya, and some complexes in the Alps. By contrast, overprinting metamorphism of Archean rocks with intermediate and high thermal gradients is most probably connected with the formation and amalgamation of small protocontinental blocks in a stagnant-deformable lid tectono-magmatic regime (Sizova et al., 2017). Rocks formed at shallow depths may become involved in local crustal overturns, generating intermediate dT/dP metamorphism, before incorporation in partially molten lower crust, where the intermediate dT/dP metamorphic mineral assemblages were overprinted by granulite (or amphibolite) facies metamorphic mineral assemblages. Amalgamation of crustal blocks with granite–greenstone domains located above high-grade lower crust resulted in more frequent crustal overturns and finally formation of high-grade gneiss complexes composed of rocks showing several episodes of metamorphic overprinting. Typical natural examples of such high-grade grey gneiss complexes include the early Archean Itsaq gneiss complex of southern West Greenland and the Archean Lewisian Complex of NW Scotland.

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Performing process-oriented investigations involving mass transfer using Rcrust: a new phase equilibrium modelling tool

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Modern quantitative phase equilibria modelling allows the calculation of the stable phase assemblage of a rock system given its pressure, temperature and bulk composition. A new software tool (Rcrust) has been developed that allows the modelling of points in pressure–temperature–bulk composition space in which bulk compositional changes can be passed from point to point as the system evolves. This new methodology enables quantitative process-oriented investigation of the evolution of rocks. In this paper we describe the procedure for using this tool to model: 1) the control of the water content of a subsolidus system based on available pore space; 2) triggering of melt loss events when a critical melt volume threshold is exceeded, while allowing a portion of melt retention; 3) entrainment of crystals during segregation and ascent of granitic magmas from its source; 4) modification of the composition of granite magmas due to fractional crystallization and 5) progressive availability (through dissolution) of slow diffusing species and their control on the effective bulk composition of a system. These cases collectively illustrate thermodynamically constrained methods for modelling systems that involve mass transfer.

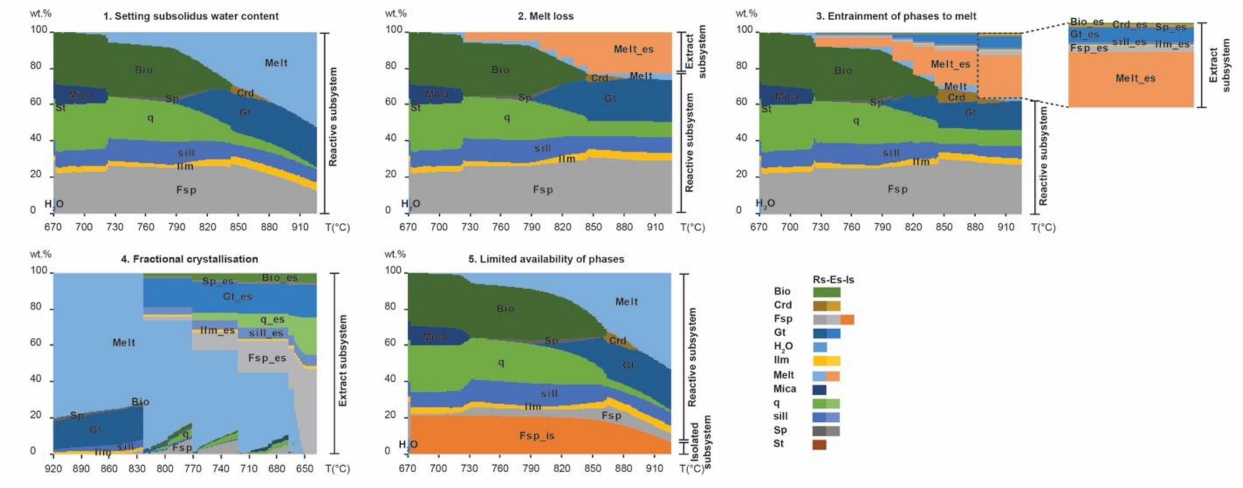

Fig. 1. Modelling examples for process-oriented investigations involving mass transfer. Paths (1-3,5) are isobaric heating paths from 640-920°C while path (4) is an isobaric cooling path from 920-650°C. (1) Setting of subsolidus water content by starting with excess water and then extracting all water that exceeds 0.1 vol.% (approximating a pore space. (2) Melt loss triggered when melt volume exceeds 7 vol.% and set to extract all melt except 1 vol.% (approximating melt retention on grain boundaries). Subsolidus water content is handled the same as in (1). (3) Entrainment of 30% of the increase in mass of all phases except melt between the current melt loss event and either the previous melt loss event or melt absent point (whichever is closer to the current event). Subsolidus water content handled as in (1) and melt loss as in (2). (4) Fractional crystallisation of the cumulative extract subsystem formed by (3) (representing a magma source), 90% of all solid phases (all phases except melt and H2O) are extracted whenever the cumulative solid phases exceed 20 vol.% of the reactive subsystem. (5) Limited availability of feldspar modelled by extracting 95% of all feldspar occurring in the reactive subsystem at the start of the heating path and then progressively reintroduced to the reactive subsystem as a function of melt volume (where mass of feldspar integrated in each step = 0.01 X ($melt_{vol.\%}$)^2).

Melting Controls on the Lutetium–Hafnium Evolution of Archaean Crust

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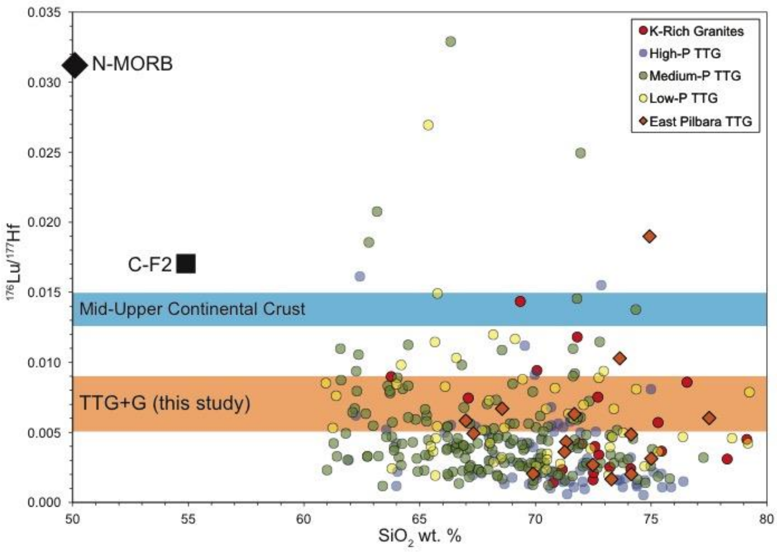
The lutetium–hafnium (Lu–Hf) isotope record, typically measured in zircon crystals, provides a major tool for the study of crustal growth and differentiation. Interpretations of Hf isotope datasets use an evolution array defined by source $^{176}Lu/^{177}Hf$. However, the very process that drives crustal differentiation to produce such arrays – partial melting – is precisely that which may modify the trajectory of the array due to variable degrees of anatexis allied with the differing compatibilities of Lu and Hf in residual minerals. Further, Lu/Hf estimates derived from the composition of present-day continental crust may be inappropriate for modelling Archaean crustal evolution, where different geodynamic styles and magmatic sources prevailed.

Using an approach combining phase equilibria, trace element and isotopic modelling, we quantify the effects of partial melting of an Archaean (C-F2) mafic source on melt Lu/Hf. Anatexis of C-F2 yields TTG melts with $^{176}Lu/^{177}Hf$ ~0.009 that are relatively unaffected by the degree of melting. Remelting TTG yields K-rich granitic melts with $^{176}Lu/^{177}Hf$ ~0.005. Thus, a partial melting event imposes a greater control on a crustal reservoir Lu/Hf than the degree of melting.

Archaean continental crust has a lower Lu/Hf than that of the average mid to upper continental crust, and a lower $^{176}Lu/^{177}Hf$ (here 0.005–0.009) is appropriate to modelling its isotopic evolution. There has been a secular change in average crustal Lu/Hf, with the median Lu/Hf of Proterozoic and Phanerozoic magmatic rocks being higher than that of Archaean TTG+G. An enriched Archaean mafic source (C-F2) with a Lu/Hf ratio of ~0.12 may produce TTG crust with a $^{176}Lu/^{177}Hf$ approaching that calculated in real rocks worldwide.



Plot of whole-rock SiO_2 versus calculated $^{176}Lu/^{177}Hf$ for TTG+G samples worldwide, and selected samples from the East Pilbara Terrane, Western Australia. Also plotted are the average C-F2 composition, and that for N-MORB. Annotated is the range of $^{176}Lu/^{177}Hf$ for the mid– to upper–continental crust (blue), and for TTG+G as calculated in this study (orange).

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Texturally-constrained SHRIMP U-Th-Pb Monazite Geochronology Reveals Two Paleoproterozoic UHT Episodes in the Khondalite Belt, North China Craton

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Sapphirine-bearing UHT granulites from the Dongpo locality in the Paleoproterozoic Khondalite Belt of the North China Craton have been well investigated on issues of petrology, mineral chemistry, metamorphic evolution and zircon geochronology. However, the precise ages of peak UHT metamorphism and other stages of the P–T–t evolution remain controversial because of the complexity of multiple metamorphic overprints and the lack of petrographic context for zircon age data. In this study, in-situ SHRIMP U–Th–Pb monazite dates for the Dongpo granulites can be divided into four age groups according to their petrographic settings. The oldest population of ca. 1.92 Ga was obtained from relic Y-high monazite cores that occur as inclusions in garnet and a grain associated with M1 spinel in the rock matrix, which is interpreted as the minimum age for the early stage of M1 (possibly UHT). A slightly younger age population at ca. 1.89 Ga yielded from Y-low monazite domains occurring in similar petrographic settings might reflect dissolution and recrystallization of the oldest monazite after substantial garnet crystallization during the late stage of M1. A ca. 1.87 Ga age population obtained from monazite grains associated with sapphirine + plagioclase or spinel + plagioclase intergrowths is interpreted as the age of peak M2 UHT metamorphism, and is older than the previous zircon dating result of ca. 1.85 Ga. The youngest ca. 1.78 Ga age group obtained from Th-rich irregular monazite rims, and a Th-poor grain associated with M3 matrix biotite, is interpreted as the age of fluid-assisted dissolution–reprecipitation and new monazite growth during retrogression, respectively. A lack of pronounced correlation between the apparent ages of the three oldest monazite populations and their Th contents indicates that the latest fluid-assisted alteration has not significantly modified these monazite domains. These results along with previous recognition of ca. 1.92 Ga UHT metamorphism suggest that there were two episodes of Paleoproterozoic UHT metamorphism in the Khondalite Belt, separated at least by 50 million years, both likely related to syn-extensional mafic magmatism during amalgamation of the North China Craton.

P–T-t evolution of the ~2.1 Ga granulitic Mistinibi Complex, South Eastern Churchill Province, Canada

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The South-Eastern Churchill Province (SECP), accreted in a transpressional regime during the Paleoproterozoic ~1900–1800 Ma Trans-Hudson Orogeny, is among the best exposed remnants of alleged transitional regime from Archean to modern tectonics. Determining its past thermal state is thus fundamental in understanding the secular evolution of tectonics. Bordered to the West by the Superior Craton and to the East by the North Atlantic Craton, the SECP is the result of successive oblique collisions between the Core Zone (CZ), a ribbon-like terrane of mixed reworked Archean and juvenile affinity, and the North Atlantic and Superior margins. Located within the Core Zone *sensu lato*, the Mistinibi Complex, composed of early paleoproterozoic supracrustal sequences, is affected by a widespread granulite-facies metamorphism, and bounded by crustal-scale ductile shear zones. We present the results of an integrated approach applied to supracrustal rocks, coupling petrography, phase equilibria modelling and petrochronology on paired metasediments and mafic protoliths, expected to have recorded complementary segments of a common pressure-temperature-time path. Results indicate a clockwise metamorphic path involving significant melt extraction in the metasedimentary protolith, followed by isobaric cooling from >815°C to ~770°C at ~8 kbar. The timing of prograde burial is revealed by garnet Lu–Hf and monazite and zircon U–Pb geochronology at 2150–2120 Ma , whereas cooling from supra- to subsolidus conditions is constrained with zircon overgrowth and monazite U–Pb geochronology at ca. 2070–2080 Ma. These results highlight a long-lived residency at mid-crustal supra-solidus conditions (>40 Ma), with preserved prograde, peak and retrograde suprasolidus monazite and zircon. LA–ICP–MS maps on garnet, zircon and monazite are in progress to investigate trace elements behaviour during anatexis. The Mistinibi Complex did not record any significant metamorphism after 2070 Ma, despite being surrounded by terranes that did record high-grade metamorphism during the gigantic ~1900-1800 Ma Trans-Hudson orogeny.

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Lewisian crustal evolution – six decades of dating and peering through the metamorphic fog

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In large part a result of its relative accessibility, the late Archean Lewisian Complex of northwest Scotland has long provided a natural laboratory for understanding the processes involved in crustal growth and reworking using geochronology and isotope geochemistry. Building on the framework provided by the pioneering geological survey mapping (Peach et al. 1907) and the subsequent development of the Scourie dyke-based relative chronology (Sutton and Watson, 1951), early K–Ar dating hinted at the antiquity of the complex (Holmes et al., 1955), albeit plagued by inaccuracies inherent in the methodology. Application of the Rb–Sr method (Gilletti, 1959) first revealed a reliable early Precambrian age for the complex, initiating six decades of isotope investigations, closely following technological developments, that have contributed to our increasing understanding of crustal processes, both in the Lewisian and comparable regions. Broadly speaking, this period may be divided into the "bulk rock isotope/population U–Pb zircon" period, which were the only methods available until the mid- 1980's and the subsequent "single zircon/in situ" period, which has become the standard for crustal evolution studies over the past three decades. In the specific context of this meeting, granulites in the commonly called "central region" of the Lewisian have presented both a dating objective in their own right as well as a hindrance to understanding pre-metamorphic history, a situation that is mirrored in many terranes worldwide.

This presentation will review the progress made during these six decades, as well as a few of the controversies that have arisen, some resolved, some still outstanding. Amongst the many issues remaining to be resolved are: (1) the protolith ages of Lewisian TTG gneisses across the complex and the character of their mantle source; (2) the age(s) of the major layered mafic intrusions and their relationship (if any) to high-grade metamorphism; (3) the timing and number of high-grade metamorphic episodes in the late Archean and their relationship to each other (if any); (4) whether the Lewisian "terrane model" describes a true collage of juxtaposed, independent crustal entities, reflects instead differences in crustal level, or contains some aspects of both; (5) the relationship between the mainland Lewisian and the relatively understudied, but equally intriguing, Inner and Outer Hebridean outcrops. This review will be made against the backdrop of modern and rapidly evolving models for crustal growth processes in the late Archean, a time that is now generally considered to represent a transition in tectonic style from crustal-lid/vertical tectonics of the early Archean towards modern horizontal plate-boundary interactions akin to present day plate tectonics.

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Unravelling the Lewisian with split stream geochronology

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Archean geodynamic interpretations can be a controversial topic, often exacerbated by complex, highly deformed field relationships. This problem can be compounded by confusing and prolonged geochronological records, in which multiple episodes of intrusive and metamorphic events are justaposed. The Lewisian Gneiss Complex (LGC) is a classic example in this regard, recording a billion years of Archean zircon ages, followed by significant retrogression and U–Pb disturbance through the Proterozoic. As a result there are many interpretations as to the nature of the geodynamic processes at work in the LGC, often with the same field evidence being used to substantiate apparently disparate models.

The Archean rocks of the LGC comprise tonalite-trondhjemite-granodiorite (TTG) gneiss, interspersed with mafic-ultramafic bodies and felsic sheets, all crosscut by the Scourie dykes. In some areas there are metasedimentary sequences comprising grt-bt gneiss and ky-crn-st schists. The smear of U–Pb ages through these rocks has compromised detailed interpretations of the igneous and metamorphic history.

K-feldspar rich felsic sheet (foreground) associated with mafic–ultramafic rocks and TTG gneiss (background) on the north side of Scouriemore in the LGC.

The recent advent of Laser Ablation Split Stream (LASS) petrochronology, along with advances in our ability to relate zircon ages to discrete metamorphic events is key to deciphering the processes at work in the Archean. Zircon from TTG gneisses and associated felsic sheets display a marked contrast in trace element signatures, defining discrete processes within the smear of Archean U–Pb ages. Emplacement of the TTG suites between 2850–2750 Ma is followed by a distinct suite of felsic sheets intruded at *c.* 2600 Ma. The trace elements associated with these felsic intrusions suggest melting of a distinctive source that could be the associated, grt-bearing mafic rocks. This may represent the foundering of an early mafic crust into the underlying TTG suite, all of which were subsequently exposed to high T during the *c.* 2550 Ma event.

New zircon data from the Lewisian mafic gneisses and leucosomes – the terrane model re-revisited?

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The mainland Lewisian complex in NW Scotland is a portion of Archaean crust consisting mostly of TTG gneiss with less abundant metamafic and metasedimentary rocks. The complex has historically been subdivided into a northern and southern region marked by amphibolite facies metamorphism and a central region that preserves in many places granulite facies assemblages and ubiquitous evidence for partial melting. In the last two decades, geochronological studies have been used to propose that the Lewisian is actually comprised of distinct tectonic terranes. The most controversial of these divisions is probably the split of the central region into the Assynt (northern part) and the Gruinard (souther part) terranes.

We present new isotope and trace element data of zircons obtained from mafic migmatites in the central region, specifically from partially melted mafic gneisses, their leucosomes and dm- to m-scale felsic sheets cross-cutting the gneisses. Three localities were sampled: two in the postulated Assynt terrane and one in the Gruinard terrane. U–Pb zircon ages in many samples show smears along concordia, typical for the Lewisian complex. The observation of constant Hf isotopic composition in zircons from within one sample (and indeed across all localities) leads us to interpret this smear as a result of variable Pb loss. Nevertheless, reasonably reliable ages can be obtained from several zircon populations, showing protolith ages for mafic gneisses of ca 2.85 Ga, as well as protolith ages >3 Ga previously unknown to these locations. Furthermore, two metamorphic events can be identified at ca 2.8–2.7 Ga and ca 2.5 Ga. Importantly, these findings are applicable to both the purported Assynt and Gruinard terranes and indicate that the geochronology-based subdivision of the Lewisian complex into separate terranes is equivocal.

The terrane model was based largely on data from TTG, i.e. metamorphic felsic plutonic rocks. Our new data show that eliminating complications inherent to felsic plutonic rocks (inheritance, pooling, mixing and hybridisation of melts from multiple sources) and focussing on mafic rocks and their *in source* partial melts may provide a less complicated approach to investigating the tectonothermal histories of polymetamorphic high-grade terrains.

Rare-metal pegmatites: mineralisation related to high-grade metamorphism and crustal melting

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Rare-metal pegmatites are pegmatites of granitic composition that host a range of rare minerals, often of economic interest, such as beryl, spodumene, and columbite–tantalite (coltan). They may also contain gemstones. Such pegmatites can represent important sources of a number of 'critical raw materials', including lithium (vital for batteries in electric cars), tantalum for capacitors, and beryllium for alloys. A large proportion of the world's supply of tantalum, as well as lithium, comes from the Greenbushes and Wodgina pegmatites in Australia, and from pegmatites in DR Congo.

The 'classic model' for pegmatite formation is based on the concept that pegmatites represent very highly fractionated melts derived from granitic magmas, with their compositions reflecting those of the parental granites (Černý et al., 2012). In this model, a granitic batholith is surrounded by zoned pegmatite swarms, with the most rare-metal enriched pegmatites at the greatest distance from the granite. An alternative view is that rare-metal pegmatites are formed by localised crustal anatexis in areas of high-grade metamorphism and crustal melting, and thus their composition reflects the crust available to melt, rather than any parental granite (Müller et al., 2017).

Our work in NW Scotland (Shaw et al., 2016) shows that crustal anatexis and pegmatite formation occurred throughout the Lewisian Gneiss Complex during the Palaeoproterozoic, towards the end of the Laxfordian (amphibolite-facies) metamorphism. In areas dominated by TTG gneisses, the pegmatites are 'barren', containing biotite and magnetite but no evidence of rare metals. However, rare-metal pegmatites do occur within the Harris Granulite Belt, which comprises metasedimentary and meta-igneous lithologies. This belt was metamorphosed to granulite facies at c. 1900 Ma, but was subsequently retrogressed and rehydrated, allowing melting and rare-metal pegmatite formation some 200 Myr later. The spatial association between rare-metal pegmatites, and retrogressed granulite-facies supracrustal rocks, is striking, and consistent with a crustal anatexis hypothesis.

Under the crustal anatexis hypothesis, an understanding of the metamorphic and melting history of the host rocks could become a crucial part of any exploration model for rare-metal pegmatites. Across Africa, rare-metal pegmatites are dominantly found in greenstone belts within Archaean cratons, and in mobile belts around the craton margins. This talk will highlight some examples and introduce ideas for future work on the genesis of these important mineral resources.

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Experimental Constraints on Metamorphic Pressures in the Lewisian Complex

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Establishing the pressure-temperature (*P–T*) conditions under which the Earth's early continental crust formed has proved to be a long and difficult exercise. This is partly this is because chemical diffusion rates in the major rock-forming minerals are sufficiently fast at high temperatures to ensure that "peak" *P–T* conditions are not recorded in the phase chemistry. This means that many of the commonly used thermobarometers are inapplicable to high-temperature rocks that saw slow cooling from their peak metamorphic conditions. If classical, mineral chemistry-based thermobarometry is ineffective under these conditions there are two alternative techniques that can be employed. One is the use of bulk-rock compositions to construct rock-specific phase diagrams (pseudosections) that allow correlation between observed and calculated phase proportions which are generally expected to show little change during cooling from peak *P–T* conditions. The other is the application of experimental data that enable the direct identification of likely mineral assemblages, for rocks of known compositions, at a variety of pressures and temperatures.

Here we aim to combine experimental data with pseudosection analysis to constrain the pressures of metamorphism for the Badcallian metamorphism of the Scourian granulite-facies gneisses of the Scottish Lewisian Complex. Part of the rationale for this was that published estimates for maximum pressures have ranged widely from 10 to 20 kbar.

We studied the major rock type present in the Scourian sequence – a pyroxene-bearing tonalitic gneiss. As there is no unmetamorphosed equivalent rock present in the Scourian we worked with two amphibolite-facies tonalitic gneisses from the immediately adjacent Laxfordian terrane. One of these is a biotite tonalite and the other a hornblende tonalite. Using rocks from the amphibolite-facies part of the Lewisian terrane enabled us to identify what kinds of melts and mineral assemblages were formed during heating granulite-facies conditions.

Experimental data from both tonalites show that melting begins at 800 ^{o}C. However, garnet is only present in the restite at pressures above 10 kbar in the hornblende tonalite and above 8 kbar in the biotite tonalite. These are important results because neither garnet nor its retrograde products are present in the granulite-facies tonalites of the Scourian terrane. The experimental results therefore imply that peak granulite-facies metamorphism of these gneisses must have occurred at a pressure <10 kbar. Recent data suggesting significantly higher pressures from mafic units within the Scourian terrane are difficult to reconcile with these data. This may imply post metamorphic imbrication of mafic and felsic units.

These experimental data for the felsic rocks have been investigated by forward modeling starting materials using THERMOCALC and recently parameterised activity–composition relations for investigation of subsolidus and suprasolidus phase relations in intermediate and mafic rocks. We will demonstrate that these calculations support a peak metamorphic pressure for the tonalites of the Scourian terrane of < ca 10 kbar.

Ti-in-quartz thermometry on ultrahigh-temperature granulite xenoliths from kimberlites of the Kaapvaal Craton, South Africa

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South African kimberlites are known to contain xenoliths of lower crustal origin, but few studies have been conducted on these as previous xenolith sampling and research focused on mantle material. An examination of deep-crustal xenoliths from various kimberlite mines on the Archaean Kaapvaal Craton revealed that, while there are differences in rock associations, granulite-facies rocks are widespread. At several locations ultrahigh-temperature material is found, which includes the Lace mine, one of the locations where UHT conditions were originally identified (Dawson et al., 1997). These occurrences are of particular interest to understand the tectonic and thermal evolution of the Kaapvaal Craton since surface exposures of high-grade metamorphic rocks in this ancient segment of crust are limited to very few locations.

With the exception of mafic granulites, the mineral assemblages of the highest-grade rocks typically contain sapphirine and/or spinel, both in quartz-rich rocks. Host-inclusion relationships and reaction textures present in these granulites mostly document near-isobaric cooling from the UHT part of the sillimanite stability field into the kyanite field. The samples discussed here contain the assemblage garnet-sillimanite-mesoperthite-quartz-rutile, with sapphirine and spinel as inclusions in garnet. An inherent problem with these rocks, just as with UHT granulites in general, is the retrieval of peak temperatures due to the retrograde modification of mineral assemblages and mineral compositions.

One particular cooling-related texture we focused on is distributed rutile being present in all the quartz grains. Rutile forms a regular distribution pattern of very thin needles. These are arranged in three sets with 60° angles between each other, evidently related to the crystal structure of the host quartz. The regular triangular pattern is visible where the viewing direction under the microscope is along the quartz c-axis. The crystallographic relationship between the two minerals suggests unmixing of TiO_2 from high-temperature, Ti-rich quartz during slow cooling. Similar rutile textures are also observed in garnets of the same samples. There is also abundant, coarser-grained rutile in the matrix, which provided conditions of TiO_2-saturation during metamorphism.

The retrieval of peak- or near-peak-metamorphic temperatures using the Ti-in-quartz thermometer (Wark & Watson, 2006, Thomas et al., 2010) requires a re-integration of the TiO_2 precipitate with the quartz host. A sensible way to do this would be to get bulk analyses of the quartz grains plus the rutile. We analysed otherwise inclusion-free domains of quartz with Laser-Ablation ICP–MS, maximising the analysed volume by using a large-radius laser beam. The resulting Ti trace element levels of the "reconstituted" quartz are indeed in line with the UHT conditions recorded by the mineral assemblages and also other thermometers. Hence, this method allows to apply the TitaniQ thermometer where granulites have experienced significant retrograde overprinting, provided that the unmixing is regular on a small enough length scale and quartz did not recrystallize under post-peak conditions.

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Anatexis of accretionary wedge and formation of vertically stratified continental crust in the Altai Orogenic Belt, central Asia

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Pacific-type convergent margins are characterized by giant accretionary wedges formed by scraping off oceanic sediments from the subducting plate (Cawood et al., 2009). It has been proposed that anatexis of these fertile sediments could produce voluminous granitic magmas and stabilize the accretionary wedge (Brown, 2010), but no details regarding the exact mechanism of crustal differentiation and formation of mature continental crust were given. In this work, granitoid magmatism and its role in differentiation and stabilization of the Paleozoic accretionary wedge in the Chinese Altai were evaluated. Voluminous Silurian–Devonian granitoids intruded a greywacke-dominated Ordovician sedimentary succession (the Habahe Group) of the accretionary wedge. The close temporal and spatial relationship between the regional anatexis and the formation of granitoids, as well as their geochemical similarities including rather un-evolved Nd isotopic signatures and the strong enrichment of Large Ion Lithophile Elements (LILE) relative to many of the High Field Strength Elements (HFSE), may indicate that the granitoids are product of partial melting of the accretionary wedge rocks. Whole-rock geochemistry and pseudosection modeling show that regional anatexis of fertile sediments could have produced a large amount of melts compositionally similar to the granitoids. Such process could have left a high-density garnet- and/or garnet–pyroxene granulite residue in the deep crust, which can be the major reason for the gravity high over the Chinese Altai. Our results show that melting and crustal differentiation can transform accretionary wedge sediments into vertically stratified and stable continental crust (Jiang et al., 2016). This may be a key mechanism contributing to the peripheral continental growth worldwide.

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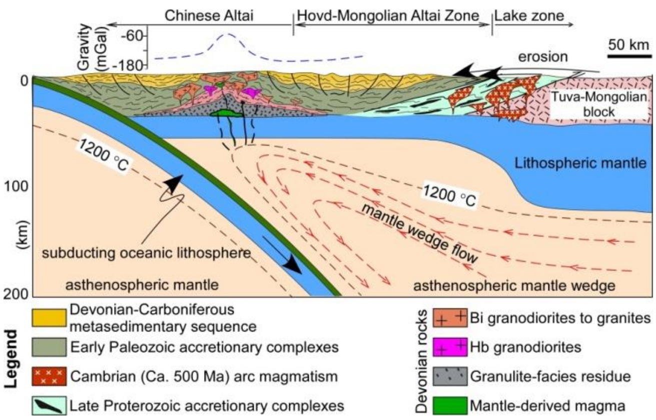

Tectonic interpretation for the generation of voluminous Silurian–Devonian granitoids and the formation of differentiated crust in the Chinese Altai due to lithosphere thinning and asthenosphere upwelling (modified after *Collins,* 2002*, Hyndman et al.*, 2005). Idealized gravity profile on the Chinese Altai and Hovd-Mongolian Altai regions shows nature of gravity anomalies related to deep structure of partially molten wedge.

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The carbonate-bearing source for the granite magmas in the Southern Marginal Zone of the Limpopo granulite complex, South Africa: study of melt inclusions in garnet

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Recent findings of coexisting carbonate-bearing and "nano-granitic" polyphase inclusions in garnets of migmatites gave implications on joint generation of carbonatitic and granitic melts via crustal anataxis of the heterogeneous carbonate-bearing source during high-grade metamorphism [1]. We present a study of the carbonate-bearing polyphase inclusions in garnets from granites intruding the Southern Marginal Zone (SMZ) of the Neoarchean (2.72-2.62 Ga) Limpopo granulite complex, South Africa. The ternary feldspar thermometry suggests the granite generation at 870–950°C, whereas abundant CO_2 fluid inclusions imply an essentially carbonic composition of the accompanying fluid. Cores of grains of almandine-rich garnet contain polyphase carbonate-bearing inclusions of 8–20 μm in size with a distinct negative crystal shapes, typical for melt inclusions. In contrast to the inclusions reported in [1], these inclusions contain (Mg, Fe)CO_3 with X_{Mg} = 0.24 - 0.78 (Fig. 1); Ca-bearing carbonates are rare. A common silicate component of the inclusions is Fe–Mg-bearing pyrophyllite (Fig. 1). Some inclusions contain rutile, Zn-spinel, zircon, ZnS. Raman spectra of unexposed inclusions revealed CO_2, CH_4 and liquid H_2O. Carbonate-silicate inclusions coexist with larger (50–400 μm) polyphase inclusions composed of biotite, quartz, K-feldspar, plagioclase, sillimanite, chlorite, which are irregular in shape and surrounded by cracks. Compositional trends between the carbonate-silicate and silicate inclusion show positive correlation of SiO + Al_2O_3 with alkalis and negative correlation with MgO + FeO.

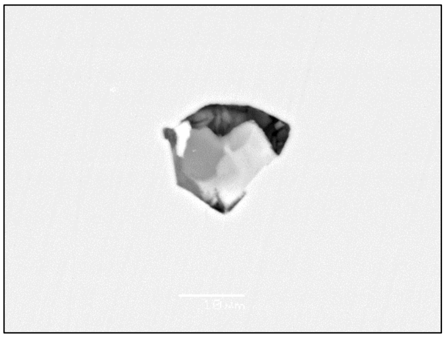

Fig. 1. An example of the polyphase inclusions in garnet, consisting of zoned Mg-Fe-carbonate (white to gray), pyrophyllite (dark gray), rutile (bright white).

Inclusions of the fluidized carbonate-silicate melts in garnets of the granites of the SMZ suggest a carbonate-bearing source for the granite magmas. This could be metamorphosed green-stone belt sequences of the Kaapvaal craton buried under the SMZ granulites during the Limpopo exhumation at 2.69–2.62 Ga. Depletion of the inclusions in Ca and enrichment in Mg, Fe and Al, as well as composition of host garnets allow assumption that two-mica metapelites intercalated with carbonate rocks could serve as the source. Anatexis of this source produced small portions of carbonatitic melts, which were subsequently dispersed in the voluminous granite melts.

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Fast eclogite-granulite metamorphism in the Usagaran Belt in the Palaeoproterozoic

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The initiation of modern-style subduction on Earth has been the focus of considerable work. From a metamorphic standpoint, the occurrence of eclogites, blueschists and paired metamorphic belts have been used as indicators for modern-style subduction (Brown, 2006). Rocks that record these types of cool thermal gradients (~400°C/GPa) are rare in the geological record before ca. 1500 Ma (O'Brian and Rötzler, 2003). While this is likely due to the Earth's inability to create these thermal regimes by modern-style subduction, it is also a probably a preservational issue.

The Usagaran Belt in central Tanzania preserves a high-pressure Palaeoproterozoic (c. 2 Ga) mafic and pelitic rock system. These rocks have been interpreted as having experienced eclogite-facies conditions followed by granulite metamorphism during exhumation (Möller et al., 1995). Similar aged low-pressure granulites in an adjacent belt (Ring et al., 1997) suggest the existence of an ancient paired metamorphic system. The Usagaran Belt therefore may be a marker for early modern-style subduction on Earth.

Retrogressed eclogite facies rocks are preserved in low strain domains that range from meter to kilometres in scale, and are enclosed by highly strained migmatitic mylonitic mafic and metapelitic rocks. In the low strain domains, mafic rocks contain garnet–clinopyroxene–quartz–rutile and are overprinted by orthopyroxene-clinopyroxene-plagioclase-hornblende-ilmenite assemblages. This transition is accompanied by conversion of a precursor Na-bearing clinopyroxene to diopside. However despite the near complete destruction of the original Na-bearing clinopyroxene, the low-strain nature of the assemblages means the original garnet abundance can still be readily determined. Taking garnet mode and composition into account, combined with whole rock geochemistry allows an original clinopyroxene composition of jd = 0.31, di = 0.38, hd = 0.31 to be estimated. Mineral equilibria modelling suggests the original garnet–Na-clinopyroxene–rutile–quartz assemblage formed at ~1.8 GPa and 750°C. Near isothermal pressure decrease resulted in the formation of orthopyroxene-bearing granulite assemblages at pressures <1.2 GPa. Hornblende occurs as inclusion in garnet, and also in the matrix granulite assemblage, suggesting a fluid phase was present during much of the high-temperature history.

A notable feature of garnet in mafic and metapelitic low strain rocks is the preservation of prograde zoning in Mn (spss 0.09 to 0.01) and Mg (py 0.12 to 0.25) in grains in excess of 1 mm. This, along with geochronology (Collins et al., 2004), indicates that the high-temperature eclogite to granulite metamorphism must have occurred on very short (<8 Ma) timescales. The structurally enclosing pelitic rocks have the comparatively rare assemblage garnet–kyanite–quartz–plagioclase–rutile–biotite–hornblende ± sillimanite, which formed at ~0.7 GPa and 700°C. However in these rocks, zoning profiles in garnets significantly larger (up to 1cm) than those in the retrogressed eclogites do not preserve prograde major element zoning. This suggests the enclosing rocks experienced a different temperature-time history to the retrogressed eclogites.

We suggest this difference in temperature-time histories reflects mixing of material in a ca. 2.0 Ga subduction channel. The retrogressed eclogites experienced rapid deep burial and partial exhumation, and mixed with migmatitic rocks that had either never been deeply buried, or had resided in the channel for long enough to obliterate their high-pressure history. This is akin to subducted high-pressure rocks in Phanerozoic oceanic systems which are exhumed and mixed with rocks of different *P–T–t* history within serpentine-filled subduction channels prior to their final exhumation.

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P–T-t evolution of the ~2.1 Ga granulitic Mistinibi Complex, South Eastern Churchill Province, Canada

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The South-Eastern Churchill Province (SECP), accreted in a transpressional regime during the Paleoproterozoic ~1900–1800 Ma Trans-Hudson Orogeny, is among the best exposed remnants of alleged transitional regime from Archean to modern tectonics. Determining its past thermal state is thus fundamental in understanding the secular evolution of tectonics. Bordered to the West by the Superior Craton and to the East by the North Atlantic Craton, the SECP is the result of successive oblique collisions between the Core Zone (CZ), a ribbon-like terrane of mixed reworked Archean and juvenile affinity, and the North Atlantic and Superior margins. Located within the Core Zone *sensu lato*, the Mistinibi Complex, composed of early paleoproterozoic supracrustal sequences, is affected by a widespread granulite-facies metamorphism, and bounded by crustal-scale ductile shear zones. We present the results of an integrated approach applied to supracrustal rocks, coupling petrography, phase equilibria modelling and petrochronology on paired metasediments and mafic protoliths, expected to have recorded complementary segments of a common pressure-temperature-time path. Results indicate a clockwise metamorphic path involving significant melt extraction in the metasedimentary protolith, followed by isobaric cooling from >815°C to ~770°C at ~8 kbar. The timing of prograde burial is revealed by garnet Lu–Hf and monazite and zircon U–Pb geochronology at 2150–2120 Ma , whereas cooling from supra- to subsolidus conditions is constrained with zircon overgrowth and monazite U–Pb geochronology at ca. 2070–2080 Ma. These results highlight a long-lived residency at mid-crustal supra-solidus conditions (>40 Ma), with preserved prograde, peak and retrograde suprasolidus monazite and zircon. LA–ICP–MS maps on garnet, zircon and monazite are in progress to investigate trace elements behaviour during anatexis. The Mistinibi Complex did not record any significant metamorphism after 2070 Ma, despite being surrounded by terranes that did record high-grade metamorphism during the gigantic ~1900–1800 Ma Trans-Hudson orogeny.

Petrology and *P–T* history of the Granja Granulitic Complex (NW Ceará, Brazil)

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The Granja Granulitic Complex (GGC) constitutes a NE-SW trending high-grade metamorphic belt in the northwestern sector of the Médio Coreaú Domain (NE Brazil). It represents a segment of the Paleoproterozoic basement intensely reworked during the Brasiliano / Pan-African Orogeny (≈ 600 Ma) which involved the collision of the Congo-São Francisco and São Luís-West African cratons during the amalgamation of the West Gondwanan Supercontinent.

In the GGC, the dominant lithological types can be grouped into two major units: (1) pelitic to semi-pelitic paragneisses and (2) igneous-derived mafic and intermediate granulites. The stromatic layering, defined by the intercalation of light quartzo-feldspathic bands (leucosomes) within the darker metasedimentary / meta-igneous layers (mesosomes), is the most penetrative structure in both units.

During the Brasiliano Orogeny, the rocks of the GGC were affected by four metamorphic events (M_1, M_2, M_3 and M_4), roughly coincident with the D_1, D_2, D_3 and D_4 Brasiliano deformation phases: a prograde metamorphic stage (M_1), a peak-metamorphic stage (M_2), a post-peak decompression stage (M_3) and a retrograde cooling stage (M_4).

In the pelitic sequence, the M_1 prograde assemblage is represented by inclusions of sillimanite, biotite, quartz, plagioclase, ilmenite and rutile within M_2 garnet neoblasts. The occurrence of very thin leucosomes folded by D_2 suggests that partial melting conditions may have been reached during M_1 through the muscovite dehydration reaction. Following the relict M_1 event, a M_2 peak-metamorphic paragenesis composed of Grt + Sil + Bt + Qz + Plg + Kfs was developed as a result of the fluid-absent incongruent melting reaction of biotite: Bt + Sil + Plg + Qz ⇒ Grt + Kfs + melt. The M_3 metamorphic decompression stage is marked by the first appearance of cordierite. This episode occurred in the sillimanite stability field and was controlled by the reaction: Bt + Sil ⇒ Grt + Crd + melt. Finally, the reaction textures related to the last metamorphic stage (M_4) appear to reflect a cooling history involving the reversal of the last two reactions, during which the melts produced during M_2 and M_3 crystallized and late stage biotite and sillimanite were formed.

The metabasites show a similar metamorphic evolution path. In these lithologies, the metamorphic peak was also reached during M_2, through the hornblende dehydration reaction (at approximately 10 kbar): Hbl + Plg + Qz ⇒ Cpx ± Grt ± Opx + melt, as revealed by the presence of peritectic garnet, clinopyroxene and orthopyroxene in their mineral assemblages. M_2 was followed by a high-temperature decompression stage (M_3), documented by the development of orthopyroxene + plagioclase symplectites around the peritectic phases. During M_4, the rocks cooled and crossed the incongruent melting reactions in the opposite sense, allowing the crystallization of the melts generated in the previous stages. The proposed metamorphic evolutionary path for the GGC rocks is illustrated in Figure 1.

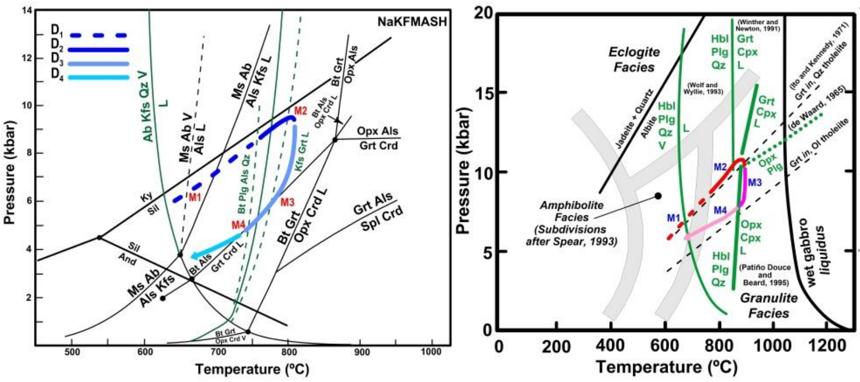

Fig. 1. Metamorphic evolution of the Granja granulites: (a) metapelites; (b) metabasites.

New studies on the Neoproterozoic Grenvillian granulites from the Oaxacan Complex (southern Mexico)

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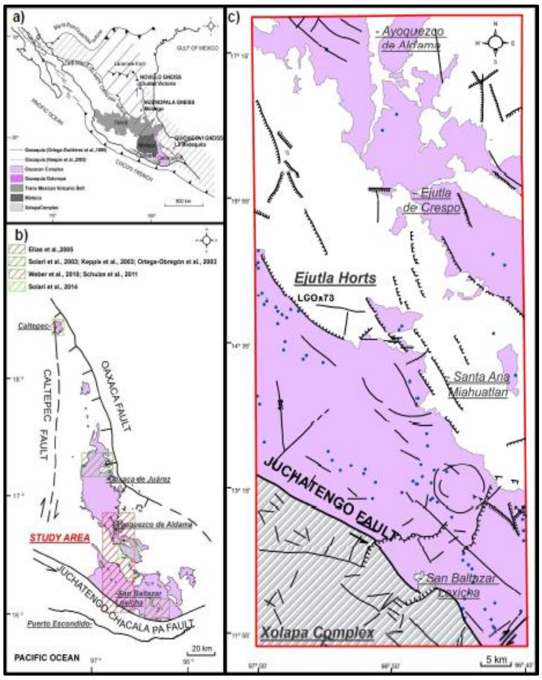

Figure 1: a) Location map of Mexico with main geological features and the proposed extension of the Oaxaquia microcontinent according to Ortega Gutiérrez et al., 1995 and Keppie et al., 2003. The four exposures of Grenvillian age granulite-facies metamorphic rocks in eastern and southern Mexico are the Novillo Gneiss, Huiznopala Gneiss, Oaxacan Complex, and Guichicovi Gneiss. b) Oaxacan Complex of southern Mexico where different studied areas are represented: Elías et al., 2005; Solari et al., 2003; Keppie et al., 2003; Ortega-Obregón et al., 2003; Weber et al., 2010; Schulze et al., 2001 and Solari et al., 2014. The study area is in red line pattern. c) Simplified geological map of the study area located between Ayoquezco de Aldama and San Baltazar Loxicha with sample locations in blue circles. Modified from 1:25.000 geological maps of Ejutla de Crespo E1412 (SGM, 2010); San Baltazar Loxicha E14D89 (SGM, 2012) and 1:25.000 geological map of Zaachila E1412 (SGM, 2000).

Eastern Mexico is made up of Grenvillian age granulite-facies metamorphic rocks which together constitute a microcontinent named Oaxaquia (Ortega-Gutiérrez, et al., 1995). Grenvillian basement rocks in Mexico occur as isolated crustal units in the state of Tamaulipas (Novillo Gneiss), the state of Hidalgo (Huiznopala Gneiss), the state of Oaxaca (Oaxacan Complex and Guichicovi complex) and in the state of Chiapas (Candelaria Unit) (Fig. 1a).

Rocks from the Oaxacan Complex (OC) (Fig. 1b) represent the largest outcrop (ca. 10000 km^2) of Grenvillian age, granulite-facies metamorphic rocks in Mexico, that correlate with the Rigolet event of North America Grenvillian terranes.

Neoproterozoic outcrops of the OC consists of metapelite, quartz-feldspathic gneisses, calc-silicates, amphibolites, and marble, all intruded by anorthosite, charnockite, garnetiferous orthogneiss, and pegmatites that have undergone granulite facies metamorphic conditions at ~1 Ga. There are also remobilized/anatectic marbles that constitute calcareous intrusions (Ortega-Gutiérrez, 1984), anorthositic suites (Valencia, 2017; Schulze, 2011), mafic, and ultramafic rocks (Culi et al., 2018 submitted). The regional structural picture defines a northwest trending crustal-scale antiform that plunges parallel to mineral lineation (Ortega-Gutiérrez et al., 2018).

The sectors of the OC that have been studied by us cover an area never addressed in detail before, equivalent to three 1:50000 maps (Fig. 1b, 1c). Our investigations are centered around five main petrogenetic subjects: a) reconnaissance of lithotypes, b) the ultramafic rocks, c) the metamorphic garnets, d) the geochemistry of lithotypes and, e) thermochronology.

Repeated high-grade metamorphism of supracrustal gneisses from Mühlig-Hofmannfjella, central Dronning Maud Land

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The bedrock of Mühlig-Hofmannfjella, central Dronning Maud Land, is part of the high-grade Maud Belt, and comprises a deep-seated metamorphic-plutonic complex where the metamorphic sequence includes gneisses and migmatites. The *P–T–t* evolution of anatectic supracrustal gneisses has been recovered through a study of mineral assemblages, textural relationships and U–Pb ID TIMS geochronology on zircon and monazite followed by pseudosection modelling. The integrated studies delineate two periods of garnet growth and associated high-temperature metamorphism during the Ediacaran-Cambrian Pan-African orogeny. Peak M_1 conditions were attained at temperatures in the range 770–820 ^{o}C at moderate crustal depths (P = 8–9 kbar) and resulted in partial melting. The M_2 event resulted in new garnet growth at lower pressure conditions and stabilization of assemblages containing garnet ± cordierite ± melt. Zircon indicates a period of growth at 570-566 Ma, interpreted to have occurred during anatexis and record the time of melting during the M_1 metamorphism. Monazite ages range from 525–610 Ma; the oldest ages are considered to have grown during the onset of M_1 metamorphism, whereas the younger population (525–535 Ma) is interpreted to date the later low-pressure M_2 metamorphism. The new data, together with previous geochronology, demonstrate that the orogenic construction of the Maud Belt was prolonged and multistage in nature with repeated high-grade metamorphism and partial melting.

Melt inclusions in anatectic metapelites from the Edixon Metamorphic Complex (Antarctica): microstructure, petrology and implications for the evolution of the Lanterman Range

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The Lanterman Range (LR) in Northern Victoria Land of Antarctica belongs to the Wilson Terrane (WT), a tectonometamorphic terrane forming part of the Cambro/Ordovician Ross Orogen (Bradshaw and Laird, 1983). The LR is generally divided into three main tectonic units represented, from W to E, by the Edixon (EMC), the Bernstein (BMC) and the Gateway Hills (GHMC) metamorphic complexes. The main EMC rock types include micaschists and gneisses preserving medium- to high-grade metamorphism with some evidence of low-pressure anatexis preserved in garnet-cordierite-K-feldspar-bearing rocks with peak conditions of ca. 700°C and 0.5–0.6 GPa (Talarico et al., 2004). Here we report the first study of anatexis and melt products based on the inclusions recovered in peritectic garnets from a muscovite-biotite-plagioclase-Kfeldspar-quartz gneiss collected in the EMC.

Inclusion types are represented by mixture of glassy (MI), fluid (FI) and polycrystalline (PI) inclusions displaying frequent negative crystal shape. In MI, glass is felsic and hydrous with shrinkage bubbles containing a fluid mixture of $CO_2 + N_2 + CH_4 \pm H_2S \pm H_2O$; the FI are composed by $CO_2 + H_2O + N_2 + CH_4 \pm H_2S$; the PI contain Ms + Qz + H_2O (liq) ± calcite/siderite ± albite. The PI were re-melted in a piston cylinder apparatus at conditions of 740 to 900°C at 0.8–1.0 GPa. At 740°C, re-melting is incomplete, glass inclusions are rare and not completely homogenized. At 760°C re-melting is widespread but glass frequently contains unresorbed crystals of albite and quartz. Full re-homogenization occurs at 780°C with negligible interaction with the host garnet. From 810°C to 900°C the interaction melt-garnet increases progressively.

In completely re-homogenized inclusions, the glass is sub-alkaline, peraluminous (ASI ≈ 1.52) with CaO ≈ 1.2 wt. % and K_2O ≈ 3.7 wt.%, and composition corresponding to granite to Qtz-monzonite in the An–Ab–Or normative classification. The melts are hydrous with volatile content measured by nanoSIMS to ≈ 4.5-6.5 wt. % H_2O and negligible CO_2 (<500 ppm).

The calculated phase equilibria for the rock in the MnCNKFMASHT model system indicate that the equilibrium assemblage Bt + Ms + Pl + Qz + Kfs + Grt + melt is stable at T < 780°C at 0.8–1.2 GPa and that the solidus locates at 700 ± 20°C in the same pressure range. The combination of calculated compositional isopleths for Grt, Bt and Pl with measured mineral compositions suggests that limited volumes of melt were produced (≈ 2–6 wt. %).

The combination of petrography, experiments and thermodynamic modelling supports the hypothesis that anatexis in the Edixon Metamorphic Complex was achieved at upper amphibolite facies conditions which have been registered in different metasedimentary portions of the area and along the exhumation path of the HP-UHP belt of the Lanterman Range (Palmeri et al., 2003 and 2007). The position of the anatectic peak (if after a prograde anticlockwise path or during decompression/exhumation with a clockwise path) open the question to whether jusxtaposition of the EMC with the BMC and the GHMC might have occurred during subduction or in the crustal footwall after their peak metamorphism. However, Ar-Ar data on white mica and biotite (Di Vincenzo et al., 2001) from the three complexes suggest that the docking of the EMC with the other complexes verified during the last part of UHP rocks exhumation at nearly 480 Ma.

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Hydration of granulite facies rocks in shear zones: aqueous fluid or silicate melt?

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Central Australia exposes many moderate and high temperature hydrous shear zones that cut the granulite facies basement. During active tectonics the crust undergoes extension, shearing and thrusting which may involve shear zones and regional scale metasomatic changes. (Newton, R.C., 1990). Fluids play a significant role as a medium of transfer of heat and material during a metamorphic event and fluids have been linked with the initiation and evolution of many orogenic processes. The nature of fluids migrating through the crust varies from CO_2 from decarbonisation, to aqueous brine and silicate melts (Touret and Huizenga, 2011). Shear zones within the crust acts as an important conduit for the migration of these fluids (Losh, 1989). Although, the rheological effect of the presence of aqueous fluid versus silicate melt in shear zones is not well known, it is likely that these would be different. This work distinguishes the role of aqueous fluid versus silicate melt in hydration of granulite facies basement rocks within shear zones of the intracontinental Alice Springs Orogeny, Central Australia. In this setting, it is proposed that hydration in shear zones significantly weakens the crust through reaction softening, perhaps enabling intracontinental orogeneis (Raimondo et al., 2014). This study shows a role for aqueous fluid in shear zones in the Reynolds–Anmatjira ranges based on field observation of quartz veins, microstructural observations typical of mylonite zones, and hydration to greenschist-amphibolite facies assemblage including muscovite and chlorite. In contrast, within shear zones in Strangways Range, field investigations identify granitic dykes and lenses that retain igneous texture. Microstructures indicative of the former presence of melt are observed in sheared rocks and include felsic minerals that form films along grain boundaries or show low dihedral angles, and string of beads texture. These suggest influx of silicate melt drove hydration in the shear zones in the Strangways range while such evidence is lacking in the samples from Reynolds-Anmatjira ranges. In addition to the field and microstructural criteria, REE patterns are shown to be useful in distinguishing between aqueous fluid and silicate melt hydration of the granulites.

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Neoproterozoic evolution and Cambrian reworking of ultrahigh temperature granulites in the Eastern Ghats Province, India

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Phase equilibrium modelling, U–Pb geochronology, the rare earth element (REE) composition of zircon and monazite, and Ti-in-zircon thermometry were applied to provide *P*–*T*–time constraints for two compositionally heterogeneous and microstructurally complex cordierite–spinel-bearing granulites from Vizianagaram, Eastern Ghats Province (EGP), India. These ultrahigh temperature (UHT) granulites preserve discrete compositional layers with interpreted peak assemblages including garnet–sillimanite–spinel and orthopyroxene–sillimanite–spinel. These mineral associations cannot be reproduced by phase equilibria modelling using whole rock compositions. In this case, the rocks have developed discrete equilibrium domains on a scale less than that of a thin section, even at ultrahigh *T* conditions. Calculation of the *P*–*T* stability fields for five compositional domains considered to have attained equilibrium suggests peak metamorphic conditions of ~6.5–8.0 kbar at ~1000°C. The subsequent evolution in most domains resulted in the growth of cordierite and crystallization of all melt at an elevated (residual) H_2O-undersaturated solidus, consistent with minor decompression (~1 kbar). U–Pb ages obtained from zircon and monazite suggest temperatures may have remained above 950°C for 100 Myr between *c.* 1000 and 900 Ma. A later concordant population of zircon dated at 511 ± 6 Ma, which crystallised at ~810°C, is interpreted to record a Pan-African thermal overprint.

Our results suggest that, in the interval 1100 to 850 Ma, the granulites at Vizianagaram followed a tight clockwise *P*–*T* path and remained at ~20 km depth at $T > 800$°C. However, these rocks are adjacent to a crustal block that experienced counterclockwise *P*–*T*–*t* paths, but which records similar peak metamorphic conditions (7–8 kbar, ~950°C) and a similar chronological history. The limited decompression at Vizianagaram may be explained by partial exhumation via thrusting over the adjacent crustal block. The residual granulites in both blocks have high concentrations of heat producing elements and likely remained hot while residing at depths ~20 km throughout a period of relative tectonic quiescence in the interval 800–550 Ma. During the Cambrian Period the EGP was located in the hinterland of the Denman–Pinjarra–Prydz orogen. Therefore, it is postulated that limited growth of new zircon at *c.* 510 Ma is indicative of low-degree melting due to limited fluid-influx, the response of hot, weak crust to convergence of the Crohn craton with a composite orogenic hinterland comprising the Rayner terrane, Eastern Ghats Province and cratonic India.

The petrogenesis of kyanite leucogranites in Bhutan, E Himalaya

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Dramatic exhumation of high-grade rocks from orogenic cores is commonly explained by variants of the 'channel flow' model[1]. This model requires weakening of the mid-crust via partial melting to trigger the change from burial to exhumation. The evidence for this melting is often sparse and is commonly overprinted by subsequent deformation, recrystallisation and decompression melting. Prograde crustal melts, or cryptic evidence of them, are however being increasingly reported in the Himalaya, in kyanite-grade rocks of the Greater Himalayan Series (GHS)[2-6]. These leucogranites are commonly formed during the Oligocene, thus pre-dating the more voluminous and better-studied Miocene granites that formed through decompression melting. This implies that the formation of these Oligocene leucogranites weakened the mid-crust, and thus was the driver of the change from the burial of the GHS to its rapid exhumation.

Deformed kyanite leucogranites from eastern Bhutan are found at the deepest structural levels of the Greater Himalayan Series in kyanite-grade biotite schists just above the Main Central Thrust (MCT). Field observations indicate that they are small-scale, cm–dm sized lenses of melt that formed in situ within the host schists. Thin section textures reveal evidence for both prograde and retrograde mineral reactions. Individual kyanite grains have been further investigated using cathodoluminescence (CL) imaging combined with trace element mapping and spot analysis[7].

Kyanite in the schist is commonly tabular in shape with complex internal structures revealed by CL imaging. In the leucosome adjacent to the schist, kyanite grains show similar internal textures, but have corroded, skeletal shapes which are rimmed by optically continuous 'moats' of coarse muscovite. We interpret these kyanite crystals to be xenocrysts incorporated into the melt from the schist, thus inheriting the complex texture of the kyanite from the schist. The muscovite rim is interpreted to be a late-stage reaction product due to the back-reaction between kyanite and the melt, a reversal of the dry muscovite dehydration reaction. Also found in the leucosome, typically further away from the schist margin, are thin, bladed kyanite crystals with little to no internal zonation. These crystals are thought to represent 'igneous' kyanite that formed either peritectically or by crystallisation from the melt.

To further characterise these different mineral populations, kyanite and muscovite trace element concentrations will be analysed by EPMA and LA–ICP–MS. This will bring greater insight to what is controlling the complex kyanite internal CL textures and will further elucidate the reaction history preserved in these rocks. Understanding the genesis of the kyanite is important for constraining future *P*–*T*–*t* modelling of the leucogranites and is crucial for the tectonic interpretation of these melts as drivers for the exhumation of the orogenic mid-crust.

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The petrological and rheological signatures of melt-present high strain zones: Examples from the intracontinental Alice Springs Orogeny, Central Australia

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Melt migration through shear zones in the middle to lower crust may be considered part of the self-organizing crustal system of melt migration, functioning as major pathways for the ascent of melt originated from anatectic processes in the lower parts of the crust, and in part responsible for batch mass transfer and felsic component increase in the upper crust.

In this study, we investigate the positive feedback between melt flow, exothermic hydrous reactions and deformation in an mid-crustal compressional environment. The studied hydrous Gough Dam hydrous shear zone forms an important structure within the Alice Springs Orogeny (450–300 Ma) in Central Australia, and is located in the granulite dominated Strangways Metamorphic Complex. The field and petrological signature for shear zone melt flow include (1) extreme glimmeritization over several meter thickness, (2) presence of pockets of granitic melt, (3) sheets of granitic composition, (4) feldspar phenocrysts in glimmerite. On the micrometer scale, we recognize microstructures indicative of trapped melt and "invasion" of host rock (granulite and quartzite), by the hydrous melt. Composition of the trapped melt suggests origin from sediment anatexis.

We infer that both the presence of melt and reaction induced hydration i.e. marked increase of rheologically soft minerals (e.g. biotite), results in significant rheological softening during the Alice Springs Orogeny facilitating this intracontinental orogeny to develop.

Si-undersaturated domains in a meta-pelitic high-pressure granulite (Qinling Belt, China)

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High-grade metamorphic rocks may show a wealth of disequilibrium textures that provide a telling record of their evolution and insight into reaction kinetics. In this communication, we report the unusual occurrence of corundum- and spinel-bearing domains in the quartz-rich matrix of a high-pressure granulite. The origin of the described sample is the Songshugou area (Qinling Belt, China). Its host, an Early Paleozoic psammitic migmatite slice, is structurally overlain by a contemporaneous association of quartz eclogite and spinel dunite. Other high-pressure granulites of this slice recorded peak metamorphism at up to 915°C, 1.45 GPa, and cooling through ~620°C, 0.75 GPa. The abutting eclogites experienced peak pressures of 2.1–2.5 GPa at 490-540°C.

The sample contains roundish to ovoid, porphyroblastic garnets and stretched Al-rich aggregates; both are millimeter-sized and always enveloped by granular, 0.1–0.2 mm thick plagioclase coronas that show an outward decrease of the anorthite content (An_{27} to An_{15}).

Garnet shows conspicuous optical zoning: colorless poiciloblastic cores ($Alm_{74}Grs_5Prp_{19}Sps_2$) either include exsolution-free plagioclase and biotite or spinel, corundum, and biotite. The garnet rims ($Alm_{65}Grs_{18}Prp_{15}Sps_2$) are pale-pink, contain distinctly more Ca but less Mg and Fe than the cores, and host inclusions of spinel and corundum. Isolated fluid inclusions (≤5 µm) in the garnet rims have negative crystal shapes and contain siderite daughter crystals; the vapor phases are, as evident from laser Raman analysis, CH_4, H_2O, and in part just detectable amounts of CO_2.

The Al-rich domains never contain quartz. Commonly, intergrowths of spinel, corundum, biotite, and little plagioclase mantle a core of a single crystal. Almost always, this is kyanite. Yet on occasion, this core is sillimanite or phengite. Staurolite is a rare retrograde phase of the Al-rich domains.

The matrix around these domains is, despite of rare biotite which accentuates an indistinct, discontinuous foliation, free of mafic phases and consists of quartz, perthite, and plagioclase, in the order of abundance.

Although it is possible to comprehend the formation of spinel and corundum during exhumation with phase equilibria modeling, the applicability of this method is limited and calculated metamorphic pressures, temperatures, and water activities greatly depend on assumptions. The preservation of spinel and corundum implies that the plagioclase coronas are an effective shield from SiO_2—its penetration depth into the coronas is consequently less than 0.1–0.2 µm—although H_2O possibly had excessed to the Al-rich domains given the retrograde staurolite development. The plagioclase coronas are interpreted to have crystallized from migmatic melt during cooling.

Metamorphic *P–T–t* paths retrieved from mafic granulite with double symplectites in the Fuping Metamorphic Complex, middle Palaeoproterozoic Trans-North China Orogen

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The Fuping Metamorphic Complex lies in the middle section of the Trans-North China Orogen, and is consisting of the following four litho-tectonic sections, i.e., the Fuping TTG gneiss, the Wanzi supracrustal association, the Nanying gneissic granite, and the Longquanguan & Ciyu augen gneiss. Garnet-bearing mafic granulite occurs as lenses or puddings within the TTG gneiss and is composed mainly of garnet, clinopyroxene, orthopyroxene, hornblende, plagioclase, quartz and accessary zircon and titanite. Four stages of metamorphic mineral assemblages have been found in the mafic granulite: (a) the prograde assemblages (M1) are inclusions preserved in the garnet porphyroblast, including clinopyroxene, hornblende, plagioclase and quartz; (b) the metamorphic peak assemblages (M2) consist of garnet porphyroblast plus matrix minerals clinopyroxene + orthopyroxene + hornblende + plagioclase + quartz + zircon + titanite; (c) the first retrograde assemblages (M3) are represented by clinopyroxene + orthopyroxene + plagioclase + quartz symplectite rimming the garnet; and (4) the final retrograde assemblages (M4) are hornblende + plagioclase + quartz symplectite rimming the garnet. The retrieved metamorphic *P–T* paths pass from 530–600°C / 6.5–7.0 kbar (M1) through 680–820°C / 7.2–11.7 kbar (M2) to 730–760°C / 3.2–3.9 kbar (M3) and finally to 600–640°C / 3.2–3.7 kbar (M4). All the *P–T* paths of the mafic granulite are clockwise including the first retrograde section of near isothermal decompression (ITD) and the subsequent second retrograde segment of near isobaric cooling (IBC). SHRIMP U–Pb dating of metamorphic zircon of the mafic granulite yields a mean weighted age of ~1.85 Ga, which is consistent with the metamorphic time of surrounding TTG gneiss. Furthermore, $^{40}Ar/^{39}Ar$ dating of hornblende in mafic granulite shows that the cooling stage passes through 1.81 Ga. These data suggest that the Fuping complex records the collision event between the Eastern and Western Blocks of the North China Craton that led to the final assembly of this craton in the late Paleoproterozoic.

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U–Pb zircon ages of granulites from the Huai'an and Jining Complexes in the North China Craton and their geological implications

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The Huai'an Complex is located at the central north of the North China Craton (NCC), where it occurs at the conjunction of the Khondalite Belt and Trans North China Orogen (TNCO). It mainly consists of a dome-like high-grade metamorphic basement, which is dominated by Archean grey gneisses with minor meta-supracrustal rocks, Paleoproterozoic mafic HP granulites, khondalite series and granitic gneisses. The Jining Complex is located at the eastern part of the Khondalite Belt of the Western Block of the NCC, it is connected with Huai'an Complex however separated and intersected by the Trans-North China Orogen. The Western Block basement is characterized by Archaean TTG gneisses in the NW, and bordered to the SE by Palaeoproterozoic khondalite related rocks which unconformably overlie the Archaean basement. For this study we collected samples from different high-grade metamorphic rocks including khondalite and associated mafic granulite, S-type granite and melt veins, to investigate genetical relationships between ages and Lu–Hf isotopic compositions at these rocks as parts of the Huai'an and Jining Complexes. The U–Pb dating and Lu–Hf isotopic analysis of zircons from metamorphic and meta-igneous rocks provide new constraints on the timing and mechanism of thermal events associated with metamorphic and melting events.

Three samples of zircons from khondalitic metapelites from the Huai'an complexes studied, which mainly comprise the assemblage of Grt + Sil + Pl + Kfs + Bt, recorded three-episode of U–Pb ages at ~ 2171–1997 Ma, 1995–1937 Ma and 1846 – 1806 Ma. They are interpreted to source from supercrustal protoliths of the khondalite-series rocks which were modified by later metamorphic events, and which reflect the age of collision between the Yinshan and Ordos Blocks, and the age of collision between the Eastern and Western Blocks respectively. Zircons of these pelitic gneiss of the Huai'an Complex, therefore, record both of the Paleoproterozoic collisional events in the North China Craton (Li et al., 2011). Two samples of khondalitic rocks from the Jining complex, which mainly consist of the UHT mineral assemblages of Grt + Spl + Crd + Pl + Kfs + Bt + Qz and Hyp + Sil + Crd + Bt + Pl + Kfs + Qz., yield two groups of U–Pb ages at 1950 ± 20 and 1870 ± 14, which record the HP metamorphic event during the collision between the Yinshan and Ordos Blocks in the NCC, and a post-orogenic exhumation metamorphic overprint respectively (Zhao & Zhai, 2013). Two S-type granites were taken from Tuguiwula and Xuwujia of the Jining complex, which consist of mineral assemblage Grt + Sil + Bt + Ksp + Qz and Spl ± Grt + Hyp+ Bt + Pl + Kfs + Qz respectively, and which yield U–Pb ages at ~1915–1891 Ma. Two mafic granulite samples from Tuguiwula and Xuwujia of the Jining complex, consisting of Cpx + Opx + An + Rt + Ilm and Cpx + Opx + Amp + Bt + Pl + Rt reveal ages at ~1900–1876. These ages are interpreted to represent the post-collisional uplift, which may have followed the exhumation of deeply buried rocks in a thickened crust, resulting from a collision event at ~1950 Ma (Zhao & Zhai, 2013). Zircons generally contains inherited domains, solid-state recrystallization and overgrown during later metamorphic stages. Inherited zircons of the protolith of the khondalitic rocks of the Huai'an complexes show relatively high $^{176}Lu/^{177}Hf$ and low to high $^{176}Hf/^{177}Hf$ ratios. The Hf isotopic characteristics of the metamorphic zircons from khondalite and S-type granite are quite homogeneous, respectively, indicating a peak metamorphism to post-metamorphic recrystallization of the magmatic zircons. Mafic granulite shows heterogeneous Hf isotopic features, which may reflect an influence from mantle-derived magmas. Almost all investigated zircons from khondalitic rocks, S-type granite and mafic-granulite yield Hf_{TDM} model ages of ~2.2–2.5 Ga, which suggests that the lower crust of the khondalite belt beneath the Western Block is dominated by Paleoproterozoic ages, and represent a decoupled sequence with the Archean metamorphic basement of the region (Zhang HF et al., 2012). This research was supported by NSF C / NRF Research Cooperation Programme (41761144061).

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Contrasting metamorphic *P–T* paths of mafic and pelitic high pressure granulites in Chicheng, northern part of the Paleoproterozoic Trans-North China Orogen

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The continent-continent collision along the TNCO was partly defined by metamorphism of high pressure (HP) granulites with clockwise *P–T* paths. In this paper, we report HP mafic and pelitic granulites among a metamorphic volcanic-sedimentary sequence south to Chicheng, northern part of the TNCO. (1) Mafic granulite experienced remarkable prograde metamorphism with a consecutive hairpin shaped clockwise *P–T* path, during which the temperatures increased from 630°C to 740°C while the pressures increased from 8 kbar to the barometric peak of 16 kbar. After the barometric peak, the mafic granulites subjected to decompression from 16 kbar to 13 kbar while the temperature continued increasing from 750°C to 790°C, suggesting the thermal relaxation process. (2) HP pelitic granulites are meter wide lenticular layers intercalated with HP granulites of mafic, intermediate to felsic compositions. They have a typical HP granulite mineral assemblage of garnet + kyanite + perthite. Phase equilibria modelling yielded *P–T* conditions around metamorphic peak of 950°C, 15 kbar. (3) The meter wide lenticular layers of pelitic granulite are very small compared with the background mafic granulite, and its peak metamorphic temperature is 160°C higher than mafic granulite while their highest metamorphic pressures are analogous, hence we speculated that the pelitic granulites were tectonically involved in the mafic granulite block during its rapid exhumation from the lowermost crust. The thermal relaxation recorded by mafic granulite must have been caused by hotter lowermost crust represented by the pelitic granulites, while the well preserved ultrahigh temperature metamorphic peak mineral assemblage and reactions in the pelitic granulites were resulted from the wrapping and carrying of the cooler mafic granulite block. As a whole, the Chicheng HP granulite terrane was likely to subject to quick tectonic exhumation after collision at ca. 1.91 Ga, causing contemporary decompression and cooling, leading to the *P–T* paths of pelitic and mafic granulites avoiding access to sillimanite and orthopyroxene formation respectivelyThis study provides reliable metamorphic record for tectonic constraint on the final assembly of the NCC along the TNCO.

Prolonged high-temperature, low-pressure metamorphism associated with ~1.86 Ga Sancheong–Hadong anorthosite in the Yeongnam Massif, Korea: Paleoproterozoic hot orogenesis in the North China Craton

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Elevated heat flow in association with mafic magmatism in an orogenic belt commonly leads to high-temperature, low-pressure (HTLP) metamorphism and the production of granulite-facies assemblages. We studied such a HTLP complex in the vicinity of the Sancheong–Hadong anorthosite-mangerite-charnockite-granite (AMCG) suite, Yeongnam Massif, Korea, in order to constrain the *P–T* conditions, timing, and duration of metamorphism. This complex primarily consists of massif-type anorthositic-gabbroic bodies emplaced at ~1.87–1.86 Ga and a series of country rocks comprising orthopyroxene-bearing gneisses as well as anatectic granites and migmatites. Migmatitic gneisses were studied in detail because melt-related features are abundant and well preserved; for example, inclusion-rich peritectic phases such as cordierite or K-feldspar are characteristic for the prograde melt-forming stage, whereas biotite-quartz symplectites mantling garnet or orthopyroxene represent the cooling stage consuming melt. Pseudosection *P–T* analyses of migmatitic gneisses suggest peak metamorphic conditions of 810–840°C and 5.9–6.2 kbar, followed by near-isobaric cooling and melt crystallization at ~780°C and ~5.5 kbar. SHRIMP (sensitive high-resolution ion microprobe) U–Th–Pb ages of zircon and monazite from six migmatitic gneisses are in the range of 1870–1854 Ma. The oldest age, recorded only in high Y monazite, suggests that prograde metamorphism commenced at ~1870 Ma. In contrast, melt crystallization had culminated by 1860–1855 Ma producing widespread leucosomes and anatectic granites. Our results suggest that high thermal gradient (~40°C km^{-1}) attending the granulite-facies metamorphism is attributable to coeval, pulse-like emplacement of anorthositic-gabbroic magmas. Moreover, the HTLP metamorphism lasted over a period of ~15 Ma, indicating a long-lived process corresponding to the late stage of Paleoproterozoic (~1.95–1.85 Ga) hot orogenesis in the North China Craton.

Neoarchean and Paleoproterozoic high-pressure granulites in the Belomorian mobile belt, north-eastern Fennoscandia

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The Early Precambrian Belomorian mobile belt (north-eastern part of the Fennoscandian Shield, North-Western Russia) is composed of several tectonic slabs consisting of the high-grade metamorphic rocks: migmatized gneisses and amphibolites, eclogites. Most of them were metamorphosed in *P–T* conditions of high-pressure amphibolite facies. Their Meso- and Neoarchean protolith was metamorphosed in ca. 2.7–2.6 Ga and ca. 1.94–1.84 Ga. During the Early Paleoproterozoic the metamorphic rocks were intruded by dykes and massifs of the basic rocks (anorthosites, Ol gabbronorites and lherzolites, Fe-Ti gabbro).

Our study revealed relics of the high-pressure (HP) granulites among the gneisses and amphibolites. These HP granulites forms two age groups. Neoarchean HP granulites have pelitic (Pl +Bt + Qtz + Grt +Ky ± Or, Rt), greywacke (Pl +Bt + Qtz + Grt ± Rt), lime-silicate (Cpx + Grt + Pl + Qtz ± Hbl, Scp, Bt, Rt) or basic (Cpx + Grt + Pl ± Hbl, Qtz, Bt, Rt, Ilm) composition. Kyanite is only aluminosilicate mineral in the pelitic HP granulites. Metabasites doesn't contain coexisting Pl + Opx (Opx-free granulites). Metapelitic granulites are slightly or strongly migmatized. The age of these granulites is ca. 2.7 Ga.

Late Paleoproterozoic granulites revealed have predominantly basic compositions. The typical mineral assemblages are: Opx + Grt + Hbl, Ath, ± Bt, Rt; Cpx + Grt + Pl ± Hbl, Qtz, Bt, Rt, Ttn (no coexisting Pl + Opx: Opx-free or Pl-free granulites). Some of metabasic Late Paleoproterozoic granulites formed after Early Paleoproterozoic intrusive rocks while other were after Archean amphibolites. Metapelitic or metagreywacke Late Paleoproterozoic HP granulites are rare. Their assemblages are: Pl + Bt + Qtz + Grt +Ky ± Rt; Pl +Bt + Qtz + Grt ± Rt. Kyanite is only aluminosilicate mineral in the pelitic Late Paleoproterozoic HP granulites. Most of these HP granulites have massive structures. Pelitic HP granulites are migmatized while migmatization of basic granulites is very slight. All these granulites were retrogressed at HP amphibolite facies conditions. The age of the Late Paleoproterozoic granulites is ca. 1.93-1.90 Ga.

The multiequilibrium thermobaromethric studies demonstrate that Neoarchean HP granulites were formed at 700–840°C and 8.5–12.5 kbar (in the kyanite stability field). Late Paleoproterozoic HP granulites demonstrate the wider PT-range: peak conditions at 950–1000°C and 20–25 kbar and then cooling and decompression. The high-pressure high-temperature assemblages and low degree of migmatization indicate the low activity of water and deficiency of the fluid during this metamorphic stage.

The geological features (thrust and nappe strusctures, intrusive leucogranites) display that both HP granulite metamorphisms happened during collision events. The high metamorphic pressures and temperatures displays that there were collsions of two continental mass (Karelian and Murmask cratons in Neoarchean and Belomorian-Karelain and Kola-Murmansk cratons in Late Paleoproterozoic).

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Effects of diffusional resetting in garnet – an example from anatectic metapelites of the Bohemian Massif

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Anatectic metapelitic granulites have been investigated from the Moldanubian zone of the Bohemian Massif (Winklarn, NE Bavaria). Associated metabasic (former eclogite) rocks show evidence for a short-lived LP/MP–HT pyroxene hornfels event that followed subduction and exhumation (Scott et al. 2013). Unusual gedrite- and orthopyroxene-bearing rocks from the same location also point to HT–LP conditions. Metapelites are characterized by porphyroblastic garnet set in a matrix of fibrolitic sillimanite, different generations of cordierite, K-feldspar and biotite. In the same sample some garnets are nearly completely replaced by an intergrowth of biotite, sillimanite and cordierite. Large garnets exhibit a complex major element zonation pattern. Multiple small discus-like cores have grown together to form large garnet porphyroblasts surrounded by overgrowth shells. The cores are Fe- and Mn-rich and show a flat pattern, while the overgrowth shells have low Mn and higher Fe and Mg. The inner and outer margins of the garnet shells act as effective rims during the LP event and show very sharp zoning to high Mn+Fe and low Mg + Ca towards the rim. All effective rims have the same composition, but their interiors are different. This is interpreted as being a result of diffusional resetting. The extent of resetting during the LP–HT event is dependent on the thickness/ size of the different shells. While larger/thicker shells preserve high X_{Mg} and high X_{Ca}, smaller/thinner shells are nearly completely reset. This can be explained by different diffusion velocities of Mn, Fe, Mg and Ca with Mn being the fastest and Ca being the slowest diffusing element. Sharply increasing Mn contents are explained by recycling of Mn from resorbed grains diffusing into and stabilizing relictic garnet. The effect of different diffusional resetting scales and recycling of certain elements stabilizing other grains of the same mineral has a considerable effect on geothermobarometric results. Inclusions in garnet cores are kyanite, rutile and staurolite, whereas biotite, plagioclase and melt inclusions can be found in the overgrowth shells. Another remarkable feature in these rocks is the occurrence of corundum next to quartz, as well as kyanite and plagioclase associated with corundum as inclusions in garnet cores inferring metastable reaction of inclusions suddenly exposed to fluid/melt along fractures. As these rocks are not immediately adjacent to intrusive bodies a regional heat source is assumed to be responsible for the high temperature metamorphic overprint (O'Brien 2000, Scott et al. 2013).

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Crustal melting in the Bohemian Massif: a treasure chest full of nanogranitoids

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The central European Bohemian Massif has undergone over two centuries of intense scientific investigation which has made it a pivotal area for the development and testing of modern geological theories. The discovery that deep melts can be preserved in natural rocks as melt inclusions either

crystallized (i.e. as nanogranitoids) or as glass, prompted the re-evaluation of the Bohemian Massif with an "inclusionist" eye (Fig. 1). This contribution provides an overview of such melt inclusions and explains the multiple constraints they provide for crustal melting.

Qualitative constraints are discussed targeting both the partial melt and the COH fluids often present during melting at depth. Crucial quantitative information on the geochemical signature of deep melts can be derived from nanogranitoid studies, a fundamental aspect for understanding the geodynamic history of the crust. Moreover, novel constraints on the mutual stability of melt and host garnet are generated as an intriguing by-product of our re-homogenization experiments on natural nanogranitoids. Overall we aim to generate microstructural guidelines and provide methodological suggestions for petrologists wishing to explore the fascinating field of melt inclusions in metamorphic terranes worldwide, based on the newest discoveries from the still enigmatic Bohemian Massif.

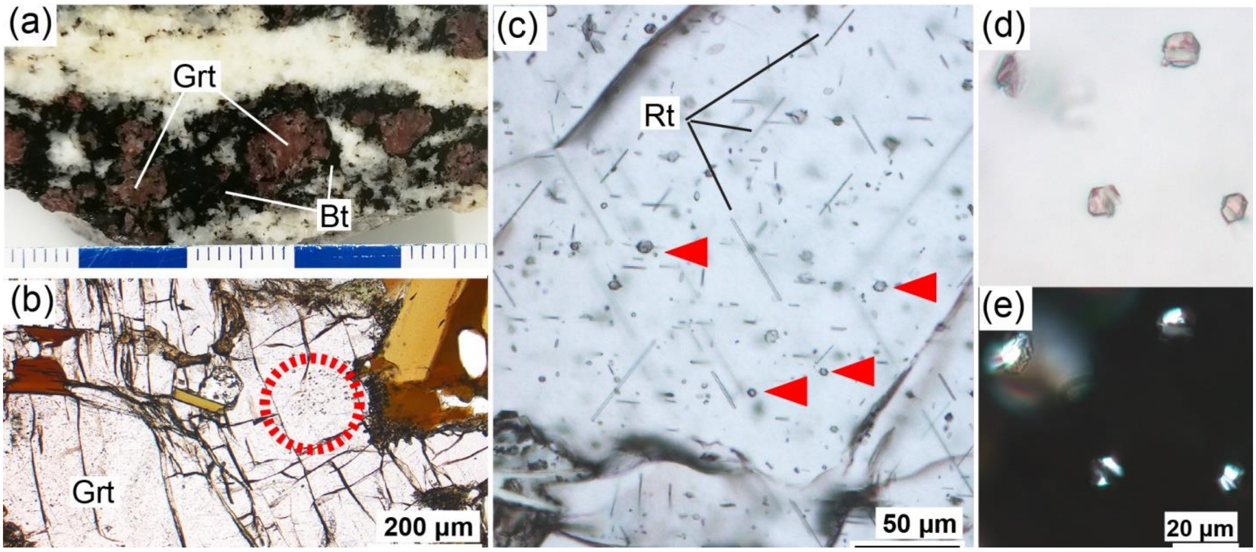

Figure 1. Example of nanogranitoid-bearing rocks from the Bohemian Massif. (a) perpotassic granulites from Plešovice (Blanský les Massif, central Moldanubian Zone) with large garnets partially resorbed by biotite (b). Several rounded inclusions occur in clusters (c) along with rutile needles (possibly exsolutions) and show a clearly polycrystalline nature (d,e). Dashed red circles: location of the inclusions in the sample. Red arrows: nanogranitoids.

Ultramafic-mafic complexes in the Lewisian Gneiss Complex: a record of petrogenetically distinct phases of Archean magmatism

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Ultramafic–mafic complexes in Archean cratons have been the focus of often contentious geological interpretations, ranging from ophiolite fragments [1] to sagducted remnants of Archean greenstone belts [2]. Such interpretations have disparate implications for Archean geodynamics, with the former compatible with horizontal tectonics and latter with vertical tectonics. The Lewisian Gneiss Complex (LGC) of the Scottish mainland – a tonalite–trondhjemite–granodiorite (TTG)-dominated fragment of the North Atlantic Craton – contains several ultramafic-mafic complexes whose origin(s) remains enigmatic [3]. Previous interpretations have ascribed the complexes to a wide-range of geological environments, including: fragments of a pre-TTG (possibly oceanic) crust [4]; accreted oceanic crust [5]; or sagducted remnants of greenstone belt(s) [2]. We present field, petrographic and geochemical data for 12 complexes in the granulite-facies Central Region of the LGC. The complexes studied cover up to 7 km² and have experienced polyphase high-grade metamorphism.

Nine of the studied ultramafic-mafic complexes – including those at Ben Strome, Achiltibuie and Drumbeg – share several salient features, comprising volumetrically subordinate layered ultramafic rocks (metapyroxenite and metaperidotite) and volumetrically dominant mafic rocks (metagabbro, garnet-metagabbro and amphibolite). These complexes, whose margins show consistent parallelism with both the layering in the ultramafic rocks and TTG gneissosity irrespective of the dominant structural regime, display several geological features characteristic of layered intrusions (e.g., gradational contacts between ultramafic and mafic units; existence of multiple ultramafic units within continuous stratigraphic sequences; and gradational contacts between individual metaperidotite and metapyroxenite layers) [6]. This is supported by fractionated chondrite-normalised platinum group-element (PGE) patterns ($[Pd/Ir]_N$ = 1.9–46.1) and spinel compositions similar to those from layered intrusions [7]. These nine ultramafic–mafic complexes are here interpreted as representing a suite of layered intrusions emplaced *into* the TTG gneiss prior to the Badcallian metamorphic event at 2.8–2.7 Ga [6].

Other ultramafic–mafic complexes – namely those at Loch an Daimh Mor, Geodh' nan Sgadan and Gorm Chnoc – are distinct from the layered intrusion group. These occurrences display selected field, petrographic, and geochemical characteristics that distinguish them from the layered intrusions. For example, the Loch an Daimh Mor Complex comprises ultramafic pods on a scale of tens of metres and exhibits Ir-group PGE-rich to mildly fractionated chondrite-normalised PGE patterns ($[Pd/Ir]_N$=0.1-3.6). These data support recent studies suggesting that the ultramafic–mafic complexes of the LGC are the product of at least 2 temporally and/or petrogenetically distinct phases of Meso- to Neoarchean ultramafic–mafic magmatism [6,8]. While the precise origin(s) of these complexes remains enigmatic, they may represent a pre-TTG crust that was invaded by the magmatic protoliths to the TTG gneiss [4].

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Assessing the origin of Nb anomalies in the Ben Strome Complex: implications for Archean geodynamic interpretations

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Geochemical fingerprinting utilises immobile element ratios to distinguish between magmas generated in different geotectonic environments [1]. One geochemical proxy – the Nb anomaly – is commonly used to identify Phanerozoic arcs and involves the relative depletion of Nb and Ta (± Zr, Hf, Ti) on primitive mantle-normalised plots. Although the Nb anomaly can also be generated by crustal contamination and hydrothermal alteration [2], its use as evidence for subduction-related magmatism is often extended to the Archean [3]. Such applications are controversial, with Archean geodynamic regimes during this eon, including the role of subduction, hotly disputed [4]. The mainland Lewisian Gneiss Complex (LGC) – a fragment of the North Atlantic Craton in northwest Scotland – is a tonalite-trondhjemite-granodiorite (TTG)-dominated terrane that contains a number of ultramafic-mafic complexes whose origin(s) and geodynamic significance are currently enigmatic [5]. In this study, we evaluate the origin and potential significance of Nb anomalies displayed by ultramafic rocks in the Ben Strome Complex, which represents the largest ultramafic-mafic complex in the LGC [5].

The 7 km^2 Ben Strome Complex, which is located in the LGC's granulite-facies Central Region, comprises volumetrically subordinate layered ultramafic rocks (metapyroxenite and metaperidotite) and volumetrically dominant mafic rocks (metagabbro, garnet-metagabbro and amphibolite) [5]. Based on bulk rock geochemistry, the ultramafic rocks of the Ben Strome Complex (n = 35) are subdivided into light rare earth-element (LREE)-poor (n = 20) and LREE-rich (n = 15) groups. The LREE-poor samples exhibit flat chondrite-normalised REE patterns ($[Pr/Yb]_N$ = 0.6–1.3) and flat primitive mantle-normalised trace-element patterns ($[Ta/Yb]_N$ = 0.6–3.2), while the LREE-rich samples display negatively sloping chondrite-normalised REE patterns ($[Pr/Yb]_N$=1.6 - 36.6) and negative Nb–Ta (± Zr, Hf and Ti) anomalies on primitive mantle-normalised plots ($[La/Ta]_N$ = 0.3–36.1). Despite this, normalised Ta/Yb ratios for the LREE-rich samples ($[Ta/Yb]_N$ = 0.8–4.4) are comparable to the LREE-poor samples.

Both geochemical groups exhibit a range of petrographic textures and neither show systematic variation in silicate modal mineralogy, but subtle petrographic variation between groups is identified. Most notably, LREE-rich samples exclusively contain µm- to mm-scale, LREE-rich carbonate mineral phases. Moreover, amphibole compositions exhibit normalised REE and trace-element patterns that reflect those for the bulk-rock data, with amphibole in LREE-rich samples showing distinctive Nb anomalies. By contrast, the composition of orthopyroxene is consistent between LREE-rich and LREE-poor samples, while the composition of clinopyroxene shows mild variation between geochemical groups. Our data indicate that the Nb anomalies of the Ben Strome Complex are the product of selective LREE-enrichment associated with secondary processes, rather than representing a primary magmatic (subduction) Nb anomaly. The LGC's protracted metamorphic evolution offers a myriad processes potentially responsible for the LREE-enrichment, with discrete carbonate metasomatism a possibility. These findings indicate that the Nb anomaly alone is an unreliably proxy for Archean subduction and hints that the role of subduction during cratonisation may have been overestimated.

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Interactions between magmatism and HT–LP metamorphism during the late Variscan orogenic phase in the North Pyrenean Massifs

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During late stages of the orogenic cycle, high temperature – low pressure (HT–LP) metamorphism is often associated with abundant magmatism. However, the nature and relative contribution of heat sources and the causal relationships between metamorphism and magmatism are still debated. A careful assessment of the chronology of i) the thermal evolution at crustal scale, ii) melt production and magma transfer and iii) tectonic evolution in representative case studies is thus required.

The Pyrenean segment of the Variscan belt is affected by such a late high temperature event without evidence of prior significant crustal thickening due to its external position during the subduction and collision phases of the Variscan orogeny. The granulitic North Pyrenean Massifs (NPM) constitute the deepest relics of the Variscan crust affected by the HT–LP event in the Pyrenees. They have been exhumed both during late orogenic phases in the Permian, the Cretaceous rifting and the Cenozoic Alpine orogeny. The aim of this study is to present the thermal evolution of the Variscan crust in the NPM and to discuss the relationship between HT-LP metamorphism and magmatism, based on a synthesis of published and new petrological and geochronological data.

The NPM are mainly composed of Precambrian to Paleozoic sediments metamorphosed up to granulitic facies and intruded by diverse magmatic bodies emplaced during the lower Palaeozoic and at the Carboniferous – Permian boundary (303 ± 8 Ma). They underwent a main phase of deformation underlined both by peak temperature and retrogressive mineral associations. The deformation activity ended by the localization of the deformation along shear zones, and led to crustal thinning. Pressure – temperature data on samples taken at different structural levels evidence a vertical variation of the thermal gradient. In the upper crust, the gradient was higher than 60°C/km. In the median crust, near isothermal conditions at a temperature between 750 to 800°C are estimated, thus drawing a vertical geotherm. Metamorphism as well as associated partial melting lasted from 320 to 280 Ma, with two peaks identified in the zircon and monazite record at 300 Ma and 280 Ma whatever the structural level. This allows to interpret the spatial variation of the thermal gradient as a kinked geotherm. The magmatic-metamorphic succession, as well as the diversity of magmatic rocks (mafic to granodioritic metaluminous bodies and peraluminous granitoids), suggest a significant contribution of a mantle heat source to the late variscan HT–LP event. The kinked geotherm is interpreted as induced by crustal melting and melt migration from the lower to the upper crust.

Prograde, exhumation and cooling history of garnet of UHT granulites (Bohemian Massif) inferred by Zr-in-rutile thermometry, thermodynamic and diffusion chronometry

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The chemical composition of garnet and its mineral inclusions can be used to constrain both the prograde and retrograde *P*–*T* evolution. In this study, we use a combination of zirconium-in-rutile thermometry on single rounded rutile grains enclosed in garnet core and rim regions and thermodynamic modelling to constrain the prograde garnet growth conditions in felsic and mafic granulites from the Moldanubian Zone in the southeastern Bohemian Massif. The retrograde cooling and exhumation process is determined via Fe-Mg diffusion chronometry modelling of the garnet zoning patterns to evaluate minimum timescales required to get from the granulite facies peak (~1000°C / 1.6 GPa) at deep crustal levels to the lower granulite facies overprint at ~760°C/ 0.8 GPa in the middle crust. Generally, two types of garnet zoning patterns can be distinguished: Profile type (1) appears both in felsic and mafic granulites and displays a broad (c. 300-800 µm wide) chemically homogenous high grossular core region with strong chemical zoning towards the garnet rims (c. 100-400 µm wide). Grossular content decreases dramatically while almandine and pyrope increase. In rare cases, garnet rims preserve a flat compositional zoning with low grossular, intermediate pyrope and high almandine contents. The spessartine content remains constant along the whole profile or shows a weak increase from core to rim. Profile type (2) is observed in felsic granulites only and is characterized by an overall weak zoning where grossular content decreases gradually from core to the rims. Almandine and pyrope contents increase from core towards the rims. Spessartine is low ($X_{Sp} < 0.020$) without remarkable zoning. Measured rutile inclusions in high grossular garnet cores ($0.354 < X_{Grs} > 0.370$) yield rather low Zr contents ranging from 385 to 1259 µg/g. Application of Zr-in-rutile thermometry using the pressure independent calibration of Zack et al. (2004) yields an average temperature of ~830°C for the early garnet growth stage. We note, that these conditions are considerably above the equilibrium garnet-in isograd (ms + bt + fsp + qz = grt + ky + liq) assumed for the prograde evolution. Results from thermodynamic modelling reproducing the observed mineral assemblages in felsic granulites, the presence of rutile inclusions and the contemporaneous occurrence of high-Ti biotite in high-grossular garnet cores suggest a pressure window from 1.2 to 1.8 GPa for the early garnet core growth at ~830°C. However, this does not necessarily rule out garnet core formation at higher pressures taking into account the possible underestimation of biotite stability in thermodynamic modelling. Rutile grains measured in garnet rims with considerable lower X_{Grs} ($0.030 < X_{Grs} > 0.166$) yield higher Zr contents in the range of 1651 to 5774 µg/g, corresponding to an average temperature of ~1000°C. Thus, thermometry data indicate UHT conditions for growth of the garnet rim. This is in perfect accordance with the granulite facies peak temperatures of 1000°C at 1.6 GPa in the studied rocks determined through composition specific phase diagrams. Binary Fe-Mg diffusion modelling of compositional zoning of the garnet profile types (1) and (2) assuming a linear path from 1000°C at 1.6 GPa to 760°C at 0.8 GPa allows to estimate minimum timescales for the exhumation and cooling process within these limits. Preliminary results of 6 selected garnet profiles suggests that a minimum exhumation and cooling period of ~3-12 Ma to reproduce the observed compositional zoning between garnet core and rim as result of diffusive alteration during cooling/exumation. These diffusion chronometry results suggest rapid exhumation and cooling (~0.025–0.1 cm y^{-1} and ~80–20°C Ma^{-1}), which are similar to extracted uplift rates determined using Fe-Mg diffusion in the Saxonian Granulite Massif (Müller et al., 2015).

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Fluid-induced eclogitisation, amphibolitisation and partial melting controlled by dehydrating metapelites (Eclogite type-locality, Austria)

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Polymetamorphic metapelites and embedded eclogites share a complex, episodic interplay of dehydration and fluid infiltration at the eclogite type locality (Saualpe–Koralpe, Eastern Alps, Austria). The metapelites inherited a fluid content (i.e. mineral-bound OH expressed in terms of mol.% H_2O) of ~6–7 mol.% H_2O from high-*T*–low-*P* metamorphism experienced during the Permian. At or near P_{max} of the subsequent Eoalpine event (~20 kbar & 680ºC) the breakdown of paragonite to Na-rich clinopyroxene and kyanite in metapelites released a discrete pulse of hydrous fluid. Prior to the dehydration event the rocks were largely fluid absent, allowing only limited re-equilibration during the prograde Eoalpine evolution. Similarly, Permian-aged gabbros have persisted metastably due to the absence of a catalyst prior to fluid-induced re-equilibration. The fluid triggered partial to complete eclogitisation along a fluid infiltration front partially preserved in metagabbro. Near-isothermal decompression to ~7.5–10 kbar and 670–690ºC took place under fluid-absent conditions. After decompression, a second breakdown of phengitic white mica and garnet produced muscovite, biotite, plagioclase and ~0.1–0.7 mol.% H_2O that enhanced extensive fluid-aided re-equilibration of the metapelites. Potential relics of high-*P* assemblages were largely obliterated and replaced by the recurrent amphibolite facies assemblage garnet + biotite + staurolite + kyanite + muscovite + plagioclase + ilmenite + quartz. The hydrous fluid originating from the metapelites infiltrated the embedded eclogites at these *P*–*T* conditions and induced the local breakdown of the peak assemblage omphacite and garnet to fine-grained symplectites of diopside and plagioclase. Further fluid infiltration led to the formation of hornblende–quartz poikiloblasts at the expense of the symplectites. Locally, previously fluid-absent eclogites commence fluid-fluxed melting of peak garnet + omphacite to produce rare, decimetre-scale pegmatitic leucosomes consisting of hornblende + diopside + plagioclase + epidote + melt ± titanite. Counterintuitively, epidote appears to be stabilised rather than consumed by the melting reaction, possibly due to fluid infiltration and liberation of ferric iron from decomposing omphacite. The metapelites re-equilibrated until the growth of retrograde staurolite consumed any remaining free fluid, thereby terminating the process. Further re-equilibration is inhibited by both the lack of a catalytic fluid and H_2O as reactant essential for rehydration reactions. The interplay between fluid sources and fluid sinks describes a closed cycle for the rocks at the eclogite type-locality. Final, near-isobaric cooling is indicated by a slight increase of X_{Fe} in garnet rims. Post decompression dehydration and fluid-aided re-equilibration arrested by the introduction of staurolite might explain the apparently homogeneous retrogression conditions as well as the notorious absence of diagnostic high-P assemblages in metapelites at the eclogite type locality.

Early stage *P–T* metamorphic evolution of retrogressed amphibolites from NE Sardinia, Italy

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The Golfo Aranci area belongs to the Migmatite Complex of the Inner Zone of the Variscan Sardinian metamorphic basement. In this area, located a few kilometres north of the town of Olbia, a large lensoid amphibolite body, 2 km long in NE-SW direction and 100-150 m wide, crops out. Within this body two main lithologies can be distinguished: retrogressed amphibolites and ultramafic amphibolites.

The retrogressed amphibolites are coarse-grained, dark-green rocks with a schistose to weakly massive aspect. Within these amphibolites centimetric-sized layers locally occur which are featured by millimetric porphyroblastic garnet. These layers, oriented parallel to the regional schistosity, consist of millimetric (up to 1 cm) euhedral and subhedral garnet porphyroblasts in a matrix of green amphibole, plagioclase, quartz and aggregates with a clinopyroxene + plagioclase fine-grained symplectite-type texture. Garnet porphyroblasts, which can reach 30% vol. in these layers, contain a large amount of inclusions of amphibole, plagioclase, quartz and rare clinopyroxene and show a thin coronitic rim made up of plagioclase and amphibole. Amphibole inside this rim and in the matrix can be zoned with a retrograde phase (actinolite) at its margin. Garnet porphyroblasts are almandine rich (56–59 mol%) and spessartine poor (1–7 mol%), with intermediate grossular (26–28 mol%) and pyrope (10–16 mol%) contents. From core to rim pyrope progressively increases from 10 to 16 mol%, spessartine contents decrease from 7 to 1 mol%.

We calculated a *P–T* path applying pseudosection modelling in the NCKFMASHO+Ti+Mn system to garnet bearing layers in retrogressed amphibolites. Pseudosections related to the garnet rim were corrected for fractionation of elements in garnet. The garnet core grew at granulite facies conditions of T = 680–720°C and P = 0.7–1.0 GPa. These conditions fit the XNa ratio of 0.07 in clinopyroxene and the XCa ratio of 0.35 in plagioclase included in garnet well. The garnet rim grew at T = 680–700°C and P = 1.3–1.4 GPa. These conditions are compatible with the XCa ratio of 0.16 in plagioclase of the matrix, which likely represents the beginning of decompression after the end of garnet growth.

The *P–T* pseudosection modelling for the retrogressed amphibolites demonstrates an anti-clockwise *P–T* path from the granulite- to the high-pressure granulite-facies with a pressure increase of 0.3–0.7 GPa and a slight decrease in temperature. It is likely that garnet porphyroblasts stopped their growth after reaching the peak pressure and, thus, before the decompression characterized by the growth of amphibole. We can assume that after this decompression phase, the retrogressed amphibolites likely followed the same metamorphic-retrograde path as the adjacent ultramafic amphibolites during further exumation.

Garnet-rich veins in ultramafic amphibolites from NE Sardinia, Italy

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In the Golfo Aranci area, located a few kilometres north of the town of Olbia, a large amphibolite lens crops out in which an ultramafic body approximately 100 m long and 50 m thick occurs. These ultramafic amphibolites are characterized by a massive to weakly-schistose structure and a medium grain size. Within this ultramafic body three main compositional layers can be distinguished. The uppermost layer (about 25 m thick) shows a dark green to black colour and is featured by a high amount of millimetric to centimetric garnet crystals, which can be cumulated in ellipsoidal nodules (up to 15 cm in diameter) or centimetric thick veins.

These veins are characterized by a well-defined structure from the margin to the centre: the boundary between the vein and the hosting amphibolites is defined by an irregular symplectitic microstructure of spinel and amphibole, up to 2 mm thick. The inner margin domain of the vein consists of unzoned garnet (up to 3 mm in diameter) which contains inclusions of amphibole, spinel, chlorite and corundum.

Garnet-rich veins locally show a central white area in which zoned garnet occurs in a matrix. This matrix consists of two epidote species: one is represented by casually oriented elongated euhedral crystals (7.0–7.6 wt% Fe_2O_3) and the other by anhedral crystals with lower contents of iron (0.3–0.9 wt% Fe_2O_3). Within the matrix patches with sub-rounded regular forms can be also found. These patches, that likely represent a pre-existing mineral according to their shape, are made of epidote, spinel, corundum and margarite.

Garnet porphyroblasts in the centre of the vein are euhedral to subhedral and show a noticeable compositional zoning and contain epidote inclusions and small chlorite veins. From core to rim four zoning stages can be defined: core, mantle, inner rim and outer rim. The garnet core is almandine rich (49 mol%), with intermediate grossular (22 mol%) and pyrope (27 mol%) contents. Towards the mantle the grossular content (52 mol%) increases and the pyrope (6 mol%) and almandine (41 mol%) contents decrease. The garnet inner rim is grossular (42 mol%) and almandine (36 mol%) rich. The pyrope content in the entire rim is 22 mol%. Almandine and grossular contents in the garnet outer rim are 40 and 37 mol%, respectively). Spessartine contents remain constantly low at 1-2 mol% throughout the whole garnet.

Preliminary thermodynamic modelling with pseudosections allowed us to reconstruct the *P–T* path segment recorded by garnet growth. *P–T* pseudosections were calculated in the NCKFMASHO+Ti+Mn system using the vein core as bulk-rock composition. The *P–T* conditions (around T = 600°C and P = 1.5 GPa) for the garnet core were obtained by using the host rock as bulk rock composition, due to the fact that mol% values for Ca, Fe and Mg in the garnet are over or under the corresponding range obtained by calculations with the vein core as bulk composition. This could mean that the garnet core grew before the vein formation. Therefore core-to-mantle *P–T* conditions deserve further insights and should be considered with caution.

The *P–T* trajectory based on the compositional change of garnet from the mantle to the rim is similar to other metabasic rocks from north Sardinia: after the peak pressure the rock experienced a strong pressure decrease and a moderate temperature increase to granulite-facies conditions The rim conditions (T = 640–680°C and P = 0.8–0.9 GPa) point to a subsequent slight *P–T* decrease towards the amphibolite facies, in which the exhumation of the rock continued during the Variscan orogeny.

*P–T–*t evolution of paragneiss migmatites from the Bavarian Unit (Moldanubian Superunit): thermodynamic modelling of polyphase garnet combined with EPMA monazite dating

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The Bavarian Unit in the Moldanubian Superunit exposes a distinct segment of the central European Variscan orogen, which is characterized by a strong, late Variscan low pressure, high temperature (LP–HT) metamorphism associated with granitic plutonism.

Large garnet porphyroblasts of a scarce paragneiss variety preserve a complex zoning (Fig. 1a) and have stored detailed information regarding the regional *P–T–t* evolution. An elevated grossular content in the core (5–6 mol % grs) is discontinuously followed by low grossular values in the garnet mantle (1–1.5 mol % grs) and then again by a discontinuous increase at the rim (3–3.5 mol % grs), defining three distinct stages of garnet growth. Two local regional metamorphic events are deduced and constrained by thermodynamic modelling and geothermobarometric calculations (Fig. 1b). First prograde MP–MT metamorphism at 0.85–1.10 GPa and 720–780°C (event 1) based on garnet core composition (grt1) and inclusions therein. Second prograde metamorphism (event 2) after decompression and cooling started with garnet mantle growth at 0.45–0.60 GPa and 580–630°C, obtained from garnet mantle composition (grt2) and related mineral inclusions. Followed by near-isobaric heating to the metamorphic peak conditions of 0.60–0.75 GPa and 820–900°C based on garnet rim (grt3) and matrix phases.

Chemical Th-U–Pb monazite dating of monazite revealed two different age groups. The first are monazite inclusions in garnet cores, which have ages between 353 ± 29 Ma and 335 ± 17 Ma (weighted mean: 340 ± 7 Ma). The second group are monazite grains in the matrix and those enclosed in the garnet mantle, which yield younger ages between 329 ± 17 Ma and 295 ± 39 Ma. The monazite grains in the garnet mantle give a weighted mean of 319 ±6 Ma, those in the matrix 312 ± 5 Ma.

Different monazite generations show a remarkable increase of the yttrium content from generation-1-monazite (inclusions in the garnet core) over generation-2-monazite (inclusions in the garnet mantle) to generation-3-monazite (in matrix), while there is no significant difference in thorium, uranium and LREE contents. The common explanation for this feature involves high-T garnet consumption during decompression and incipient cooling, coupled with the liberation of yttrium from the garnet.

The first metamorphic event at 340 ± 7 Ma is correlated to the widespread collisional metamorphism that is observed throughout the central and eastern Bohemian Massif and commonly attributed to the Moravian-Moldanubian terrane collision. The second LP–HT event Ma is typical for the main metamorphic overprint in the Bavarian Unit – the so-called "Bavarian event". The *P–T–t* evolution of the Bavarian Unit to mid-crustal levels (around grt2 evolution), before isobarically heated to granulite facies conditions, point to a significant external heat influx into the middle crust at the final stage of the Variscan orogeny.

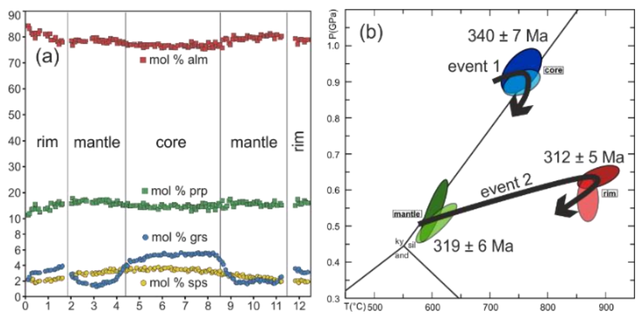

Fig.1 (a) Garnet profiles from migmatitic paragneiss. y-axis indicates mol %, x-axis indicates distance in mm. (b) Inferred P–T path of grt-crd-sil-migmatite

Polyphase garnet growth in granulite facies paragneiss and amphibolite in the southeastern Moldanubian Superunit: evidence for a pre-granulite facies evolution

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High-grade metapelitic K-feldspar + sillimanite bearing gneiss as well as pyroxene-amphibolite are typical rocks in the southeastern Moldanubian Superunit. Exceptional types of these rocks contain large garnet porphyroblasts with a complex zoning pattern indicating a polyphase metamorphic evolution.

Paragneiss exhibits the matrix mineral assemblage garnet + sillimanite + K-feldspar + biotite + plagioclase + quartz + ilmenite. Garnet is common and occurs as two different generations:

(1) The smaller (1–2 mm) and more abundant garnet grains have a calcium rich core composition ($Alm_{66}Prp_{18}Grs_{15}Sps_{1}$) followed by a strong decrease towards the rim ($Alm_{67}Prp_{25}Grs_{5}Sps_{1}$) (Fig. 1a). This garnet is relatively inclusion free, but sometimes staurolite and kyanite inclusions appear close to the garnet core. Thermodynamic modelling indicates a clockwise *P–T* path starting from approximately 0.6 GPa and 550°C (high grs core) progressing to 0.9 GPa and 650°C (kyanite + staurolite inclusions) and reaching finally the thermal peak at 0.8 GPa and 780°C (matrix and low grs rim).

(2) A second generation of garnet is recognised as large porphyroblasts (5–6 mm) which occur only sporadically and are frequently mantled by the smaller garnet generation. The large garnet porphyroblasts have abundant mineral inclusions such as muscovite + kyanite + biotite + rutile + K-feldspar + plagioclase + quartz + ilmenite and display a prograde zoning pattern seen in a change in chemical composition from $Alm_{68}Prp_{20}Grs_{7}Sps_{6}$ in the core to $Alm_{68}Prp_{24}Grs_{5}Sps_{2}$ at the rim. The occurrence of rutile as the stable titanium phase compared to ilmenite in the matrix and the high phengite content (3.20 apfu) of muscovite inclusions indicate elevated pressure for the formation of this garnet generation at conditions of approximately 1.5 GPa and 600°C. During the progressing metamorphic evolution the rock must have crossed the muscovite breakdown reaction and the solidus line (~700°C), leading to the formation of K-feldspar, kyanite and a melt phase and is evidenced by the presence of ms + qtz + kfs + ky as inclusions. The thermal peak of this first event is assumed to be 750°Cs followed by decompression and cooling resulting in a partly resorption of garnet.

Amphibolite appears next to paragneiss and has the mineral assemblage garnet + hornblende + clinopyroxene + plagioclase + ilmenite + quartz ± orthopyroxene ± biotite. The outermost rim of garnet is typically resorbed and displays plagioclase + orthopyroxene ± clinopyroxene ± amphibole symplectite coronae, which indicate an isothermal decompression path (ITD) at elevated temperatures. Garnet porphyroblasts often preserved a chemical zoning (Fig. 1b) with a core composition of $Alm_{54}Prp_{13}Grs_{29}Sps_{4}$ followed by a strong increase in grossular and a decrease in almandine and pyrope to $Alm_{48}Prp_{7}Grs_{43}Sps_{3}$. Towards the rim, grossular then decreases to low values whereas almandine and pyrope are increasing to $Alm_{56}Prp_{18}Grs_{24}Sps_{2}$. Most of the garnets are rich in inclusions such as clinopyroxene + plagioclase + quartz + sphene ± muscovite ± biotite. The high grossular annuli and the following strong decrease towards the rim indicate a *P–T* path similar to paragneiss with a thermal peak at 0.8 GPa and 800°C followed by a decompression, which forms the symplectite coronae around garnet. The higher sodium content of plagioclase inclusions compared to matrix plagioclase and the high phengite content of muscovite inclusions (up to 3.30) indicate also for this rocks a preceding metamorphic event at elevated pressure.

The results for the granulite facies peak are similar to findings of comparable rocks from the Moldanubian Superunit and are correlated to thrusting and nappe stacking processes. The first pressure dominated metamorphism could possibly be correlated to felsic granulites from the Gföhl nappe (Moldanubian Superunit) which show similar pressure conditions (1.4–1.7 GPa), although temperature conditions for granulites are much higher (~1000°C) compared to temperatures obtained in this study.

Nanogranitoid inclusions in sapphirine-bearing granulites from the Gruf Complex (Central Alps): new insights on crustal differentiation associated with ultra-high temperature metamorphism

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Partial melting up to ultra-high temperature conditions (> 900°C) is one of the major processes controlling the geochemical differentiation, reworking and rheology of the continental lower crust. The Gruf Complex (European Central Alps) is a 12 x 10 km migmatitic body embedded between the Penninic units of the Alpine nappe stack and the Oligocene intrusions of Bergell and Novate. The main rock types outcropping in the Gruf Complex consist of migmatitic orthogneisses, paragneisses and micaschists, leucogranites and charnockites. Migmatitic orthogneisses and charnockites are characterized by the presence of Permian UHT granulites, which occur as schlieren and massive enclaves. The enclaves are mostly composed of prismatic sapphirine, up to 2 cm large garnet porphyroblasts, Al-rich orthopyroxene, sillimanite and cordierite. Porphyroblastic garnets contain numerous trapped melt inclusions (MI), which are preserved as both glass and crystallized nanogranitoids. These MI have variable sizes, ranging from 5 to 100 μm in diameter. Larger MI are irregular in shape and display offshoots, while tiny inclusions are more isometric. Commonly, crystallized MI contain biotite, quartz, feldspars, apatite and minor ilmenite and rutile. Larger nanogranitoid MI frequently show intergrowth structures between the crystallized phases, although lobate-cuspate microstructures are also observed. Rare polycrystalline inclusions also occur within sapphirine. These inclusions often display a negative crystal shape and typically are less than 10 μm in size.

Nanogranitoid MI from the Gruf granulites are interpreted to represent anatectic melts produced during incongruent, fluid-absent, biotite melting reactions and have therefore the potential to shed light on the crustal reworking associated with ultra-high temperature metamorphism.

Evidence for a rapid uplift of the migmatitic Gruf complex and mechanical erosion of the adjacent Chiavenna unit (European Central Alps)

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We present a detailed field, petrological and geochemical study along two cross sections from the Chiavenna unit to the migmatitic Gruf complex in the southern part of the Lepontine dome of the Central Alps (Switzerland / Italy).

The Chiavenna unit is mainly composed of metaperidotites, mafic rocks and rare metacarbonates and is interpreted as an incomplete, overturned, ophiolitic sequence representing the remnant of the Cretaceous Valais through. The rocks of Chiavenna unit show a strong metamorphic field gradient characterized by an isobaric increase of the temperature from north to south dated at 32 Ma. In the north, metaperidotites are antigorite-bearing while amphibolite are epidote-bearing. In less than 4 km, towards the south, in the metaperidotites the diopside-out, talc-in, antigorite-out, talc-out, entastite-in and spinel-in isograds are progressively crossed whereas amphibolites progressively bear diopside and show evidence of in-situ partial melting. Mineral isograds are parallel to the contact with the Gruf complex and indicate a thermal gradient of ca. 80°C/km.

The Gruf complex is mostly composed of partially molten ortho- and paragneiss migmatized between 32 and 30 Ma. The northern part of the Gruf complex is characterized by an enclave rich-biotite orthogneiss and rare sillimanite-biotite-garnet paragneiss. The main foliation in the orthogneiss strikes ENE–WSW and displays a NE-plunging stretching lineation. Some shear bands filled by leucosomes indicate a top to the NE sense of shear. However, the most of shear bands are leucosome-free and indicate a top to the SW sense of shear. Enclaves in the orthogneiss are mainly mafic and impregnated of granitic melt from the host orthogneiss suggesting a partially molten state of the orthogneiss during incorporation of the enclaves. The average aspect ratio of the enclaves increases from 2 to 6 toward the contact with the Chiavenna unit. Traces elements compositions suggest, that these enclaves probably arise from the adjacent Chiavenna amphibolites.

Conventional geothermobarometric calcualtions, and P-T pseudo-sections show that migmatitic paragneiss in the Gruf complex were migmatized at T = 700–780°C and P = 7–7.5 kbar. In contrast, P–T estimates of Chiavenna amphibolites gave T= 650–750°C and P = 4–5kbar. These results show a pressure difference of ca. 3 kbar in 600 meters between the two units, which suggests a strong differential uplift of the Gruf complex in respect to the Chiavenna unit. We propose that during the rapid uplift of the Gruf complex, the enclave-rich biotite-orthogneiss was strongly partially molten and acted as a low-viscosity layer accommodating the movement between the two units. Enclaves have been probably incorporated into the orthogneiss during the uplift by mechanical and thermal erosion of the adjacent Chiavenna unit. Rapid uplift of "hot" Gruf complex produced the strong metamorphic field gradient in the Chiavenna unit, which led to the dehydration of the ultramafic rocks. This hypothesis will be tested by hydro-thermo-mechanical modelling.

Origin of garnet-gedrite-grunerite-cordierite rocks from garnet-biotite-sillimanite psamopelitic gneisses during melting and granulite grade metamorphism (Osor Complex, CCR, NE Iberia)

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g-oam-cam-crd-q gneisses (COR) occur in lenses within g-bi-sil-q semipelitic gneisses (QSP) in the sil zone of the LP-HT Variscan Osor Complex in the Catalan Coastal Ranges (NE of Barcelona). Both show similar q contents (≈ 35%), are affected by an S2 foliation, contain syn-tectonic q ± pl ± g veins with big subhedral g porphyroblasts near the veins and smaller, anhedral syn-tectonic g crystals far from the veins. In both, g show rims almost devoid of inclusions (q, op and MI's) and inclusion-rich inner zones. The outcrop relations also suggest a genetic link among the two rock types. Here we support a derivation of COR bulk composition (BC) from QSP bulk during granulite-grade metamorphism at ca. 5.5±0.5 kbar and 750±50 ºC. Geochemistry of major and trace elements suggests clear bulk composition trends going from melt-rich QSP towards Fe-Mg-Mn-Ti richer and Na-Ca-K-Al poorer, melt-depleted COR. NCKFMASTO Theriak-Domino (de Capitani and Petrakakis, 2010) closed and open system thermodynamic models of COR and QSP suggests the necessity of losing melt ± hydration. Both geochemical and thermodynamic models predict that the lost melts should have been first Na-rich and evolving towards a K-richer granitic melt, which fits with observed g-pl-q (throndhjemitic) and leucogranitic leucosomes. The closed system modelling show some inconsistencies between predicted and observed mineralogy. In QSP the observed assemblage (g-bi-sil-pl-q-op) is predicted to be supersolidus (with Na-rich liq) at around 700-750ºC and 5.5 kbar. Some observed features (decreasing bi and pl, increasing sil and crd) require higher T (≈ 800ºC), but at these conditions the model also predict kfs, which is not observed. In addition, the model predicts high melt proportions that should have been clearly unstable according to rheological critical melt percentages RCMP proposed by different authors (Rosember and Handy, 2005). On the other hand, in the improbable case that melts where not lost, retrogression would have given rise to an almost g-absent bi-sil-pl-oam-q-op assemblage, which is also not compatible with the observations. In COR the model predicted assemblage at 800 ºC and 5.5 kbak is g-q-liq-op and the genesis of cam and oam clearly requires retrograde T (< 750 ºC) and P (< 4.5 Kbar), well below the solidus. Assuming a starting QSP bulk, an open system isobaric (5.5 kbar) and isothermal (at T's 750, 800 and 850 ºC) model, that incorporates single melt losses alternating with hydration episodes that increment melt volume to the melt scape conditions of ≈10% (RCMP of Rosemberg and Handy, 2005) was performed. This model takes into account the probable melt loos, but also does not reproduce the observed assemblages. At the QSP end of the T-X diagram (X= melt loos + hydration) the inconsistencies continue being those of the closed system, whereas at the opposite end the obtained BC has differences with the real COR (the BC after successive melt loses is ≈ Na,Ca,K,Al and Ti, but it contains less Si, Fe and Mg). The assemblage predicted is g-bi-oam-sil-crd-pl-q-op and also does not fit the observed bi-sil absent, grun-bearing one in observed COR. We consider that although petrography and geochemistry support COR derivation from QSP, a thermodynamic model that reproduce accurately the genesis of the COR assemblage from the QSP one is still not achieved, although it should be an open one, incorporating melt loos ± hydration along evolving P and T and the possible non-synchronic genesis of the BC and mineral assemblage in COR.

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Titanium Stable Isotopic Fractionation during Partial Melting of Mafic Lithologies and Intracrustal Differentiation

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The recent advent of MC–ICP–MS has opened up the periodic table, enabling measurements of so called 'non-traditional' stable isotopes of elements such as titanium (Ti). Ti is a highly immobile, refractory lithophile element. As such it is unaffected by core formation, impact-driven volatilisation or fluid-mediated processes such as metasomatism and weathering. It can therefore potentially be used to trace magmatic processes alone. More specifically, because Ti predominantly exists in 5-fold co-ordination in silicate melts, in contrast to amphiboles and oxide minerals in which Ti occupies 6-folded sites. This contrast in co-ordination serves a major driver for Ti stable isotopic fractionation during magmatic processes. Because amphibole and rutile play an important role in the formation of crustal lithologies, the stable isotope composition of Ti has the potential to trace crustal formation and evolution processes by allowing us to distinguish between processes usually invoked for crustal formation and evolution such as magma differentiation, eclogite and amphibolite melting. Here, we show preliminary data aimed at unravelling the mechanics of Ti stable isotope fractionation in these three processes and testing the applicability of this new tracer to crustal processes.

All samples were processed and measured using a double spike method[1]. Following HF-HNO_3 digestion, purification of Ti was achieved using a two-step column chemistry[2]. $^{49}Ti/^{47}Ti$ isotope ratios (expressed as $\delta^{49}Ti$) were acquired using a Nu-Plasma 2 MC–ICP–MS installed at the Cardiff Earth Laboratory for Trace Element and Isotope Chemistry (CELTIC) at Cardiff University. Isotope measurements were performed in a medium resolution mode and were also bracketed by measurements of the OL-Ti standard to account for polyatomic interferences on ^{47}Ti and ^{48}Ti. Typical precision of the double spike measurements are around ± 0.02 ‰ at 95% confidence.

Previous work[3] has shown a progressive enrichment of heavy Ti isotopes with increasing SiO_2 (wt%) due to crystallisation of Fe–Ti oxides during magmatic differentiation, consistent with stable isotope fractionation theory. Preliminary data for samples from Santorini exhibits a similar positive correlation between $\delta^{49}Ti$ and SiO_2, yet, shifted to heavier $\delta^{49}Ti$ at similar SiO_2 content relative to previous data. This may indicate that Ti stable isotopic fractionation is dependent on the onset of oxide fractionation and thus, on the redox state of the primitive melts.

Preliminary studies show no significant fractionation of Ti isotopes during partial melting of mantle lithologies[3]. However, metabasic lithologies such as amphibolite and eclogite contain Ti-rich phases such as amphibole and rutile, which host Ti in 6-fold co-ordination. Partial melting of these rocks could thus induce significant Ti isotope fractionation. We tested this using a set of residual eclogites and associated leucosomes from the Sulu Orogen (China). Initial data suggests progressive partial melting of rutile-bearing eclogites drives leucosomes to heavy $\delta^{49}Ti$ values (heaviest $\delta^{49}Ti = +1.22 \pm 0.03$‰), whilst eclogite residues are progressively enriched in light isotopes. Further work will focus on partially melted eclogites from Koidu (Sierra Leone) and eclogite-leucosomes pairs from Kristiansund (Norway), as well tracing amphibolite melting processes in the Lewisian Complex (Scotland). Doing so, this will enable us to better constrain the mechanics of Ti isotope fractionation in magmatic processes, which will be a key step towards establishing its usefulness in the study of crustal processes.

Geochemical mapping of melt-related features at outcrop scale

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Partially molten rocks are heterogeneous at all scales, from the mineral (or sub-mineral) scale to the map scale. Short wavelength chemical variations are described in the thin section using e.g. microprobe. Chemical variations at 100–1000 m scale are described using whole rock analyses of more or less regularly spaced samples. However, chemical variations at the scale of the hand specimen or the outcrop are rarely, if at all described.

This poster aims at discussing some methods, and showing preliminary results towards that end. We used two main tools: portable XRF, and gamma-ray spectrometry. Portable XRF allows to analyze a large range of elements, on a 5–10 mm spot. It is therefore highly sensitive to grain-scale heterogeneities, especially in coarse-grained rocks. It is also strongly affected by surface alteration or uneven surfaces, restricting its use to fresh and polished outcrops. Gamma-ray spectrometry integrates gamma from a volume of ca. 1 m^3 and is therefore unaffected by alteration or large grains. It is also used as an airborne sensor, allowing to cover relatively large areas (1–1000 km^2). On the other hand the spatial resolution cannot be better than ca. 1 m, and only three elements (U, Th and K) are analyzed. We present some examples of both methods.

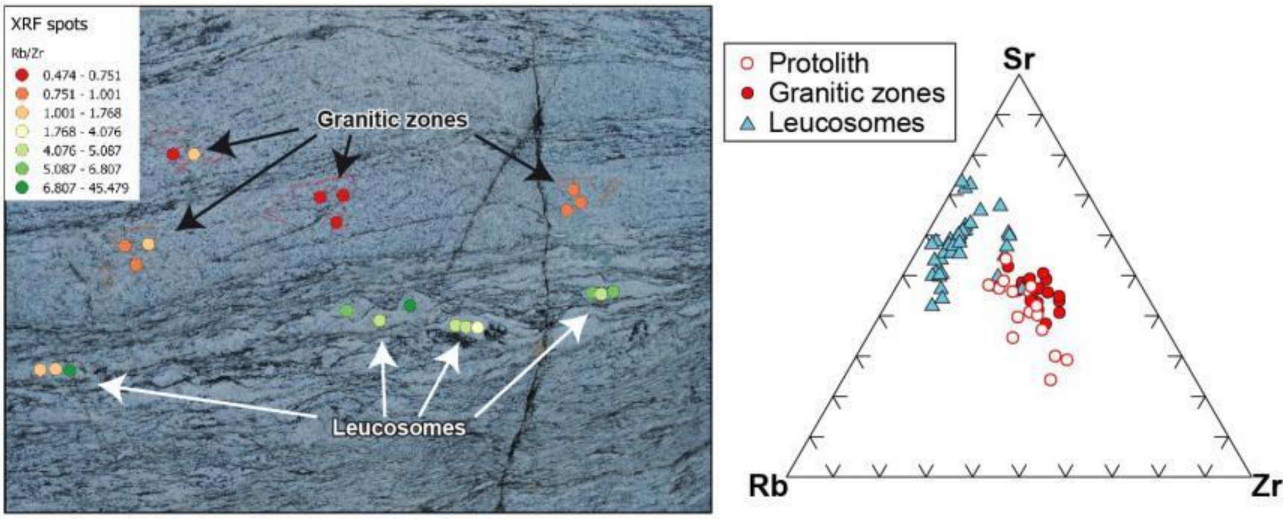

Figure 1: pXRF data on an outcrop of Variscan migmatitic orthogneisses in the French Massif Central. Two types of melt features ("leucosomes" and "granitic zones") have strongly different Zr contents (and Rb/Zr ratios), probably evidencing the differet behavior of zircon during two successive melting events.

Water redistribution in the continental crust

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Fluids circulation in the lithospheres (e.g. H_2O, CO_2) exerts a direct control on a large range of processes such as the nature of partial melting mechanisms; magma crystallization in the crust; magma ascent and the explosive behavior of volcanic eruptions. Quantifying the volume and flux of crustal water and fluid-mobile species through the aid of phase equilibrium modelling has been the focus of many recent studies. In the oceanic lithosphere, this approach has been used to predict the behavior of noble gas in subduction zones[1] and even the fate of plate tectonics on other planets[2]. By applying a similar approach to continental rocks metamorphosed under Barrovian conditions, we found that the relatively minor compositional variation that exists between Archean, Proterozoic, and Phanerozoic siliciclastic rocks can lead to significant variations in the depth and sequence of dehydration.[3] This variation is largely a response to differences in the bulk ferromagnesium and potassium content of the protolith. In the Archean, the high ferromagnesian content of the supracrustal lithologies increases chlorite stability at high temperatures and is responsible for more 60% of the water contained in H_2O-bearing mineral phase to be released from the rock during the prograde path. Such phenomenon will prevent or limit the formation of subsolidus muscovite. Consequently, fluid-absent biotite dehydration melting is likely to play a greater role in the generation of peraluminous melt during high-grade metamorphism of Archean aged siliciclastic units and will generate highly viscous Ca-poor and Mg-rich magmas.

To test the hypothesis that water loss in Archean metasedimentary rocks led to water-fluxed melting of surrounding lithologies[4], we used the well-study example of the Dharwar craton where an entire 500 km long Meso- to Neoarchean crustal section of low grade to migmatitic units (850°C and 8 kbar) is exposed. These supracrustal units are believed to have been brought down lower crustal levels via gravitational instabilities trough a short period of time (5–20 Ma)[5]. Thermodynamic modelling show that the *ca.* 3.0 Ga TTG basement can retain a maximum of 0.2 wt% water in hydrous minerals. For a basement/supracrustal unit ratio of 3.2[6], the supracrustal lithologies will release 0.44 wt% of water to the basement, leading to the production of >20 vol% of melt at peak metamorphic conditions, in contrast with <5 vol% melt for fluid-absent melting. The generated melts and peritectic phases from the basement and the supracrustal units match the composition of the post-tectonic granites in the Dharwar craton.

Our findings suggest that composition of the source material may perceptibly influence the chemical properties of the lower crust and the nature of crustal reworking mechanisms through time. The capacity for Archean supracrustal lithologies to carry mineral-bound water to higher temperatures may allow greater production of anatectic melt during the reworking of ancient terrains.

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Crustal and associated volatile recycling through Archaean subduction: evidence from $\delta^{18}O$ and δD values in mantle eclogites

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Mantle eclogites represent the oldest relics of the primitive crust, preserved in the lowermost part of continental roots, accessible only as xenoliths sampled by kimberlite magmas. This study focuses on the petrology and geochemistry of 13 non-metasomatized eclogite xenoliths from the Kaapvaal and Siberian cratons. These samples derive from the base of the cratonic keels (150–200 km) and include bimineralic, (garnet (grt)-omphacite (cpx)) and corundum (cor)-bearing eclogites.

Reconstructed whole rock incompatible element compositions of bimineralic eclogites are consistent with an Archaean to Paleoproterozoic protolith derived from an evolved picritic liquid, whereas cor-bearing eclogites reflect a pyroxene-dominated cumulate. Together with the wide range in $\delta^{18}O$ values (1.1–6.6 ‰), these compositions adhere to a depleted oceanic crustal protolith, which underwent low-to high-temperature hydrothermal alteration.

The omphacite within these samples preserve a total water content roughly between 2750 and 5300 ppm and between 720 and 4900 ppm in eclogites from the Siberian and Kaapvaal cratons respectively. It is generally accepted that water can be introduced into the mantle via a subducting slab, bearing hydrous minerals, however this is believed to be restricted to the shallow part of the mantle. However, water preserved in nominally anhydrous minerals (NAMs) attest to water being preserved in the subcratonic mantle down to the Lithosphere-Asthenoshpere Boundary (LAB), among which omphacite, a main constituent of mantle eclogites, have the highest water content.

Regardless of craton and eclogite emplacement, omphacites with highest water contents (> 4000 ppm) generally have low δD values (< –110 ‰) and samples with lower water contents have slightly higher δD values (–100 to –90 ‰), as a possible result of partial dehydration. Two distinct trends towards present mantle composition (–90 to –60 ‰) are preserved, interpreted as evidence for slow re-equilibration with the surrounding mantle. It is inferred crustal recycling in the Archean was an important factor on global water cycle and water incorporation in the upper mantle. Nevertheless, dehydration effects on hydrogen isotope fractionation remain poorly understood at mantle conditions and no experimental data on hydrogen fractionation in NAMs during dehydration is available for comparison. Recent studies suggest Archaean mantle had lower oxygen isotope composition than modern mantle, which may be the case for hydrogen and other volatile components.

Secular evolution of UCC as inferred from Ti isotope composition of glacial diamictites

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The processes by which continental crust was generated and has evolved through time remains controversial due to the incomplete nature of preserved rock record [1]. It is not clear when and in what geodynamic settings the presumably basaltic proto-crust of Earth evolved into modern continental crust of largely andesitic composition. Non-traditional stable isotope systems such as titanium (Ti) provide a promising tool to track continental crust generation as Ti isotopes undergo significant mass-dependent fractionation during magmatic differentiation [2]. Millet et. al. (2016) has shown that differentiated magmas are characterized by enrichment in heavy Ti isotopes, possibly due to preferential extraction of isotopically light Ti into Fe-Ti oxides during fractional crystallization, while basalts display homogeneous Ti stable isotope composition that is indistinguishable from bulk silicate Earth. Using fine-grained terrigenous sediments (shales) as a proxy for the composition of the emerged continental crust [3], it was shown recently that the Ti isotope composition of the upper continental crust was largely invariant with time and remained isotopically heavy relative to bulk silicate Earth. This was used to infer prevalence of felsic continental crust on Earth since at least mid-Archean and thereby early initiation of plate tectonics. Several studies have, however, pointed out that mineral sorting during weathering could result in the loss of heavy minerals such as rutile and ilmenite affecting the Ti-budget in shales [e.g. 4].

Glacial diamictites, which are composed of poorly sorted sediments derived from physical erosion of upper continental crust by ice sheets with little evidence for chemical weathering, have been used as an alternate proxy for estimating the upper continental crust (UCC) composition in several studies (e.g. 5). Diamictites derived from continental ice sheets reflect an expansive provenance and could provide a more robust estimate of average composition of UCC as they avoid grain size-related elemental loss. We investigate the mass dependent Ti isotope composition of glacial diamictite reference suites of Gashing et. al. (2016) derived from four pre-Cenozoic statigraphic intervals with ages ranging from 2.9 Ga to 0.3 Ga. The results are used to constrain secular variations in the composition of continental crust in the context of initiation of plate tectonics and onset of crustal reworking. In addition, we will also present Ti isotope data for representative sorted sediment suites derived from mafic and felsic lithologies to understand the effect of source rock mineralogy and grain size sorting during transport in the Ti-isotope record of sediments.

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Mineral equilibria constraints on the feasibility of fluid-fluxed melting in the continental crust

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Fluid-fluxed melting was largely refuted as a significant petrogenetic process in the 1980s when dehydration melting became established as the primary mechanism for the generation of granitic magmas in the continental crust. However, it has regained some recognition as a potentially important process in crustal differentiation during the last few years. This renewed interest is prompted by specific case studies of mostly amphibolite-facies grey gneisses and low-pressure metapelites that demonstrate anatectic features that are inconsistent with dehydration melting. These are (1) voluminous melting at relatively low temperature, at conditions where hydrous minerals are still stable and (2) melting occurring via the consumption of anhydrous phases such as alkali feldspar, whereas (3) hydrous minerals are not consumed. In this study, fluid-fluxed melting of these rock types is investigated through phase equilibria modelling in order to constrain the conditions and mechanism(s) by which it might be a viable petrogenetic process. Our modelling results reproduce the key petrological observations of the process, including the continued stability of hydrous minerals, the preferable consumption of alkali feldspar, quartz, and plagioclase, and the growth of observed peritectic phases. The modelling indicates that the feasibility of fluid-fluxed melting critically depends on the size and water activity (aH$_2$O) of the reservoir that supplies fluid. A nearby fluid reservoir with higher aH$_2$O than the unmelted protolith is capable of diffusing H_2O into the site of melting. Once melting has initiated, melt production is only limited by the volume of external fluid available and the amount of each solid reagent, chiefly alkali feldspar and quartz, in the protolith. Given these constraints, about 4 vol.% melt is produced for every 1 vol.% of H_2O that is fluxed into the site of melting. Potentially viable fluid sources that are available in the anatectic region of the crust are crystallising magmas and low-aH$_2$O metamorphic fluids. In addition, shear zones are required to focus and concentrate these diffuse fluids to the sites of melting. Therefore, whereas fluid-fluxed melting is a feasible petrogenetic process, it requires specific conditions and circumstances that preclude it from being a major contributor to crustal differentiation.

Tiny timekeepers witnessing high-rate exhumation processes

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Tectonic forces and surface erosion lead to the exhumation of rocks from the Earth's interior. Those rocks can be characterized by many variables including peak pressure and temperature, composition and exhumation duration. Among them, the duration of exhumation in different geological settings can vary by more than ten orders of magnitude (from hours to billion years). Constraining the duration is critical and often challenging in geological studies particularly for rapid magma ascent. Here, we show that the time information can be reconstructed using a simple combination of laser Raman spectroscopic data from mineral inclusions with mechanical solutions for viscous relaxation of the host. The application of our model to several representative geological settings yields best results for short events such as kimberlite magma ascent (less than ~4,500 hours) and a decompression lasting up to ~17 million years for high-pressure metamorphic rocks. This is the first precise time information obtained from direct microstructural observations applying a purely mechanical perspective. We show an unprecedented geological value of tiny mineral inclusions as timekeepers that contributes to a better understanding on the large-scale tectonic history and thus has significant implications for a new generation of geodynamic models.

Re-evaluating the high-temperature metamorphic evolution of Rogaland, SW Norway

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The Rogaland–Vest Agder (RVA) Sector of SW Norway is a high-grade metamorphic complex containing a number of magmatic suites, including the voluminous (1000 km^2) anorthosite massifs of the Rogaland Igneous Complex (RIC; 930–920 Ma). The RVA Sector has experienced limited overprinting following the Sveconorwegian Orogeny (1200–900 Ma). Two alternative *P*–*T* evolutions have been previously proposed for the Sveconorwegian metamorphic evolution. The first proposes a polymetamorphic evolution, with a clockwise regional *P*–*T* path followed by a later lower-*P* higher-*T* contact metamorphic event related to the intrusion of the Rogaland Igneous Complex [1,2]. The other proposes a single long-lived UHT clockwise *P*–*T* path, with no connection between metamorphism and the RIC as a result of the interpreted age of metamorphism predating the emplacement of the RIC [3].

Through a combination of SHRIMP U–Pb geochronology, LA–ICP–MS trace elements, $^{40}Ar/^{39}Ar$ thermochronology and phase equilibria modelling, we re-evaluate the *P*–*T*–*t* evolution of the RVA Sector. Prograde high-*T* partial melting began at 1059 ± 12 Ma based on the recrystallisation of zircon and $^{40}Ar/^{39}Ar$ dating of osumilite. Peak regional metamorphism reached 800–950ºC at 7–8 kbar [4] at ca. 1035–995 Ma, followed by regional melt crystallisation at 951 ± 14 Ma, after which no further zircon or monazite growth occurred in rocks outside the metamorphic aureole. Samples within the aureole show a continuum of ages (ca. 1050–900 Ma) with no clear evidence of a melt crystallization event until ca. 900 Ma, some 30 Myr after the emplacement of the RIC. The continuum of ages is interpreted to represent prolonged residence at high-*T* associated with slow cooling between regional and later contact metamorphism. Contact metamorphism reached >900ºC at 3–6 kbar [4], with rocks at the RIC contact reaching conditions of ~1100ºC for between 1–5 Myr based on diffusion modelling. We conclude that high-*T* conditions were sustained in the RVA Sector for ~100–160 Myr.

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Pulsed versus protracted ultrahigh temperature metamorphism in Rogaland, contrasting records of monazite and zircon

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In Rogaland, South Norway, a polyphase granulite facies metamorphic domain surrounds the late-Sveconorwegian anorthosite–mangerite–charnockite (AMC) plutonic complex. Investigation of zircon U–Pb geochronology and Ti-in-zircon thermometry provides firm evidence of protracted melting lasting up to 110 My (1040–930 Ma) in the UHT zone[1]. In apparent contrast, combined Y-in-monazite thermometry and monazite U–Th–Pb geochronology allows to identify discrete metamorphic phases culminating twice at ultrahigh temperature (UHT), in the time window between 1040 and 930 Ma[2]. The geological signals of zircons and monazite may be reconciled to draw polyphased geological evolution by evaluating their respective mineralogical behavior during granulite facies metamorphism, highlighting their complementary strength and weakness as petrochronometers. Overall, monazite records discrete chemical events, fingerprinted by tracers such as REE, Y or S, that are linked to changes of metamorphic conditions including changes of redox state[3] . In contrast, zircon mimics apparent "continuous" crystallization, between 1040 and 930 Ma, with no or little REE variation to discriminate different populations. The spread of apparent ages captured by zircon results both from open-system growth and closed-system post-crystallization disturbance. Post-crystallization disturbance is evidenced by inverse age zoning induced by solid-state recrystallization of metamict cores while zircon neocrystallization is documented by specific cathodoluminescence characteristics and O isotope open-system behaviour. Deciphering between a pulsed or protracted metamorphism thus requires to bear in mind that the mineralogical record is affected both by time dependant processes such as radiation damage recovery and geologically instantaneous mechanisms such a dissolution–precipitation. The unmatched strength of zircon to survive several metamorphic cycles may become in this precise case a weakness, preventing a total resetting of its U–Pb clocks and chemistry *via* open system processes. The zircon record is thus more likely to give an impression of continuous metamorphism whereas monazite give a taste of catastrophism with well identified crystallization events through time. Although zircon is a very accurate tool for U–Pb geochronology, monazite provides better chemical discrimination of specific petrological events in granulite facies rocks.

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Formation of sillimanite nodulargneisses, Western Gneiss Region, Norway

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Coarse-grained sillimanite-bearing nodular gneisses are found in the Western Gneiss Region following a zone extending from Sunndalen, through Romsdal to Sunnmøre. Sillimanite-bearing gneisses from the mountain massif Mannen in Romsdalen have been investigated with respect to the formation and origin of the nodular gneisses. Foliated augen gneisses with coarse K-feldspar porphyroblasts occur with domains of sillimanite, or a mantling of sillimanite around K-feldspars. Muscovite (Si = 6.1 a.p.f.u.), plagioclase ($An_{29\text{-}30}Ab_{69\text{-}70}$), biotite (Mg# = 0.48–0.51) and locally garnet ($Alm_{52\text{-}56}Prp_{15\text{-}16}Grs_5Sps_{24\text{-}29}$; Mg# = 0.22–0.23) are part of the assemblage. Related garnet-mica schist show garnet composition $Alm_{52\text{-}54}Prp_{10\text{-}12}Grs_{11\text{-}18}Sps_{16\text{-}27}$ and Mg# = 0.16–0.18, phengite (Si < 6.5 a.p.f.u.), K-feldspar, plagioclase ($An_{29\text{-}43}Ab_{56\text{-}70}$) and biotite (Mg# = 0.44–0.46).

P–*T* calculations were performed on Grt–Sil-bearing gneiss, based on the assemblage Grt + Pl + Qtz + Bt + Wm + Sil, and on Grt-Wm-bearing gneiss, based on assemblage Grt +Pl +Qtz +Bt + Wm. The calculations yield T up to 838 ± 75°C at P = 0.85 ± 0.22 GPa for the Grt–Sil gneiss, and P up to 1.04 ± 0.12 GPa at T = 701 ± 39°C for the Grt–Wm gneiss. This is in accordance with results achieved by calculation of *P*–*T* pseudosections where phase stability shows production of the Grt–Sil assemblage above 750°C, and garnet–white mica above 0.9 GPa.

Detailed petrographic studies revealed replacement of K-feldspar by sillimanite-quartz-white mica paragenesis following the reaction K-feldspar = sillimanite + quartz + white mica. The reaction needs addition of water, and produces a large amount of SiO_2 and excess K as shown by the following balanced reaction:

$$5\ KAlSi_3O_8 + H_2O = Al_2SiO_5 + 11\ SiO_2 + KAl_2(AlSi_3O_{10})(OH)_2 + 4\ K$$

The excess K needs to be removed and may cause metasomatism in the adjacent rock. Our results show that the sillimanite-gneisses in Western Gneiss Region originated at about 30 km crustal depth and temperature in excess of 750°C. Presence of K-feldspar porhyroblasts may represent a precursor and site for the sillimanite-production.

Localized occurrences of granulite: *P–T* modeling, U–Pb geochronology and distribution of early-Sveconorwegian high-grade metamorphism in Bamble, South Norway

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Documentation of new localities of granulite north of Kragerø in the Bamble lithotectonic domain (south Norway) illustrates localized distribution of granulite facies rocks in an amphibolite facies gneiss terrain. U–Pb zircon SIMS data constrain the magmatic age of the protoliths to be both 1545 ± 7 to 1542 ± 5 Ma and 1149 ± 8 Ma. The oldest age corresponds to abundant Mesoproterozoic calc-alkaline magmatism in Bamble, while the second age represents a regional 1200-1150 Ma intrusive event. The timing of a granulite-facies metamorphism is provided by a robust date of 1139 ± 11 Ma for metamorphic zircon, supporting available estimates for early Sveconorwegian metamorphism in Bamble.

P–T modeling using Grt + Opx ± Cpx +Pl + Bt + Qz assemblages yields pressures up to 1.15 GPa and *T* >850°C. Clinopyroxene-free granulite assemblages are preserved in low-strain lenses, while high-strain granulite shows crystallization of clinopyroxene. Clinopyroxene-free granulite samples are in general preserved in low-strain lenses, while high-strain granulite shows crystallization of clinopyroxene. The presence of high-strain Cpx-bearing granulite in the hangingwall of the Kristiansand-Porsgrund Fault and Shear Zone, gives evidence that the deformation along this shear zone started at high metamorphic grade. The replacement of orthopyroxene by amphibole within the same strain-regime illustrates hydration and reequilibration at amphibolite facies.

The new findings in Bamble show that granulite-facies rocks occur unevenly distributed in high-grade metamorphic terrains and that relationship between granulite and amphibolite facies are more complex and irregular than integrated in the isograd concept. It suggests that factors as fluid availability, deformation and whole-rock composition are important for metamorphic evolution in addition to pressure and temperature gradients.

Mechanically controlled chemical zoning in UHP garnets from the Western Gneiss Region, Norway

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Garnets from the Western Gneiss Region (WGR) experienced Caledonian ultra-high pressure (UHP) metamorphism with peak metamorphic conditions around 800°C at >3.2 GPa, and a post-UHP amphibolite-facies overprint during exhumation. Garnets from this region preserve prograde chemical zoning, despite being exposed to high temperature during slow subduction and exhumation of the WGR. Current knowledge on chemical diffusion rates in garnet may not be enough to explain the preservation of zonation in these garnets because at the million-year time scale it predicts complete chemical re-equilibration at such high temperature. Interestingly, when chemical diffusion is relatively fast, the development and preservation of compositional zoning in minerals can be strongly influenced by mechanically maintained pressure variations (Tajcmanova 2015).

Here, we compare the application of conventional diffusion methods with the newly developed unconventional quantification methods (Vrijmoed & Podladchikov, 2015) on natural garnets from the WGR. The new approach predicts compositional zoning as a result of spatially varying pressure at chemical equilibrium. The results are used to test whether the observed chemical zoning can be fit by equilibrium at heterogeneous pressure. First results show a good fit with natural observed chemical zoning in garnet multi-component systems. This enables an explanation for chemical zoning by local pressure variations instead of sluggish kinetics.

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