Metamorphic Studies Group

40th anniversary
Research in Progress meeting

29–31 March 2021
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### Notes:
- *Keynote/invited/prize talk (30 minutes)
- All times = British Summer Time = BST = GMT+1
- All sessions hosted on Zoom except for the poster sessions, which will be on Gather.Town

**Author index**
A perspective on 40 years of advances in metamorphic geology

Brown, M.

Department of Geology, University of Maryland, College Park, MD 20742-4211, USA

In the late 1970s the changing focus of research presented at the Tectonic Studies Group annual meeting, summarized nicely by Rob Butler in his TSG@50 lecture, led me to propose to the Geological Society Council, via Tony Barber, the formation of a new group for metamorphic studies. The Metamorphic Studies Group was approved by the Councils of the Geological Society and, at Bernard Leake’s suggestion, the Mineralogical Society in 1980. I convened the inaugural RiP meeting at Burlington House on the 5 March 1981, with >150 people attending. Scientific advances go hand in hand with major developments in theory, experimental methods and instrumentation, and computational power and modelling capabilities. However, allow me to extend this perspective by about a decade. Some of us at this RiP meeting were also present 40 years ago, but our formative years as students in the 1960s coincided with the first major development in the Geosciences in over a century—the paradigm shift from geosynclinal theory to plate tectonics. Over more than 50 years, there have been amazing changes as the Geosciences matured from a mostly observational science into one based on sound theory, quantification and modelling. We have seen an evolution from the manual electron probes and X-ray diffractometers, the first commercial X-ray fluorescence spectrometers, and the early clean labs and mass spectrometers to the wide range of sophisticated instrumentation available today. Some worry that this transition has led to a lack of understanding of fundamentals, but I believe this concern is exaggerated. Our first 40 years has been a golden age in which quantification of $P$–$T$–$t$ has developed from simple thermobarometry, hard-won major element maps and limited geochronology in the 1970s to the widespread application of calculated pseudosections, pixel-scale major and trace element maps and petrochronology today. In the last decade, the use of numerical modelling to test geodynamic hypotheses has become common.

Metamorphic rocks serve as flight recorders—tracking the $P$–$T$–$t$–$d$ paths of crustal rocks through (mostly) orogenic cycles. Reading these records requires an integrated approach using multiple types of analysis, synthesis and interpretation, from the atomic to the map scale, leading to tectonic reconstructions. This has been our ‘bread-and-butter’ for the past 40 years and we have become really good at it. However, these studies, which are based on equilibrium thermodynamics under hydrostatic stress conditions, are now (mostly) routine. To make further progress in understanding metamorphic and orogenic processes we will have to develop the theory of thermodynamics under nonhydrostatic stress conditions [1]. Tajcmanová [2] estimated that four-fifths of new journal articles concern regional $P$–$T$ studies. Although many of these studies apply a wide range of techniques, all too commonly the resulting articles only address regional implications rather than advancing understanding of Earth processes; consequently, such articles are read by few. What have we gained or lost in 40 years (see also [2])? We have discovered that heterogeneity in chemical composition and mechanical properties occurs at all scales, but maybe our ability to measure natural variability has outstripped our capability to interpret it. Are we losing our observational, particularly petrographic, skills; does this matter? We now realize that disequilibrium and kinetics are as important as equilibrium. However, we don’t fully understand the source of orogenic heat, the role of ‘pressure’ (stress) on equilibrium, or how metasomatism (e.g. during subduction) works. These may be fundamental questions in metamorphic studies, but are they important to the broader Earth Sciences community or Society? Metamorphic studies should be placed in the broader context of Earth as a fully-coupled system. We must ask and answer important questions. Tajcmanová [2] argued that we are the materials scientists of the Earth, but will this guarantee survival of the field in the future? Of the priority research questions in Earth Sciences for the next decade [3], to which can we contribute?

References:
**Polychromatic polarization: new spectacles for the good old petrographic microscope**

Cesare, B.\(^1\) and Shribak, M.\(^2\)

\(^1\)Department of Geosciences, University of Padova. Via Gradenigo 6, 35131 Padova, Italy. Email: bernardo.cesare@unipd.it

\(^2\)Marine Biological Laboratory, 7 MBL St, Woods Hole, MA 02543, USA

The polarizing microscope, the fundamental tool for any first characterization of geological materials, suffers from one major limitation, namely the poor ability to image microstructures where minerals have a retardance <400 nm and display interference colors in the gray scale. This problem, so far considered intrinsic and unsolvable, has prevented detailed optical observation of many low-birefringence (e.g., quartz, feldspars, leucite) or quasi-isotropic (e.g., garnet) rock-forming minerals. For these, alternative microscopic techniques, mostly electronic, have been developed and are routinely used. Polychromatic polarization microscopy (PPM, [1]) is a new optical technique that overcomes the above limitations and allows for the inspection of materials with retardations between 1 and 400 nm. This is achieved by means of a full spectrum color palette, where the hue depends on orientation of the slow axis and the saturation depends on the retardance amount.

We have applied the PPM technique to regular 30 µm rock thin sections, with a particular interest for the subtle birefringence of garnet, due both to non-cubic growth [2] or to strain induced by external stresses or by mineral inclusions. The PPM produces striking, colorful images that highlight different types of microstructures in very low retardance phases, which are virtually undetectable by conventional polarizing microscopy (Figure 1).

The PPM will open new avenues for microstructural analysis of geological materials. On one hand, the direct detection and imaging of microstructures will provide a fast and cheap alternative (or complement) to time-consuming and more expensive SEM-based analyses such as, e.g., EBSD. On the other hand, this powerful imaging method will provide – again in a very fast way – a much better texturally constrained basis for the location of targets for cutting-edge applications such as, e.g., FIB-TEM or Atom Probe.

![Image](image.png)

**Figure 1** – The same crystal of tetragonal garnet studied in [2] viewed under crossed-polarizers (left), with the \(\lambda\) plate (center), and under PPM (right). The thin section has a regular 30-µm thickness.

**References:**


Despite some 50 years of intense research on samples returned from the Apollo missions and lunar meteorites, along with remote-sensing and Earth-based observations, many questions regarding the formation and evolution of the Moon persist. These include the detailed compositional and density structure of the lunar mantle and the source and petrogenesis of the diverse suite of extrusive and intrusive igneous rocks. There is broad agreement that the primary internal structure of the Moon reflects crystallisation of a lunar magma ocean (LMO), and that an inverted density gradient within the mantle cumulates led to some reorganisation of layers by partial convective overturn. Experimental studies have provided invaluable constraints on crystallisation of the LMO, but are limited by the relatively small number of experiments that can practically be undertaken. Here we use recently-developed thermodynamic models for minerals and melt in the \( \text{K}_2\text{O–Na}_2\text{O–CaO–FeO–MgO–Al}_2\text{O}_3–\text{SiO}_2–\text{TiO}_2–\text{Cr}_2\text{O}_3 \) system to model crystallisation of a full-moon LMO based on two existing end-member bulk compositions—Taylor Whole-Moon (TWM), and Lunar Primitive Upper Mantle, LPUM—on which many experimental studies have been based. We follow several recent studies in considering equilibrium crystallisation of the first 50 vol.% and fractional crystallisation thereafter. Our results match well with experimental studies, and provide detailed constraints on the major oxide composition, mineralogy and density structure based on the two starting compositions that, while exhibiting some similarities, show important differences. The more fertile TWM composition contains significant quantities of garnet in the deep mantle, whereas the LPUM composition has none. By contrast, prior to any gravitational overturn, the uppermost mantle cumulates for TWM are strongly silica-undersaturated and contain abundant aluminous spinel, whereas those for LPUM are silica-saturated. For both starting compositions, with the exception of TiO\(_2\) and Na\(_2\)O, our modelled compositions of the final dregs of fractionated melt show a reasonable match with existing estimates on the composition of urKREEP. Modelled partial melts of the upper-mantle cumulates at low to moderate melt fractions have major oxide compositions that match well with low- and intermediate-Ti lunar basalts. The correspondence is particularly good for picritic (green) glasses that likely represent melts derived from deeper levels within the upper mantle. The wide spread in TiO\(_2\) concentrations in lunar basalts and basaltic glasses is consistent with density-driven reorganisation involving ilmenite. Our simulations provide thermodynamically-robust estimates of the compositional, mineralogical and density structure of the lunar interior that are unprecedented in their detail, and which provide the foundation for several lines of future research addressing the origin and secular evolution of the Moon.
Earth’s metamorphic signal, supercontinent cycle and plate tectonics

Nobili G.¹, Moreira H.² and Schannor M.³

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Plate tectonics is the surface expression of Earth’s internal geochemical and geophysical evolution, but its origin and how it evolved towards its modern-style remain highly debated questions[1]. In modern convergent settings, the coexistence of subduction and back-arc related metamorphism represents a hallmark of present-day tectonic processes[2]. The gradual increase in the abundance of paired metamorphic belts in the geological record since the Paleoproterozoic[2,3] indicates Earth’s progressive shift towards a generalised plate tectonic regime. Although such evolution has been argued to reflect the secular cooling of the mantle[4], there is a lack of detailed information concerning the metamorphic evolution of each supercontinent cycle taken separately. Similarities and/or differences between these cycles are keys to decipher the linear or episodic nature of plate tectonic processes.

In this study, we introduce the notion of Earth’s metamorphic signal, a time series defined by both the apparent metamorphic gradient (i.e. temperature/pressure – T/P) and the speed at which rocks were buried in convergent settings (i.e. apparent burial rates - ABR). Using change point analyses on the metamorphic time series we show that the Earth went through two main changes at ca. 1850 Myr and 550 Myr ago. We define a classification system for specific tectonic scenarios based on the distribution of T/P and ABR through time that allows evaluation of the diversity of metamorphic processes during supercontinent cycles. This approach enables using Earth’s metamorphic signal as a proxy to investigate Earth’s ability in efficiently coupling surface processes (e.g. weathering, sedimentation) and solid earth mechanisms (e.g. convection). Our results show that the deviation of the metamorphic signal from its background value (900 °C/GPa⁻¹ and 0.69 km Myr⁻¹) is different for each supercontinent cycle. The new data support pervasive subduction mechanisms since 2200 million years ago and suggest a significant change in burial rates and metamorphic conditions at 1850 ± 50 and 550 ± 50 million years ago. The period within the two significant changes between 1750 and 850 million years shows reduced plate tectonic activity.

We propose that Earth’s metamorphic signal reflects the fluctuation in the coupling efficiency between surface mechanisms and mantle processes and its interplay with supercontinent cycles. Such model offers an integrated view on the evolution of plate tectonics. In addition, our model can be used to link deep geological and surface biological processes, necessary to further our understanding of the apparition and evolution of life on Earth.

References:
Ultra-high temperature metamorphism in space and time

Roberts, N.M.W.¹

¹Geochronology and Tracers Facility, British Geological Survey, Nottingham, NG12 5GG. nirob@bgs.ac.uk

The global metamorphic record provides crucial insight to Earth’s evolution, in particular, the nature of tectonic and orogenic processes in response to secular mantle cooling. Ultra-high temperature metamorphism (UHT-M) is now recognised in many ancient orogens, as well as in several recent and active tectonic environments. The tectonic settings and causes of extraneous heat flow producing UHT-M are debated, wide-ranging, and for many ancient occurrences, still elusive. Using an updated compilation of around 75 UHT terranes, I review the tectonic settings of UHT-M through Earth history, compare these with numerical geodynamic models, and evaluate potential links with the supercontinent cycle. The results provide insight to the thermal and tectonic evolution of Earth.

The duration of UHT-M is highly variable, with short (<5 Myr) and long (>50 Myr) events occurring throughout most of the Neoarchean to Cenozoic record. The formation of UHT-M in orogens with major continent-continent collision compared to those within accretionary orogenic settings occurs in a ratio of about 3 to 2. The majority of ancient UHT-M terranes formed in time periods associated with supercontinent assembly, but not exclusively. The supercontinents Columbia (Nuna), Rodinia, Pannotia (Gondwana) and Pangea, all include UHT-M formation in both collisional and accretionary orogens. This indicates that UHT-M forms on the exterior of supercontinents along convergent margins, as well as within the major collision zones such as the East African Orogen. Links between supercontinent assembly and UHT-M have been commonly invoked, but the existence of numerous modern and recent occurrences in both collisional and non-collisional tectonic settings, suggests that the link is related to preservation, rather than generation.

Claimed tectonic settings of UHT-M cover continental arcs, back-arc, arc-continent and continent-continent collisions, as well as ultra-hot collisional orogens for some ancient examples. Back-arc are a commonly invoked setting, as they comprise several features suited to the formation of UHT-M, critically, thinned lithosphere above hot asthenospheric mantle. Even where UHT-M is found in collisional orogens, UHT-M is oft cited as forming in the precursor back-arc environment prior to collision. Numerical modelling shows that the temperatures required for UHT-M are unlikely to be reached in stable continental arcs, but that short durations of heating can occur in compressional arcs and extensional arcs. Of the ca. 75 UHT terranes, mantle heating after lithospheric thinning is the most commonly cited process. Recent work suggests this process is even applicable to modern thick continent-continent collisions[1].

Back through time, hotter average mantle temperatures influenced tectonic processes. Numerical modelling, particularly of Archaean conditions, describes several tectonic processes that differ from those operating today. ‘Peel-back’ tectonics[2] and ultra-hot orogens with wide zones of convergence[3] are two permissible settings that fit various natural observations of preserved Archaean terranes. Weak lithosphere and voluminous decompression melting of the mantle imply that UHT-M conditions were more readily produced in the lower continental crust of the Archaean, and probably well into the Proterozoic. The lack of abundant UHT-M terranes greater than 2 Ga thus, clearly relates to issues of preservation. The Proterozoic is a time of transitional change between Archean and modern-day tectonics, and comprises a large abundance of UHT-M that can be ascribed to formation in back-arc settings. Except for the Archaean, the range of geothermal gradients exhibited by the preserved UHT-M record are largely unchanged through time.

References:
The absence of ultrahigh pressure (UHP) orogenic eclogite in the geological record older than c. 0.6 Ga is problematic for evidence of subduction having begun on Earth during the Archean (4.0–2.5 Ga) [1]. Many eclogites in Phanerozoic and Proterozoic terranes occur as mafic boudins encased within low-density felsic crust, which provides positive buoyancy during subduction; however, recent geochemical proxy analysis shows that Archean continental crust was more mafic than previously thought. Here, we show via petrological modelling that secular change in the composition of upper continental crust (UCC) would make Archean continental terranes negatively buoyant in the mantle before reaching UHP conditions. Subducted or delaminated Archean continental crust passes a point of no return during metamorphism in the mantle prior to the stabilization of coesite, while Proterozoic and Phanerozoic terranes remain positively buoyant at these depths. UHP orogenic eclogite may thus readily have formed on the Archean Earth, but could not have been exhumed, weakening arguments for a Neoproterozoic onset of subduction and plate tectonics. Further, isostatic balance calculations for more mafic Archean continents indicate that the early Earth was covered by a global ocean over 1 kilometre deep.

References:
High-grade Archean gneiss terranes expose mid to lower crustal rocks and are generally dominated by tonalite-trondhjemite-granodiorite (TTG) gneisses. Occurrences of mafic-ultramafic bodies and garnet-bearing felsic gneisses within these environments have been interpreted as supracrustal or near-surface rocks requiring a tectonic process involving mass transfer from the near-surface to the mid-crust. However, there is significant uncertainty regarding the nature of this mass transfer, with suggestions including a range of uniformitarian and non-uniformitarian scenarios. One non-uniformitarian scenario, ‘sagduction’, has been proposed as a possible mechanism ([1] and references therein), although the dynamics of sagduction are still relatively unexplored.

This study focuses on mafic, ultramafic and garnet-bearing felsic gneiss bodies in the central region in the Lewisian Gneiss Complex of northwest Scotland as test cases to investigate the behaviour of possibly supracrustal rocks in a mid-crustal environment. Existing datasets of TTGs [1] mafic gneisses [2] and ultramafic gneisses [3] from across the central region were utilised in addition to felsic and mafic gneiss samples obtained in this study from the ~10 km² Cnoc an t-Sidhean (CAS) suite. The CAS suite is the largest reported supracrustal in the Lewisian, and dominantly comprises garnet-biotite felsic gneiss assemblages and an associated two-pyroxene mafic gneiss. Field mapping was undertaken to collect samples representative of the observed heterogeneity of the suite, and to assess field associations between possible supracrustals and surrounding TTGs. Phase equilibria modelling was conducted on all lithologies to ascertain peak pressure-temperature ($P$-$T$) conditions, and to calculate the density of the modelled rocks at peak conditions.

The results obtained in this study indicate peak metamorphic conditions of 950 ± 50 °C and 9 ± 1 kbar for the CAS suite, consistent with the central region of the Lewisian Complex [2]. Density contrasts at mid-crustal conditions of 0.12–0.56 g cm$^{-3}$ were calculated between TTGs and the other lithologies and used to estimate the buoyancy force that drives density-driven segregation. This allowed us to investigate the rates of vertical motion that result from density contrasts, as a function of the effective viscosity during metamorphism. Independent viscosity estimates were attained using mineral flow-laws and our estimated $P$-$T$ conditions, and from examination of modern-day regions of crustal flow. We were therefore able to estimate the conditions under which sagduction could have been a viable mechanism for crustal evolution in the Lewisian and similar high-grade metamorphic terranes. We conclude that sagduction was unlikely to have operated in the Lewisian under the dry conditions implied by preserved mineral assemblages.

References:
The Si isotope composition of Archaean continental crust from ~3.8 Ga West Greenland rocks

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Earth’s earliest continental crust has been widely studied to better understand differentiation, tectonic regimes through time, and co-evolution of the atmosphere and continents. The first continental crust is thought to have formed by the early Archaean eon [1], and though Archaean rocks are scarce, there are a few exemplary samples that have been analyzed to elucidate ancient geodynamics. Among these are the tonalite-trondhjemite-granodiorites (TTGs) and metamorphosed lithologies of SW Greenland. Many geochemical studies of these rocks have been conducted, but advances in stable isotope geochemistry may provide new insights into crustal processes in the Archaean.

Due to its potential to trace various geologic processes, Si isotope analysis of ancient rocks could reveal information about the early crust when compared to δ30Si signatures of modern analogues. The δ30Si of the bulk silicate Earth is used as a metric against which to measure these signatures (δ30Si\textsubscript{BSE} = −0.29‰ [2]), and values for modern-day rocks (eg. δ30Si for average Phanerozoic upper continental crust = −0.25‰ [3]) provide context for the δ30Si composition of Archaean crust. Characterizing the Si isotope makeup of Archaean samples could illuminate the mechanisms behind TTG formation, the inputs that contaminated TTG melts, and the extent of ancient continental weathering. Recent silicon isotope investigation of Archaean TTGs from the Kaapvaal craton, South Africa resulted in the finding that ancient Si signatures are generally isotopically heavier than those measured in Phanerozoic crust [4]. These signatures were interpreted to reflect melting of silicified basalts derived from seawater, a theory corroborated by another study that observed heavy Si isotope signatures in Archaean granitoids [5].

Here we have measured the Si isotope composition of ~3.8 Ga TTGs, metabasalts, felsic volcanics, and metasediments from the Itsaq Gneiss Complex, SW Greenland. We report a narrower range for Archaean TTGs than prior analysis [6] of these rocks, as well as an average δ30Si = −0.13 ± 0.03‰, which is isotopically heavier than modern analogues, suggesting a seawater-derived or otherwise heavy melt source during TTG formation. For Isua metasediments we report δ30Si values from −0.19‰ to −1.20‰, lighter than the prior range [6], which may reflect an Archaean TTG protolith subjected to intense weathering. Our Si isotope data for metabasalts and felsic volcanics closely approximate Si signatures for modern igneous analogues, which could evidence similarities between the geodynamic regimes operating on Archaean and modern Earth.

References:
Mapping equilibrium relationships in metamorphic rocks—petrological modelling beyond equilibrium phase diagrams

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Equilibrium thermodynamics is a fundamental theoretical framework to model how a rock with a specific bulk composition responds to changes in pressure ($P$) and temperature ($T$). However, the underlying assumption that metamorphic minerals form and evolve at equilibrium conditions restricts the application of the models to relatively simple scenarios. Examples include isochemical models allowing phase relationships at equilibrium to be mapped out in the $P$–$T$ space (e.g. phase diagrams), or non-isochemical models involving dynamic reactive bulk compositions (e.g. mineral or melt fractionation) along fixed $P$–$T$ trajectories. By contrast, most of the metamorphic minerals in nature exhibit compositional zoning and patterns suggesting sluggish diffusion and/or partial re-equilibration associated to deformation and/or fluid-rock interaction. Where metastable relics are present, thermodynamic equilibrium was at best achieved locally during the evolution of the rock. This simple observation raises several questions about the general limits of the equilibrium models and potential biases on $P$–$T$ estimates. Is the bulk rock composition of a hand-specimen sized sample representative of a reactive volume at any stage of the $P$–$T$ path? What are the size and the geometry of the equilibrium volumes that have to be considered for accurate modeling?

To address these questions, we developed a modeling framework based on iterative thermodynamic models integrated with quantitative compositional mapping of thin section stitched into the software package BINGO-ANTIDOTE [1,2] that is integrated in the mapping software XMAPTOOLS [3,4]. The subroutine Bingo contains a scoring technique to quantitatively compare modeled and observed mineral assemblage, modes and compositions. One of the key features is that the local bulk composition ($X$) and the observations (modes and compositions) are taken in the same area. This mutual correspondence permits to build a fully quantitative comparison between model and observations as well as providing a statistical framework for evaluating the quality of the model. In addition, the subroutine Antidote includes mapping functions and a heuristic search method that can determine optimal $P$–$T$–$X$ conditions. Bingo-Antidote is a powerful alternative to traditional modeling tools as the textural and compositional complexity of any sample can be taken into consideration when applying equilibrium models.

The detailed investigation of a classical Grt–Bt–Ms–Ky–St–Pl–Qz metapelite from the Central Alps will be discussed. A series of Iterative thermodynamic models applied to local domains with different mineral assemblages revealed a detailed $P$–$T$ history but also suggests that only 50 vol% of the rock volume was equilibrated at peak temperature conditions of 620 °C [5]. Partial re-equilibration during prograde-to-peak metamorphism has several implications for the modelers as the reactive part of the rock controlling the mineral reaction evolves outside the $P$–$T$ section mapped by traditional isochemical phase diagrams based on bulk rock composition.

References:
Model-derived uncertainties in the calculation of geological phase equilibria

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Phase equilibrium modelling offers a welcome window onto rock-forming processes. It underpins the principles of geothermobarometry, which today is commonly carried out via pseudosection calculations in software such as THERMOCALC and Perple_X. Increasingly, phase equilibrium modelling is combined with complementary approaches such as diffusion or geodynamical calculations, in order to simulate Earth processes.

However, as anyone with experience of pseudosection calculations will know, it is not always easy to make sense of a rock through phase equilibrium modelling. Problems may relate to: (1) in what way the assumption of thermodynamic equilibrium may, or may not, be applied; (2) uncertainties in compositional analysis; and (3) uncertainties in the composition-dependent equations of state (x-eos). The x-eos are the building blocks of the modelling — one x-eos is needed to represent each of the mineral and fluid phases in the calculation.

Of the problems listed above, (3) is the most opaque for the user. In this talk I will discuss the uncertainties associated with the x-eos, and the implications of those uncertainties for thermobarometry and the simulation of Earth processes. I will describe two tools, currently in development, for investigating x-eos-derived uncertainty in thermobarometry.
Ferrous/Ferric (Fe$^{2+}$/Fe$^{3+}$) partitioning among silicates in metasedimentary rocks

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$X_{Fe^{3+}}$ (Fe$^{3+}$/ΣFe on a molar basis) is now increasingly recognised as a key parameter in phase equilibrium modelling, with recent activity-composition relations adding Fe$^{3+}$ end members to a number of silicate phases [1]. Despite this, analytical techniques used to measure $X_{Fe^{3+}}$ (e.g., Mössbauer [2], electron energy-loss [3] and X-ray absorption near edge spectroscopy [4]) are not routinely used by metamorphic petrologists. Whilst methods exist for determining $X_{Fe^{3+}}$ ratios using the electron probe micro-analyser [5,6], these are not applicable to minerals that readily contain vacancies [7] (e.g., biotite, muscovite, chlorite and staurolite). Therefore, researchers are in need of appropriate estimates of $X_{Fe^{3+}}$ in several common rock-forming minerals.

This work collates wet chemical, Mössbauer and X-ray absorption near edge spectroscopy analyses of rocks and minerals from 72 studies of metasedimentary rocks in the literature. The resulting database contains 552 samples, including 239 with $X_{Fe^{3+}}$ determined for the whole rock and 214 with accompanying modal abundance estimates. There are 736 measured $X_{Fe^{3+}}$ ratios of individual minerals, which include in decreasing order of abundance: biotite, muscovite, chlorite, staurolite and chloritoid. Average (±1σ) $X_{Fe^{3+}}$ ratios for whole rock, muscovite, biotite, chlorite and staurolite are 0.23±0.16, 0.54±0.19, 0.11±0.08, 0.08±0.07, and 0.06±0.05, respectively.

We examine the control of pressure, temperature and oxidation state on the Fe$^{3+}$ contents of these common silicates, by categorising samples based on pressure-dependent facies series, metamorphic zone and the type of Fe-oxide present. Whilst there is little variation with pressure and temperature, there is a general increase in $X_{Fe^{3+}}$ in muscovite and biotite with increasing oxidation ratio, as found in the study of a metamorphic sequence in SE Maine by Guidotti, Dyar and others [2,4,8,9]. We then compare our estimates and observations with the predictions of the latest thermodynamic activity-composition relations for the partitioning of Fe$^{3+}$ between coexisting minerals [1]. Suggestions are made for the types of rocks and minerals that would most benefit from new measurements of $X_{Fe^{3+}}$.

References:
Metamorphic Petrology Information System (MetPetIs): The new cyber-infrastructure for the management of metamorphic rocks analyses from outcrop- to micro-scale

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Metamorphic rocks' petrogenesis is controlled by chemical-physical counterbalancing factors driven by deformation vs. recovery processes [1]. For this reason, a complete database management of metamorphic rocks analysis cannot do without a correct organization of the different levels of the interdependent analytical sessions, which start from the acquiring of the geological survey observations to arrive to the laboratory analysis, where the microfabric control play a crucial role [e.g. 2,3]. In the frame of the info-treatment of the geological survey analyses, the Geo-Scientific Mark-up Language (GeoSciML) is considered the international standard for the construction of the rock-analysis data infrastructures. This is because GeoSciML permits a data storage based on a widely shared correlations lexicon, a pyramidal view of differential scaled data, and a more reliable data comparison [4]. Despite its solid logical structure, GeoSciML provides to investigate just the mesoscopic part of the metamorphic field of observation, do not allowing to overcome the problem of the dialogue between the field-based data with the laboratory metamorphic rock analyses.

Parallelly, while the cataloguing, management, and sharing of geological and petrological data for plutonic and volcanic rocks have been increasingly developing [e.g. 5], the unique noteworthy cyber-infrastructure in the field of the metamorphic rocks dataset management have been carried out by the experience of Metamorphic Petrology Data Base (MetPetDB) [6]. Nevertheless, Spear et al. (2009), while giving a significant boost in the implementation of the first geochemical database specific for metamorphic rocks, taking care to the rock fabric control on the composition of the mineral-chemical parageneses, they have not been able to give a unitary, intuitive, and easy to use tool to all metamorphic-geologists and -petrologists.

Metamorphic Petrology Information System (MetPetIs) intends to streamline and design for the first time a unique GIS-based information system applied to the field of metamorphic rock data analyses, able to integrate structural data analytical tools (i.e. ArcStereoNet [7]), with web-interactive sample location maps, linked through a solid Local Information System (LIS) infrastructure. This LIS is able to handle different types of laboratory analytical data (i.e. primary data) with different types of post-processing elaboration (i.e. Derived data), such as those derived from the Image analysis of X-Ray maps (i.e. Quantitative X-Ray Map Analyser [8]) or from the high-definition (HD) optical thin section elaboration for edge detecting purposes (i.e. Micro Fabric Analyser [9]). MetPetIS permits then the transition from GIS to LIS, starting from the concept of "Sample", which is the key to merge the two different environments, within a frame, where geological maps with sampling locations, HD thin-section scans, micro X-ray fluorescence, EPMA data and so on is accompanied by several qualitative and quantitative data extrapolation within several easily navigable layers from any web browser and/or downloadable in the most popular Open Geospatial Consortium (OGC) formats, ready to run by any GIS software.

References:
Kyanite, the high-pressure Al₂SiO₅ polymorph, is traditionally thought to be a high-pressure, high-temperature mineral. Common kyanite-forming reactions such as pyrophyllite [1] or chlorite [2,3] dehydration take place at ~ 400°C and >600°C respectively. In this study, vein and matrix kyanite is observed within greenschist facies (chlorite-grade) blocks, hosted in post-evaporitic breccia, and closely associated with abundant Cu sulphides, in the Menda deposit of the Congolese Copperbelt. The occurrence of kyanite in low pressure-temperature rocks indicates unusual conditions of kyanite growth. Petrographic observations show that kyanite is abundant within dolomite-magnesite carbonates and carbonaceous siliciclastic lithologies. Kyanite occurs in both lithologies as matrix porphyroblasts as well as coarse-grained, vein-hosted crystals intergrown with quartz, dolomite, chalcopyrite and monazite. Corroded crystal shapes indicate breakdown of kyanite to Mg-chlorite.

The Central African Copperbelt (CACB) is the world’s primary source of copper and cobalt, producing about 70% of the metal [4] which is critical for the production of batteries needed to help decarbonise our societies. Highly saline fluids are associated with extensive mineralisation and alteration in the CACB [5]. Intimate association of kyanite-bearing veins and Cu-sulphide mineralisation indicates that the unusual thermodynamic conditions encountered play a role in the understanding of Cu-Co systems. The occurrence of kyanite in Al-poor carbonates suggests that Al, thought to be relatively immobile, has been transported. This is likely due to the highly saline conditions influencing metal mobility in such systems. The preservation of sedimentary features indicative of an original grainstone, also suggest that there was a compositional control on kyanite growth. Understanding the paragenesis of kyanite in relation to Cu, Ni and U mineralisation at Menda, as well as the unusual thermodynamic conditions required for low-temperature kyanite growth and Al-mobilisation, has implications for the interpretation of the kyanite-bearing assemblages in the high-pressure Domes region of the Zambian Copperbelt, as well as metal mobility in highly saline systems.

References:
Even the low-T garnet from the iconic Barrow’s zone is tetragonal

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Common (anhydrous) Fe-Mg-Ca-Mn garnet, the archetypal cubic mineral, has been recently discovered to be tetragonal in metapelites and metabasites from low-temperature regional metamorphic terranes [1].

Despite the differences in bulk rock composition and pressure conditions, such low-T tetragonal garnets share common chemical features, namely high grossular (>25 mol%) and low pyrope (<7 mol%) contents. Similar compositions are documented in other contexts worldwide, both in blueschists-eclogites and in phyllites, including the metapelites from the garnet zone of the iconic Barrovian metamorphism of the Scottish Highlands [2].

We have analysed a garnet crystal from a chlorite-biotite schist kindly collected by Ben Harte at the Barrow’s garnet zone in Glen Esk. The unit cell parameters were refined using diffraction reflections between 1.20 and 0.55 Å providing a tetragonal cell with a = 11.5731(5) Å and c = 11.5887(8) Å and volume V = 1552.15(15) Å³. Systematic absences analysis on complete intensity data collected up to 2theta = 80° indicated I41/acd space group confirming the cell parameters refinement. Therefore, the garnet is tetragonal and not cubic, as suggested by its weak birefringence under crossed polarizers.

These results show that the tetragonal structure of common Fe-Mg-Ca-Mn garnet is verified whenever this mineral displays the Ca-rich, Mg-poor composition often observed in low-T metamorphic rocks. And support the hypothesis that the lowering of symmetry is composition-dependent.

References:
Plate tectonics on other planets: a stochastic analysis of interior mineralogy and composition

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Earth is currently the only known planet to exhibit plate tectonics – a mobile lid geodynamic regime that is considered critical for regulating atmospheric composition, surface climate, and a planet’s protective magnetic field\cite{FoleyBDriscollP16}. Ultimately, plate tectonics is thought necessary for the development of complex life. With the development of high-definition space telescopes that can scan vast swaths of the night sky, such as the Kepler and Transiting Exoplanet Survey Satellite (TESS) missions, the study of exoplanets has attracted interest from scientists and the public alike, and there has been a particular interest in whether these bodies could develop plate tectonics. However, confirmed exoplanets are primarily identified by transit and radial velocity measurements, which are skewed towards bodies with a much larger radius than that of Earth’s. Furthermore, the elemental composition and structure of exoplanets cannot be directly determined and instead relies on mass and radius measurements\cite{UnterbornCetal16}, which results in inherent degeneracies in composition and structure. To constrain the mineralogy of exoplanets, stellar abundances may be used as a proxy for exoplanet composition. Using this technique, we investigate the mineralogy of hypothetical Earth-like planets orbiting stars documented in the Hypatia Catalog\cite{HinkelNetal14}. The mineralogical constituents of their mantles are analysed to constrain the likelihood of convection, and the mineralogy of their derivative crusts are used to constrain the likelihood of subduction. From these data, we consider the habitability of exoplanetary systems within the framework of the chemistry of their host stars.

References:
The effect of fluorine on reaction rim growth dynamics in the ternary CaO-MgO-SiO$_2$ system

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Metamorphic corona and reaction rim structures are examples of a net-transfer reaction, where pre-existing mineral phases react to new phases. Growth of these metamorphic structures indicates a change in physical parameters such as pressure and temperature, a change in the chemical composition of the system and/or the presence of volatiles. The effect of volatile components on net-transfer reactions remains poorly constrained. Volatiles other than water such as N, C, S and the halogens F, Cl, and Br in particular received little attention with regards to component mobility and phase stability, limiting our ability to establish their significance in the upper mantle. In order to accurately model metamorphic and metasomatic processes and test the potential of natural reaction rims to be used as geofluidometers, a quantification of the effect of volatiles on reaction-rim growth dynamics is necessary.

In this study, we investigate the effect of fluorine on reaction rim growth dynamics in the ternary CaO-MgO-SiO$_2$ system. A series of piston cylinder experiments was conducted at constant upper mantle P-T conditions of 1000°C and 1.5 GPa. In each experiment, reaction rims were grown for 20 minutes between a natural wollastonite crystal and MgO powder matrix with the addition of 0 to 10 wt% fluorine. Electron microprobe analyses and Raman spectroscopy were used to analyse the crystal phases present in the reaction rim.

In the fluorine free system, we produced a rim sequence of wo | mer | di | fo | per, complying with phase stabilities at water saturated conditions. As soon as 0.1 wt% fluorine was introduced into the system, humite group minerals (HGMs) and monticellite were stabilized resulting in the multilayer rim sequence wo | mer | mon | fo + HGMs | per. In experiments with fluorine concentrations >1 wt%, cuspidine is stable and represents the major fluorine sink. Our data show that the addition of fluorine stabilizes the fluorine bearing phases cuspidine and HGMs to higher temperatures, which is in agreement with previous studies [e.g. 1]. However, stabilisation of the nominally anhydrous mineral (NAM) monticellite at this P-T-condition suggests that addition of fluorine also affects the stability of nominally fluorine free minerals. This may be explained by the effect of fluorine on the Gibbs free energies of fluorine bearing phases, which in turn affect the relative Gibbs free energies and thus stabilities of all phases, including NAMs, that might potentially be stable in the CaO-MgO-SiO$_2$ (+F) system.

Furthermore, results of this study reveal a positive correlation between overall rim thickness and fluorine content. Reaction rim widths increased from 12.50 (146) to 105.49 (185) μm in fluorine free and 10wt% F experiments respectively.

Our results illustrate the significance of fluorine during net-transfer reactions, where its presence changes relative component mobility and phase stability. This implies not only that reaction rims may be used as a tool to infer the amount of fluorine present during metamorphic reactions, but also that we need to consider the role of fluorine for a correct interpretation of the P-T-t history of metamorphic and metasomatic rocks.

References:

**Geochronometers; What do they really record?**

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Orogenic belts often appear complex, recording numerous overprinting and sometimes synonymous metamorphic and tectonic events over protracted time. Consequently, changes in bulk rock composition, deformation and metamorphic conditions have a significant impact on accuracy and precision when constraining geochronological and geochemical information, and as a result, metamorphic histories are difficult to unravel and evaluate. Many studies have shown that mineral dates on an outcrop scale area can yield variable results, often outside of analytical uncertainty indicating that more localised geological parameters have a great influence on geochemical and isotopic processes. Close spatially associated changes in bulk composition and a fluctuating deformational environment (altering mineral paragenesis, incorporating percolating fluids and mineralisation) are shown to have a strong control over the responses of accessory minerals and record minute changes in chronological history. Understanding these processes and their effects are of paramount importance to make robust interpretations of geochronologic data from metamorphic rocks. The purpose of this study is to investigate the effect of bulk composition and ductile deformation heterogeneity on metamorphic chronology and develop workflows for future petrochronological analysis.

Two case studies will be used; the COSC-1 drill core from the Seve Nappe of the Scandinavian Caledonides, containing felsic and mafic gneisses, variably deformed towards mylonites, and a sample set younger in origin from the Lepontine dome in the European Alps. Firstly, we will be focusing on the COSC-1 drill core, which allows us uninterrupted sampling of differing compositions and suites of similar geochemical/metamorphic origin and variable strain rates at a sub-meter scale. Once we have a framework of key parameters, we can then apply our methods and knowledge to samples from the Lepontine dome. We will be using detailed thin section and mineral imaging and in-situ analytical techniques to maintain petrographical context of the accessory phases for geochronology and linking them to deformational phases, fluid pathways and local bulk rock compositions. This project will help us to unravel the often complex petrochronological findings of collisional tectonics and continental orogens.
U-Th\textsubscript{total}-Pb chemical dating, phase equilibria modelling and geochemistry of high-grade gneiss from Daltonganj, Chhotanagpur Granite Gneiss Complex, Eastern India.

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U-Th\textsubscript{total}-Pb electron probe micro-analysis chemical dating of monazite from the Daltonganj area in the Chhotanagpur granite-gneiss complex (CGGC) in India was conducted to determine the age of metamorphism of high-grade gneiss and correlate this with major tectonic events. Four metamorphic events (M\textsubscript{1} - M\textsubscript{4}) have been identified in the CGGC terrain [1], of which we have observed three events in high-grade gneisses from Daltonganj [2]: M\textsubscript{2} (~1424 Ma), M\textsubscript{3} (~972 Ma), and M\textsubscript{4} (~855 Ma); the first stage of metamorphism is only preserved within pelitic granulites at ~1600 Ma [3]. The ~1424 Ma age has been interpreted as the age of magmatic emplacement, but it is commonly incorporated with a second metamorphic event in the CGGC. Pseudosection modelling in the NCKFMASH (Na\textsubscript{2}O-CaO-K\textsubscript{2}O-FeO-MgO-Al\textsubscript{2}O\textsubscript{3}-SiO\textsubscript{2}-H\textsubscript{2}O) system using Perple_X ver.6.8.2 shows the peak stage of metamorphism at 9.07 kbar/ 750°C with garnet-orthopyroxene-amphibole-biotite-melt-quartz-H\textsubscript{2}O, suggesting high pressure (HP) metamorphism, which is recognized as the M\textsubscript{3} event. Subsequently, the rocks experienced isothermal decompression from peak metamorphic conditions and is characterized by the mineral assemblage garnet-cordierite-amphibole-biotite-melt-quartz-H\textsubscript{2}O, stable at 7.5 kbar/701°C, representing the M\textsubscript{4} metamorphic event. The geochemical composition of the high-grade gneiss reveals that the protolith had characteristics of calc-alkaline basalt from an orogenic island arc setting and the gneisses developed from a ‘restite’ after the elimination of granitic melts.

References:
Adapting phase equilibria modelling to crustal and planetary scale problems

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Modern quantitative phase equilibria modelling techniques utilizing internally consistent datasets and activity-composition models have been successfully applied to a number of problems in metamorphic geology from hand sample to outcrop scale. Attesting to this the term “phase equilibria” appears in 1 548 articles in the Journal of Metamorphic Geology and one third of those are within the last 10 years. These techniques traditionally proceed either through the manual solution of non-linear equations or by a more automated Gibbs free energy minimization approach. However in order for these techniques to be scaled up to deal with crustal or planetary scale problems a number of hurdles still need to be overcome.

Spatial dimensions in a crustal or planetary model are estimated by grids with modelling conducted on individual cells. This allows processes within cells to effect chemical change to partner cells and thereby approximate open or conditionally open systems. Compositional constraints to the chemical system such as oxygen fugacity are pressure and temperature dependent therefore in order to model a planet wide set of conditions oxygen fugacity buffers are enabled that are dependent on the pressures and temperature of the individual grid cells. Stratigraphic layering is introduced by automating the procedure for setting the initial composition of cells and dependence relations determine the hierarchy of compositional change induced within crustal columns. Phase manipulations such as fluid, melt or crystal addition or extraction are defined by mechanistic parameters that simulate boundary conditions for example melt accumulation thresholds, fluid porosity threshold, rheological lockup conditions etc. Since certain key chemical parameters used in identifying crustal processes such as trace element ratios cannot be traditionally modelled due to their absence from the internally consistent thermodynamic datasets new methods of component approximation are introduced following the methods of trace element partitioning and accessory phase saturation for supersolidus systems.

Finally the increased complexity and number of calculations required to scale up phase equilibria modelling systems to the crustal or planetary scale provides an increased computational challenge therefore new potential strategies are explored for the optimizing of calculation load via parallel processing.
Syenite formation after tonalite gneisses: Example from the Madiapala massif, Limpopo Complex, South Africa

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The Madiapala syenite massif is situated within the host Alldays TTG gneisses in the western part of the Central Zone (CZ) of the Limpopo high-grade complex, South Africa. The age of the massif about 2.01 Ga [1] corresponds to the Paleoproterozoic tectono-thermal event (D3/M3) in the CZ, which was characterized by fluid activity along regional and local shear-zones.

Following to [2], the interaction of a biotite-amphibole tonalite gneiss with H2O-CO2-(K,Na)Cl fluids could have led to the formation of syenitic assemblages within the TTG gneisses. Thus, the Madiapala syenites could be a product of the syenitization of the TTG gneisses. In fact, ICP-MS and ICP-AES data for the syenite rocks, syenitized gneisses and host TTG gneisses revealed two varieties of syenite rocks in the massif (syenites and syeno-diorites), confirmed the crustal source of the syenites and their close genetic relationship with the Alldays tonalite gneisses. The REE pattern for the syenites indicates active crystallization differentiation within the syenite body.

The earliest magmatic assemblage of the syenite rocks is K-feldspar + clinopyroxene + titanite ± apatite, while the later one is amphibole+ albite. P-T pseudosections for the syenites constructed using the PERPLE_X software [3] showed that the earliest assemblage was formed in the temperature range 800-850°C and pressures between 6 and 9 kbar. The lg(aH2O) – lg(aCO2) pseudosections for the Alldays gneiss composition showed that the formation of the syenite assemblage proceeds via the increase of the K2O activity at constant P and T.

In order to reproduce the syenite mineral assemblage, experiments on the interaction of a biotite tonalite Alldays gneiss with a H2O-CO2-(K,Na)Cl fluid with variable salt concentrations were performed at 850°C and 6 kbar for 10 days using an internally heated gas pressure vessel. The experiments reproduced the assemblage clinopyroxene + titanite ± K-feldspar via incongruent melting reactions of Ti-bearing biotite with quartz and plagioclase, initiated by the alkali-rich fluid. This assemblage coexists with syenitic melt. Amphibole-bearing assemblages were produced in the experiments with high contents of NaCl in the fluid. These results are consistent with the proposed model for the syenite formation.

Thus, the syenites of the Madiapala complex were formed at 6-9 kbar and of 800-850°C via the active interaction of the Alldays TTG gneisses with an aqueous-carbonic-salt potassic fluids. The determining factor for the formation of the syenite assemblage was the increased potassium activity in the fluid. Later amphibole-bearing assemblages were formed in the course of the syenite magma cooling. This stage corresponded to a change in the regime of alkaline components in fluid, so that the increase in Na activity led to the replacement of the clinopyroxene + K-feldspar assemblage with the amphibole + albite assemblage.

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References:
Integrated chemical and mineralogical characterization of the Alta Skarn, Utah, USA


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The nature of calc-silicate contact metamorphism forming skarns depends on the proximity to the main intrusive body, as well as its depth and temperature, protolith composition, reaction potential and fluid interactions which typically yields characteristic mineralogical zonations from which some chemical and genetical conclusions can be drawn. In this case, the long and well studied Alta skarn, related to the Alta Stock, a dike-like conduit part of the “Alta Stock-Little Cottonwood Stock plutonic and volcanic system”, itself part of the Eocene-Oligocene Wasatch Intrusive Belt consisting of a series of plutons that intruded the thickened crust in northern Utah following the Sevier Orogeny [1], represents a great opportunity to study the textural, chemical and mineralogical relations between rocks and fluids involved.

We analyzed seven thin sections each one typical of a corresponding zone (talc, tremolite, forsterite, periclase, vesuvianite and ludwigite) through transmitted and reflected light petrography, Raman spectroscopy, X-ray diffraction methods and cathodoluminescence images in order to establish a paragenetic model of the Alta Skarn, Utah, USA. Using for the first time Raman and XRD analysis on this skarn, we discuss the genesis of mineral phases already proposed and others not reported yet, this way interpreting the chemical and physical processes that could develop zoning in vesuvianite crystals and identify chemical changes of mineral phases due to retrograde metamorphism, hydration reactions, mineral assemblages changes due to protholith variations, fluid interactions and impurities-driven reactions disturbing the CaO-MgO-SiO2-H2O-CO2 (CMS-HC) system [2, 3].

As this research is still in progress and, due to the pandemic, there are delays in the Electron Probe Micro Analyzer (EPMA) analysis which will led us take out a quantitative approach to elemental variations, zonations and textures, and its relation with metamorphic processes and rock-fluid interactions. Nonetheless, we conclude the presence of malachite in the ludwigite zone, which at its time have paragenetic relation with hydrated periclase as brucite pseudomorphs. On the other side, vesuvianite zonation evidenced in birefringence heterogeneity could be due to elemental variations from the inner to the outer zone of the crystal, of Al, Fe, Mg and Ti, also related to textural reactions forming skeletal calcite and diopside crowning around vesuvianite crystals.

References:
Growth of non-typical garnet textures during amphibolite facies metamorphism: Dwalile Supracrustal Suite, Ancient Gneiss Complex, Swaziland

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The Dwalile Supracrustal Suite of the Ancient Gneiss Complex, Swaziland (Eswatini) represents one of the oldest greenstone belts in the world with a crustal evolution history from Palaeo- to Mesoarchaean times. The garnet-staurolite metapelites of this area preserve evidence for amphibolite facies metamorphism at ca. 3.15 Ga.

The main mineral assemblage of the samples consists of garnet, staurolite, biotite, muscovite, quartz with accessory ilmenite and monazite. The garnet grains contain non-typical textures and are distributed as thin layers consisting of elongated ribbons together with coarse recrystallized quartz. The older, euhedral garnet cores are only visible in compositional maps and have a composition of Sps19-Grs5-Alm70-Prp6. The lobate rim around the core and the ribbons have the same composition of Sps7-Grs1-Alm81-Prp12. The garnet ribbons are up to 1 cm long and 3 mm thick.

The garnet cores contain inclusions of quartz, chlorite and orthoamphibole (anthophyllite). The inclusions in the garnet ribbons consist of straight inclusion trails of quartz, ilmenite and minor staurolite. The staurolite in the matrix has been mostly replaced by sericite, chlorite and locally by chloritoid.

P-T conditions were calculated using pseudosection modelling in the MnNCKFMASHTO system. Pseudosections yielded P-T conditions of ~510-540 °C and ~5.5 kbar for the garnet core growth and a peak temperature of ~600 °C.

Possible mechanisms to explain these garnet textures are dissolution and precipitation of the old garnet [1] or transport-controlled growth due to matrix heterogeneity [2].

References:
Pyrometamorphism in calc-silicate xenoliths from Merapi (Indonesia)

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Interaction between magma and carbonate rocks is an increasingly recognised process occurring at active volcanoes worldwide, with implications for the magmatic evolution of the host volcanic systems and volcanic CO₂ budgets. Calc-silicate (skarn) xenoliths represent remnants of this magma-carbonate interaction, and their detailed petrographic and geochemical study provides insights into the architecture of subvolcanic skarn contact aureoles and the physico-chemical conditions of magma-carbonate interaction.

At Merapi volcano (Indonesia), abundant calc-silicate skarn xenoliths are found in pyroclastic deposits [1]. We identify two distinct xenolith types: 1) Magmatic skarn xenoliths, representing fragments of entrained carbonate which is caught in the process of being metamorphosed within the magma itself, and 2) exoskarn xenoliths, which represent fragments of metamorphosed wall-rocks. The magmatic skarn xenoliths comprise distinct compositional and mineralogical zones with abundant Ca-enriched glass. These mineralogically distinct zones are controlled by Ca transfer from the limestone protolith to the magma and by transfer of magma-derived elements in the opposite direction. In contrast, the exoskarn xenoliths are unzoned and essentially glass-free, representing equilibration at sub-solidus conditions. The major mineral assemblage in the exoskarn xenoliths is wollastonite + garnet + Ca-Al-rich clinopyroxene + anorthite ± quartz, with variable amounts of either quartz or melilite + spinel.

Thermobarometric calculations, fluid inclusion microthermometry and newly calibrated oxybarometry based on Fe³⁺/ΣFe in clinopyroxene indicate magmatic skarn xenolith formation conditions of ~850 ± 45 °C, < 100 MPa and oxygen fugacities between the nickel – nickel oxide (NNO) and hematite – magnetite (HM) buffers [2]. The exoskarn xenoliths formed at 510-910°C and some record oxygen fugacities of > NNO+5. These high oxygen fugacities are imposed by the large volumes of CO₂ liberated from the carbonate, promoting formation of andradite garnet and highly aluminous clinopyroxene in the xenoliths. In situ carbon and oxygen isotope data of texturally distinct calcites provide unique evidence for decarbonation, magma-fluid interaction, and the generation of carbonate melts [3]. Extremely light δ¹³C values down to −29.3‰ in the magmatic skarns demonstrate highly efficient remobilisation of crustal CO₂, which may influence the eruptive intensity of the volcano [4] and impact global carbon cycling. Residual calcite in the exoskarn xenoliths can be modelled as a two-step process involving fluid mixing followed by decarbonation.

References:
Fate of CO$_2$-bearing fluids trapped in granulites – old perspectives and new insights

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Presence of superdense monophase CO$_2$-bearing fluid inclusions (FI) have been the main advocate for active role of fluids in the deep crust. Yet, the timing of entrapment of those inclusions relative to peak metamorphic conditions remains a controversial issue.

In this study, granulites from Ivrea Zone (NW Italy), Athabasca (Canada) and Gruf Complex (Central Europe) are interrogated in order to evaluate the fate of primary CO$_2$ and COH fluid inclusions trapped during the prograde path. An important starting point is that in the three locations, FI are reported to coexist with melt inclusions in peritectic garnet [1; 2; 3]. Moreover, the zonal arrangement of the inclusions in the host is indisputable evidence that the inclusions are primary and were certainly trapped in the same anatetic event, during the growth of the garnet.

A combination of cutting-edge techniques indicated that the FI are composed of fluid and solid phases [4]. These multiphase fluid inclusions usually comprise siderite (Sid), magnesite (Mgs), pyrophyllite (Prl), corundum (Cor), quartz (Q), and in some cases kaolinite (Kaol), graphite (Gr), calcite, dolomite, biotite and muscovite. In the fluid phase, CO$_2$ is the most common component and no free H$_2$O has been detected, whereas CH$_4$ and N$_2$ may be also present.

The solid assemblage of carbonates and OH-bearing phases are unlikely to have precipitated directly from the original fluid as daughter phases. These minerals require additional cations (e.g. Fe, Mg, Ca, Al, Si) which are only dissolved into a common COH fluid in very low amounts. Yet, the cations needed are very abundant in the host garnet. Therefore, a possible interpretation is that the initial composition of the fluid must have been changed by the interaction with the host garnet during cooling. A thermodynamic modelling of such fluid-host interaction (Fig. 1) demonstrates that indeed, after entrapment, the fluid and garnet interact to form metastable assemblages, similar to those found in the natural multiphase FI.

These results show that instead of monophase CO$_2$-bearing inclusions, actually primary multiphase fluid inclusions in garnet are the most reliable witnesses of fluid operating during deep crustal metamorphism.

References:

Figure 1. (top) SE images of natural multiphase FI. (bottom) P-T pseudosection considering fluid-garnet interaction.
Experimental study of generation of granite melt and aqueous-carbonic fluid in carbonate-bearing pelitic protolith at the mid-crustal conditions

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Granitoid magmatism is the most important process contributing to the redistribution of material within the continental crust. The formation of granite magmas is usually associated with the processes of high-temperature metamorphism and with the formation of granulites in the lower and middle crust, which are considered to restites from the partial melting of various crustal protoliths. In turn, the formation of granulites is characterized by a specific fluid regime, in which CO$_2$ plays the leading role [1]. Therefore, a reasonable question arises, what is relation between the formation of granitoid magmas and generation of the CO$_2$-rich fluids. This problem can be partially resolved by a model, which suggests a generation of granitoid magmas in protoliths that initially contained carbonates. In the course of prograde metamorphism, such protoliths can surely serve as a source of both magmas and CO$_2$–rich fluids. This model sets the problem of the experimental study on the generation of granite melts and associated fluids in carbonate-bearing metamorphic protoliths at the middle and lower crustal conditions.

We report results of the experimental study on partial melting and dehydration/decarbonation of carbonate-bearing pelitic rock at temperatures of 850°C, 900°C and 950°C and a pressure of 10 kbar. Carbonate-bearing metapelite containing biotite, plagioclase, quartz, muscovite, calcite and dolomite from the Giyani greenstone belt, Kaapvaal craton, South Africa, was used in the experiments.

Melting of the rock begins just at temperature of 850°C with formation of thin films of a melt of the trachyte-tephrite composition at the grains boundaries between biotite, plagioclase, and quartz. The silica-poor melt composition implies that these films are the first melt portions formed during partial melting of the rock with the active participation of the carbonate component. With an increase of the degree of melting, the melts are increasingly approaching rhyolite composition. At a temperature of 900°C, large areas of the melt appear, and carbonate is absent in the run sample indicating a complete decomposition of the carbonate in the range between 850 and 900°C. Alkali-calcic melt (MALI = 7-8 with SiO$_2$ = 71-75 wt.%) shows FeO/(FeO+MgO) > 0.8, ASI < 1.1 and a normative composition close to granite. Clinopyroxene rims form around the former carbonate grains. The sample still contains relict biotite, but it decomposes to form orthopyroxene. At temperature of 950°C, the amount of the melt increases insignificantly. Large areas of melt form at the boundary between quartz grains, plagioclase and residual biotite, while in areas without quartz (for example, between plagioclase grains) the volumetric content of the melt is insignificant. The composition of the melt is close to those of melts at 900°C, differing just in lower values of MALI = 5-7 at SiO$_2$ = 69 - 74 wt. %, thereby getting into the area of calc-alkaline varieties. Glasses quenched at 900°C and 950°C contain numerous voids indicating the presence of a free fluid phase during the experiment. Some voids contain quenched calcite and/or dolomite grains filling a significant portion of the void volume. These carbonates indicate high Ca and Mg content in the complex aqueous-carbonic fluid.

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References:
Melting and ultrahigh temperature in the Adirondack Highlands: a melt inclusion perspective

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Melt inclusions in garnet porphyroblasts offer an invaluable gateway to access melt-producing and metamorphic processes in the lower crust. The mafic metaigneous rocks of the central Adirondacks, NY (US) - a Mesoproterozoic outlier of the Grenvillian orogeny, are well known examples of lower crustal rocks metamorphosed to amphibolite and granulite facies during continent-continent collision. Garnet-bearing mafic rocks from two inactive quarries formerly dedicated to garnet extraction, the Barton Mine and the Hooper Mine, were collected and investigated to study in detail mafic melting processes via inclusion studies.

The Barton Mine is renowned worldwide for its garnet megacrysts (up to 1 m in diameter), whose formation is classically attributed to the abundant presence of fluids during the late stage of the Ottawan orogeny (1080–1050) [1]. We provide undisputable evidence, in the form of polymorph-bearing nanogranitoids and partially glassy inclusions, that a thondhjemitic melt was present during garnet growth as result of water-present melting of an olivine-bearing gabbro. The similarities with Archean tonalitic–trondhjemitic–granodioritic (TTG) melts - typically originated from mafic melting- suggest that these inclusions can be regarded as TTG embryos. Such melt formed at relatively shallow depth (∼1 GPa), yet in presence of garnet -commonly regarded as evidence of a much deeper source (>2 GPa). In the Hooper Mine (5 km NW of the Barton Mine), preliminary investigations show that garnet-bearing mafic granulites record a complex P-T loop –now visible in the garnet zoning- with peak metamorphism at pressure similar to the Barton Mine, ≈1 GPa. The external portion of the garnet hosts polymorph-bearing nanogranitoids with a more granitic/granodioritic composition with respect to Barton Mine inclusions. These two new findings of nanogranitoids are the first in the Adirondacks mafic rocks: nanogranitoids have been recently recognized in metapelites from Ledge Mountain in the same area [2] and, earlier on, from metapelitic gneisses in Port Leyden [3] on the western edge of the massif.

The temperature at which nanogranitoids can be re-homogenized via piston cylinder experiments corresponds to the partial melting condition experienced by the host rock. At the Barton Mine, full re-homogenization is achieved at T> 925°C, remarkably higher than the classic estimates for the area (800-850°C, 0.6-0.85 GPa [4]), but in complete agreement with the outcomes of the most recent modelling studies, which indeed suggest ultrahigh temperature (UHT) conditions during the metamorphic peak for the central Adirondacks [2][5]. Our study thus not only provides natural constraints for the water-present gabbro melting, but also contributes to the on-going reappraisal of the metamorphic history of the Adirondacks.

References:
Fluid regime and P-T conditions of formation of granulite xenoliths from Udachnaya kimberlite pipe, Siberia

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It is widely accepted that granulite xenoliths from kimberlites provide a record of granulite facies metamorphism at the basement of cratons worldwide [1]. However, application of the phase equilibria modelling for seven representative samples of mafic granulites from xenoliths of the Udachnaya kimberlite pipe, Yakutia, revealed that a granulitic garnet + clinopyroxene + plagioclase ± orthopyroxene ± amphibole ± scapolite mineral assemblage was likely formed in the middle crust under amphibolite facies conditions (600-650 °C and 0.8-1.0 GPa). Clinopyroxene in the rocks is characterized by elevated aegirine content (up to 10 mol. %) both in the earlier magmatic cores and in the later metamorphic rim zones of the grains.

The phase equilibrium modelling in PERPLE_X [2] for all samples indicates surprisingly reduced conditions, i.e. oxygen fugacity 1.6-3.3 log units below the FMQ (Fayalite-Magnetite-Quartz) buffer. In contrast, the coexistence of Fe-Ti oxides indicates temperatures of 850-990 °C and oxygen fugacity about lg(FMQ)±0.5, conditions which correspond to earlier stages of rock evolution.

Mineralogical data such as significant amount of Cl and SO3 in amphiboles and scapolite and presence of Cl-F-apatite grains in all samples evidence that metamorphic process took place in condition of deficient of fluid existed as a polyionic brine. Small portions of brines and reduced conditions could be further retained during subsequent crystallization and modification of minerals in the course of sub-isobaric cooling down to the temperature of final equilibration at 600-650 °C. Such a feature seems to be typical for the fluid-deficient metamorphism in metaigneous complexes [3].

The reconstructed P-T conditions [4] for the final equilibration in the mafic granulites indicate that temperatures were ~250 °C higher than those extrapolated from the continental conductive geotherm of 35-40 µW/m² deduced from peridotite xenoliths of the Udachnaya pipe. Although the granulites resided in the crust for a period of at least 1.4 Ga, they did not reequilibrate to the temperatures of the geotherm, likely due to the blocking of mineral reactions under relatively low temperatures and fluid-deficient conditions.

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References:
Preservation of sharp composition gradients during high-temperature deformation in gabbros

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Strain localization in oceanic crust along large scale strike-slip structures may often be accompanied by the growth of hydrous minerals as amphibole that deeply change the rheological behaviour of gabbros. However, it remains unclear how fluid percolates into the anhydrous gabbros, especially during the first stages of deformation and how pervasive mineralogical hydration reactions can be in deforming rocks. This study investigates a series of gabbros collected along a shear gradient in the Poroshiri belt (Japan) - a plate boundary strike-slip structure active during the opening of Japan sea at the Miocene. All stages of deformation and mineralogical transformations are preserved, from the initial network of en echelon cracks filled with amphibole, to meter-thick ultramylonites. The characterisation of metamorphic conditions, mineral reactions and length scales of composition variations are used to discuss the timing and mechanisms of fluid percolation relative to deformation.

Far from the shear zone, the magmatic mineral assemblage is preserved in fracture-free gabbros, while in gabbros with mm-size fractures clinopyroxene is replaced by granoblastic pargasite ± Ca-rich plagioclase domains or by drop-like pargasite crystals along clinopyroxene cleavages. The incomplete, fluid-driven breakdown reactions formed isolated domains of different compositions. Textures and plagioclase-amphibole thermometry suggests temperature conditions for this early alteration of ~800-880°C and local partial melting. Large crystals of pargasite, similar in composition to the ones replacing clinopyroxene, grew into fractures. Therefore, fracturing was at this stage, along with percolation at grain boundaries, an effective way for water to circulate into the gabbros. In the more deformed gabbros, strain localization occurs along and around earlier pargasite-bearing fractures and is accommodated in fine-grained amphibole + plagioclase domains. Sharp compositional gradients between these domains are observed, accompanied or not by secondary clinopyroxene. These differences in the mineral assemblage and composition within the sheared zones are not related to P-T variations but rather to local variations in break down reactions of magmatic mineral during the early metamorphic stage, as also suggested by thermodynamic calculations. Within the core of the shear zones, gabbros are totally re-equilibrated in amphibolite-facies conditions with hornblende + plagioclase assemblage formed at ~700-750°C. Thus, despite the high strain and high temperature during shearing, mineral composition did not systematically re-equilibrate at the µm scale, likely due to a lack of fluid during the retrograde path. The amount and localisation of early alteration in gabbros seems therefore to strongly control (i) the equilibration length scale and the stable mineral assemblage during successive shearing and (ii) where the strain is localized.
Melt- to shear-controlled granulite exhumation related to granitic diapirism: Record from the Ha-Tshanzi structure, Limpopo Complex, South Africa


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Granite-gneiss domes mapped as regional-scale closed structures within high-grade metamorphic complexes are considered as links between metamorphism, partial melting and diapirc emplacement of granitoid magmas during the exhumation of these terranes. Uplift of such structures is considered to be controlled by a melt-enhanced process followed by ductile shear-deformations accompanied by an external fluid flow. This study reports on the exhumation history of metapelitic granulite from the Ha-Tshanzi closed structure located in the Central Zone of the Neoarchean-Paleoproterozoic Limpopo high-grade complex, South Africa [1, 2]. The metapelite is a banded gneiss comprising granoblastic quartzofeldspathic leucosomes (plagioclase+K-feldspar+quartz+garnet+biotite) that alternate with melanocratic shear bands consisting of biotite, cordierite, sillimanite and quartz that envelope strongly deformed garnet. Garnet cores in both structural domains preserve polyphase and cryptocrystalline inclusions that are interpreted as crystallized inclusions of melt that coexisted with the metapelite mineral assemblage. Equilibrium of the mineral assemblages with the melt is also recorded in a specific zoning of garnet with respect to some trace elements (P, Cr, Sc). Phase equilibria modelling (PERPLE_X; [3]) indicates that the H2O and CO2-bearing melt coexisted with the garnet + biotite + plagioclase + quartz ± sillimanite assemblage at the metamorphic peak of 800-830°C and 10 – 10.2 kbar. The presence of the melt served as a trigger for the subsequent sub-isothermal exhumation of the rock to pressures of 7-7.5 kbar. This is clearly reflected in zoning of garnet with respect to the grossular component at almost constant XMg. Exhumation is assumed to have occurred during the Neoarchean (2.65 – 2.62 Ga) and was accompanied by voluminous leucogranite magmatism (Singelele granites). During exhumation, melt was partially lost being segregated into leucosome. Growth of cordierite sequestered water from the melt assisting to its active crystallization. As a result, the rheology of the rock changed, so that the further exhumation from the ~20-km level was accompanied by solid-state ductile shear deformation. It occurred in the Paleoproterozoic (ca. 2.01 Ga) being associated with thermal/fluid flow. This high-grade overprint event is clearly recorded in U-Pb ages of zircon, monazite and rutile. It caused reactivation of the shear-zones formed during the Neoarchean event and was accompanied by influx of low-aH2O aqueous-carbonic-salt fluids. Metamorphic evolution during the Paleoproterozoic event proceeded along the decompression-cooling path to pressures of about 5 - 4.5 kbar and temperatures below 600°C recorded by the garnet-cordierite-sillimanite-quartz assemblage in the shear-zones. The results of this study highlight the significance of domical structures related to granitic diapirs in the exhumation of polymetamorphic high-grade terranes with fluid and anatectic overprints, like the Central Zone of the Limpopo complex [2].

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References:
The Grampian Shear Zone (GSZ) located within the Grampian Highlands of mainland Scotland, is a shear zone that is suggested to separate the Dalradian Supergroup from the Badenoch Group. Within the GSZ are synkinematic pegmatite bodies with a possible formation age of c. 808Ma [1] from monazite dissolution U/Pb analyses. The Badenoch Group represents a poorly investigated basement to the Dalradian Supergroup, and records migmatization which has been dated at c. 840Ma [2]. Lithologies structurally above the GSZ within the Dalradian Supergroup only show evidence of Caledonian deformation and metamorphism [3].

New LA-ICP-MS in situ analyses of monazite from within a sample of a syn-shear pegmatite from within the GSZ, hosted within sericitized feldspars (sample RG1716 Corie Each Sheared Pegmatite). As well as a sample of a migmatic semipelite from the lower Dalradian Supergroup, in which the sampled monazite is hosted within bitoties and associated with apatite within the melanosome (sample RG1718 Ruthven Semipelite; Grampian Group) show major and REE zonation. U/Pb LA-ICP-MS spot analyses yield ages from sample RG1716 monazite 784.11 ± 1.2 Ma from the mineral core, 442.58 ± 0.66 Ma from the mineral rim, the same analysis applied to sample RG1718 yielded an age of 440.87 ± 0.37 Ma.

U/Pb LA-ICP-MS spot analyses of titanite from a Dava Subgroup (sample RG1710) metasediment yielded ages of 491.39±6.05 Ma, 475.4±0.85Ma. The same analysis applied to a pre-Caledonian amphibolite body (sample RG1703) yielded an age of 472±1.84Ma.

The U-Pb monazite data gathered suggest that monazite growth within the northern Grampian Highlands occurred during the late Ordovician after the Grampian Orogeny, and probably associated with regional D3 deformation within the Dalradian Supergroup. Monazite from within the GSZ pegmatite sample shows greater complexity of HREE zonation than the monazite grains from the Grampian Group sample. The c. 784 Ma age of the GSZ monazite core implies a complex history within the GSZ, the age of 784Ma likely overprints earlier ages associated with the Knoydartian pulse (840Ma to 780Ma) of accretionary orogenesis along the margin of Rodinia found within the NW Highlands [4].

References:
Petrologic modelling and geochronology of Paleoproterozoic migmatites in the Zenaga inlier (Anti-Atlas, Morocco)

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Understanding the nature, physicochemical conditions and timing of metamorphic processes is of paramount importance in deciphering the Earth history and, when happening during the Precambrian, they can also shed light into the now standing hot debate on the age of the onset of plate tectonics and related processes [1, 2]. One of the best suited areas to study the Paleoproterozoic (2.25-2.00 Ga) metamorphic events is the Eburnean of the West African Craton (WAC) and its extension on the basement to the Pan-African terranes in the Anti-Atlas belt of Morocco. In this region the controversy between the Archean type hot-orogen evolution is expanded to the Paleoproterozoic, as the WAC constitutes one of the youngest cratonic provinces on Earth [3].

The Paleoproterozoic rocks studied comprise a metamorphic complex (Zenaga Complex or Zenaga Group) intruded by numerous plutonic rocks of the Tazenakht Suite, predominantly granites to granodiorites, together with dolerite dykes and sill swarms. In this work, we study the metamorphic evolution of g+bi+sill+pl+q bearing migmatite samples from the northern part of the Zenaga inlier basement using petrological modelling (pseudosections), combined with U-Pb zircon geochronology.

Predicted models in the MnNCKFMASHTOZr system through P/T−X (Fe\textsubscript{2}O\textsubscript{3}; ZrO) and P−T pseudosections provides migmatisation conditions at 8.5 kbar and 750 °C. The obtained conditions are part of the cooling history of the inferred clockwise P−T−t path of the studied rocks and, according to phase diagrams, peak conditions could have been in the range of 10-14 kbar.

U-Pb LA-ICP MS analyses performed on ca. 150 zircon grains (average Th/U=0.51) have provided a single age population with a narrow range of ages from 2020 to 1980 Ma. Using this dataset an estimated migmatisation age of 2076.0 ±4.6 Ma is calculated.

The obtained P-T paths and time constraints allows us to propose an evolutionary model for the oldest known rocks in the Anti-Atlas Belt. The new data would presumably permit better constraints for palaeographic reconstructions, geodynamic models, and a better knowledge of the behaviour of old continental dynamics in the WAC.

References:
The metamorphic architecture of the transpressional Gondwanide Orogen in southern South America: Insights from P-T-D-t paths

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The Gondwanide Orogeny represents a major late Palaeozoic tectonometamorphic event along southern Gondwana, roughly coeval with the Variscan collision recorded along the northern Gondwana margin. In South America it is nearly ubiquitous along the proto-Pacific margin, being intimately associated with protracted subduction. Most relics of the Gondwanide Orogen were upper crustal rocks, but lower to middle crustal remnants are well-exposed in Patagonia (Argentina & Chile). Since robust P-T-D-t constraints are still scarce for the region, the aim of this contribution is to present a regional evaluation of integrated structural, petrological and petrochronological data, in order to evaluate the spatial and temporal evolution at the orogeny scale.

The orogen core comprises medium- to high-grade metamorphic complexes exposed between the North Patagonian Andes and the western North Patagonian Massif, recording dominantly high-T/high- to medium-P metamorphic conditions between the middle Carboniferous and the early Permian [1, 2, 3]. They are spatially associated with coeval calc-alkaline granitoids with continental arc affinity [4, 5, 6]. Further northeast, regional medium- to high-grade metamorphism is documented by the middle to late Permian in the eastern North Patagonian Massif, yielding comparable high-T/high- to medium-P metamorphic conditions. In a similar way, these metamorphic rocks are intruded by middle to late Permian granitoids [e.g., 4]. Finally, Permian low- and very low-grade metamorphism is documented in the Ventania System to the northeast of the North Patagonian Massif as part of the Gondwanide foreland. Permian felsic magmatic rocks are also present, but mainly restricted to tuffs within the sedimentary sequence and a small syenitic-granitic intrusion. In all these areas the Gondwanide Orogen is dominated by NNW-ESE- to NNW-SSW-striking fabrics, mainly associated with a regional metamorphic foliation and, locally, late shear zones. Deformation fabrics and kinematic data suggest a dextral-transpressive regional deformation regime. The marked contrast between metamorphic conditions in northern Patagonia and the Ventania System seems to result from different crustal-scale geodynamic controls. In Patagonia the pre-Gondwanide evolution was related to protracted Palaeozoic subduction and basin evolution along an accretionary margin [7]. In contrast, in the Ventania System there was reactivation of a crustal discontinuity between its Neoproterozoic basement and the adjacent Río de la Plata Craton (RPC) [8]. In this context, widespread crustal thickening during the Gondwanide Orogeny in northern Patagonia might have favoured stabilization of the Palaeozoic accretionary margin [1]. In contrast, the RPC had already attained a high thermal stability during Late Paleoproterozoic cratonization, thus resulting in a thick lithospheric mantle that behaved as a relatively rigid keel. Consequently, the RPC only recorded limited far-field Gondwanide deformation and exhumation [9].

References:
Petrochronology applied into understanding the tectonometamorphic evolution of a Neoproterozoic metasedimentary unit in the Ribeira Belt, SE Brazil and its challenges

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The Ribeira Belt, SE Brazil, formed during an amalgamation process during the Neoproterozoic in the Pan-African orogeny. Understanding of the tectonometamorphic history is limited, especially, in its southernmost part, therefore this study uses high precision in-situ geochronology coupled with systematic thermodynamic modelling to provide new constraints for the P-T-t paths that some metasediments have experienced. Schists and paragneiss in distinct metamorphic conditions crop out and they are all assumed to be part of the same unit, the Turvo-Cajati Formation (TCF). A better understanding in P-T-t paths in this unit could help to have a better picture of its tectonometamorphic evolution. TCF is a Neoproterozoic metasedimentary unit forming the Curitiba Terrane, a major segment of the southern Ribeira Belt. It is composed of rocks of greenschist (Low-TCF), amphibolite (Medium-TCF) to granulite (High-TCF) facies conditions. Previous studies in High-TCF indicates that the unit underwent extensive partial melting under high-pressure conditions (670-810 °C and 9.5-12 kbar), within the kyanite stability field, Faleiros [1]. They also indicate maximum depositional age about 650-630 Ma, Faleiros [2] and Ricardo [3]. The metamorphic zoning within Low and Medium-TCF is detailed in this study. The P-T investigation is made using petrography and pseudosection modelling in the NCKFMASHTO and MnNCKFMASHTO systems with Perple_X software. P-T pseudosections are modelled considering different stages of garnet growth and their respective P-T conditions. Four metamorphic zones were recognized for the Low-TCF and Medium-TCF: biotite, garnet, staurolite and sillimanite zones, with pressures below 8 kbar, as staurolite breaks down straight to sillimanite. This suggests that different parts of the TCF may have experienced distinct metamorphic histories. Timing constraints were determined using in-situ U-Th-Pb monazite petrochronology techniques. Combining in-situ U-Th-Pb Laser Abation-ICP-MS dating of monazite, geochemical/isotopic analyses and pseudosection modelling allows P-T-t paths to be determinate for TCF sub-units. Monazite ages indicate an overlap on the metamorphism of High-TCF and Medium-TCF yielding growth between 620-580 Ma, but some older cores are also recorded. TE distribution indicates monazite growth correlated with partial melting (Eu* in High-TCF) and garnet growth (HREE and Y). By comparing metamorphic ages in High-TCF and Medium-TCF, we can better understand the relation of the metamorphic events on both units and their current tectonic disposition.

References:
Graphite within the Granjeno Schist metamorphic complex: a metamorphic indicator for the NE mexican basement


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The basement complex of the Sierra Madre region in northeastern Mexico is classified into four domains: a) granulite facies rocks of Grenville age (ca. 1 Ga) known as the Novillo Gneiss, b) the Paleozoic Granjeno Schist, c) an unmetamorphosed succession of Paleozoic marine siliciclastic and volcanic rocks, and d) an Ordovician plagiogranite body. Metamorphosed Paleozoic rocks in the Sierra Madre terrane of northeastern Mexico are tectonically juxtaposed against granulite-facies rocks of Grenville age (~1 Ga) and an unmetamorphosed succession of Paleozoic marine siliciclastic and volcanic rocks [1]. These units constitute the main exposures of Precambrian and Paleozoic rocks in the vicinity of Ciudad Victoria in northeastern Mexico.

The Paleozoic Granjeno Schist metamorphic complex (GSMC) crops out in the cores of anticlines and in basement highs of the Sierra Madre Oriental. This metamorphic complex comprises both sedimentary (psammite, pelite, turbidite, conglomerate, black shale) and igneous (tuff, lava flows, pillow lava and ultramafic bodies) protoliths [2]. These rocks are considered as remnants of the Laurentia-Gondwana collision [3]. Within the variety of lithologies in the GSMC it is possible to recognized graphite and fine-grained dispersed carbonaceous material.

Previous works estimated, according to a chlorite geothermometer and the presence of phengite in the metasedimentary units as well as 40Ar/39Ar ages on metavolcanic rocks, that the GSMC was metamorphosed under sub-greenschist to greenschist facies with temperatures ranging from 250-345°C with 2.5 kbar during Carboniferous time (330-300 Ma) [2].

Graphitization conditions due as this process is an irreversible process. During metamorphism, organic matter is progressively transformed into graphite and the degree of maturation or graphitization of graphitic materials is considered as a reliable indicator of peak conditions of the metamorphic temperatures experienced by the host rocks [4].

According to our results graphitization process in the GSMC occurred at different temperature ranges of 318-339°C and 426-432°C, revealing higher metamorphic temperatures than previously proposed. We suggest that the sediment rich in organic matter were part of the floor of an ancient sea deposited in pull-apart basin possible related to the Paleo-Pacific Ocean, at the periphery of Gondwana to Oaxaquia, and that it was affected by high-grade and regional metamorphism during the final closure of Pangea.

References:
Kyanite-Andalusite-Sillimanite crystallization sequence during two separated orogenic episodes: new occurrence from the Northern Andes

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A metapelitic rock from the Silgará Schist in the Northern Andes (Colombia) contains the three Al₂SiO₅ polymorphs that were formed in the crystallization sequence Kyanite \( \rightarrow \) Andalusite \( \rightarrow \) Sillimanite, a not so common sequence in samples where the three polymorphs coexist. Al₂SiO₅ polymorphs in the sample represents metamorphic reactions that took place during two separated metamorphic events. The Silgará Schist Barrovian sequence (early Paleozoic orogeny) shows staurolite appearing almost coincidently with garnet and before than kyanite. Kyanite crystallized in a chlorite free assemblage following a prograde trajectory and persisted metastably during a late Triassic - Jurassic overprinting regional low pressure event where andalusite and then sillimanite (fibrolite) formed. Reaction producing andalusite and kyanite most likely involved consumption of staurolite, muscovite and quartz and also produced garnet, biotite, and plagioclase. Polymorphic transformations were also important in the development of the coexistence of the three Al₂SiO₅ polymorphs. For high-Al metapelites from Barrovian terranes, the presence of andalusite coexisting with kyanite and/or sillimanite must be related to andalusite growing during a different tectonic episode; in the reported occurrence here, andalusite formed during an overprinting low pressure heating event.
There's no accounting for oscillations: rhythmic garnet zoning unrelated to heterogeneous high pressure low temperature fluid transfer?

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Since first documented in Franciscan eclogites by Dudley [1], records of oscillatory chemical zoning in garnet—short wavelength (≤ 20 μm) cycles of peaks and troughs in elemental concentration parallel to primary mineral interfaces—have proliferated. Electron microprobe and laser ablation–inductively coupled plasma–mass spectrometry mapping of metabasic garnet porphyroblasts from numerous subduction settings, presented here, reveal that even in cases where the major element record has been modified by diffusional homogenization or late fluid-related alteration, fine oscillations are preserved in trace element zoning. Owing to the ubiquitous nature of this zoning across unrelated subduction zones it likely reflects some fundamental petrogenetic process operating during metamorphism.

Here, we investigate the potential link between fluid fluxing and the development of oscillatory zoning. Despite the inferred absence of a persistent wetting fluid at these high-pressure conditions, rock-wide similarities between both major and trace element zoning patterns in given samples are consistent with cm-scale chemical equilibration during garnet growth at c. 500–550 °C. However, a lack of spatial covariance between elemental and δ18O records (determined via secondary ionized mass spectrometry) is inconsistent with the notion that oscillations are directly linked to infiltration of chemically and isotopically distinct fluids in a fluid-buffered scenario. Instead, discrete vacillations in δ18O of < 2 ‰ (over 50–100 μm), coupled with < 1 ‰ net core-to-rim δ18O change may point to the predominance of an internally-controlled grain boundary fluid and relatively stagnant fluid conditions at high pressure. If persistent, such regimes may account for the accumulation of excess argon and periodic overpressure, and the down-slab transfer of shallow geochemical signatures. For the rare cases in which rocks experience transient open system porous behavior—evidenced by infiltration of low δ18O reducing fluids that dramatically changed the reactive bulk composition—the formation of trace element oscillations is core-ward of external fluid fluxing, further demonstrating the decoupled nature of the two records. Thus, the link between fluid fluxing and oscillatory zoning documented in other fluid-rich settings (e.g., [2],[3]) does not seem to persist at high pressure. Alternatively, we explore the possibility that oscillations may result from P–T cycling along either clockwise or anticlockwise prograde paths or repeated cycles of overstepping and isothermal growth.

References:

Subduction fluids are fundamental in regulating long-term chemical cycles and their reliable characterisation is of primary importance for our understanding of processes related to mantle wedge metasomatism, oxidation and melting. UHP fluids are composed by solvent C-O-H-N-S molecular volatiles and by solute non-volatile elements (e.g., Si, Al, Ca, Mg, Fe, K, Na, Cl) bounded to inorganic and organic species. Both direct (fluid inclusion, FI) and indirect (thermodynamic modelling, TM) approaches to study these fluids have reliability issues due to the complexity of the investigated processes. The chemical fingerprint of UHP FI can be easily modified by post-trapping processes (e.g., solvent loss, chemical interaction with host mineral), while TM of solute-bearing fluids at UHP conditions is still in its infancy.

In this work, we apply and compare the data obtained by FI study and TM on UHP FI (Fig. 1) trapped within peak diopside from a chemically simple marble from the UHP Brossasco-Isasca Unit of the Dora-Maira Massif (Western Alps). Classical molecular-fluid TM allowed to model post-trapping reactions between FI and host diopside, and then to discriminate among daughter, step-daughter and incidentally trapped minerals present within the inclusions. Electrolytic-fluid TM allowed to model the chemical composition of the peak solute-bearing aqueous fluid (H$_2$O: 96.3 mol%/88.5 wt%; solutes: 3.7 mol%/11.34 wt%; CO$_2$+H$_2$S+CH$_4$: 0.09 mol%/0.17 wt%) generated by progressive rock dissolution. The comparison between the modelled composition with that reconstructed by FI study allows to recognise the type and the extent of post-trapping chemical re-equilibrations (up to 35 mol% of host diopside contamination and 18-99 mol% of the original H$_2$O lost by diffusion and decrepitation; Fig. 1) occurred within UHP FI. Applying this multidisciplinary approach, we demonstrate that the most impacting FI post-trapping process is the H$_2$O loss, with consequent preservation of the geochemical information in those FI lacking relevant post-trapping host-diopside chemical contamination (Fig.1). Moreover, we also show how FI complemented with electrolytic fluid TM can be employed to retrieve geochemical information on deep subduction fluids and the fluid and rock geochemistry of C-bearing systems (especially regarding all the multiple C-oxidation states contemporaneously in equilibrium at the same time). Finally, this work demonstrates the potentiality of this type of multidisciplinary work in developing a more complete and meaningful geologic model of the petrologic processes occurring during deep subduction, thanks to the ability of FI studies and TM to access different and complementary information, that would not be accessible otherwise.
Deformation and textural evolution during devolatilization of meta-ophricharbonate lenses hosted in subducted ophicarbonates from Almirez serpentinite—hazburgite of the Milagrosa and Almirez ultramafic massifs in the Nevado-Filábride Complex (Betic Cordillera, Spain), which record high-pressure alpine subduction metamorphism. In the Milagrosa massif, serpentinite underwent prograde metamorphism to foliated antigorite-diopside-dolomite rocks and Ti-clinohumite-bearing diopside marbles (550–600 °C, 1.0 – 1.4 GPa). In Almirez, they were transformed to high-grade assemblages of Ti-clinohumite, olivine, diopside, chlorite, aragonite and dolomite (650 – 680 °C, 1.7 – 1.9 GPa) [1]. We combine microstructural and textural data obtained from electron backscatter diffraction (EBSD) and optical cathodoluminescence (CL) imaging to investigate the relationship between deformation and metamorphic devolatilization during the prograde reaction of antigorite with Ca-carbonate to diopside and Mg-silicates. In the Milagrosa massif, Atg-serpentinites and Cpx-serpentinites show a fabric with a crystal preferred orientation (CPO) of antigorite typical of prograde deformation and metamorphism of high-P Atg-serpentinites in subduction zones. Antigorite in antigorite-diopside-dolomite rocks displays the same fabric, with a girdle distribution of the poles to (010) in the foliation plane and a strong c-axes maximum coinciding with the pole to the foliation. Dolomite and calcite in the Milagrosa meta-ophricharbonate lenses have a consistent CPO with their c-axes orientated subparallel to that of antigorite, which correlates with the poles to (100) of diopside. In the Almirez meta-ophricharbonate lenses, diopside, dolomite and calcite show a very similar distribution of their crystallographic axes with respect to foliation.

CL imaging reveals a concentric core-rim zonation of diopside and dolomite in both localities. These zonation patterns and low internal misorientations point to diffusion creep by dissolution-precipitation as the dominant deformation mechanism. The strong correlation of diopside, carbonate and antigorite CPOs may have been caused by oriented crystal growth due to anisotropic fluid flow in the reacting ophricarbonate, possibly in addition to a topotactic relationship between precursor antigorite and product carbonate/diopside. We infer that antigorite dehydration in meta-ophricharbonate at temperatures of 580 – 600 °C was related to transient ductile deformation enhancing fluid drainage, followed by compaction and an increased bulk rock strength once all antigorite devolatilized. This might have caused deformation and fluid flow during dehydration of the host serpentinite at 650 °C to focus around the meta-ophricharbonate lenses, shielding carbonate from dissolution.

**In situ** measurements of nitrogen contents in formerly subducted rocks reveal variable behaviour of nitrogen during fluid-rock interaction.

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Nitrogen recycling from the Earth’s surface to the mantle through subduction zones is a key component of the long term global nitrogen cycle. Data on the nitrogen contents of formerly subducted rocks is key to constraining this flux and to understanding nitrogen behaviour during subduction dehydration. Studies have so far been restricted to analyses of whole rocks or mineral separates, which masks textural controls and mineral heterogeneity\(^1,2,3\). Here we present the first *in situ* SIMS analyses of nitrogen contents in white micas and other minerals from a suite of subduction-related crustal rocks. We determine the nitrogen distribution in these rocks and explore the behaviour of nitrogen, compared to other fluid-mobile elements, during subduction and fluid-rock interaction. Samples from three localities were investigated: blueschist and eclogite from the Raspas Complex, Ecuador; blueschist and eclogite from the Franciscan mélangé (Jenner, California); eclogite and garnet-phengite quartzite from Lago di Cignana, Italy.

Our data confirm that white mica (phengite, paragonite) is the primary host for nitrogen across all samples. Both phengite and paragonite contain substantial amounts of nitrogen (up to 320 ppm), but the concentrations vary widely across different samples. Chlorite replacing garnet in eclogites and blueschists contains little nitrogen. In contrast, chlorite occurring with garnet, phengite (108-270 ppm N), glaucophane and titanite in the matrix of a blueschist from Jenner contains measurable quantities of nitrogen (10-83 ppm). Other minerals (clinopyroxene, amphibole, epidote, titanite, garnet) contain little nitrogen (<5 ppm) in all samples.

A blueschist from Raspas contains coexisting phengite and paragonite, in addition to garnet, glaucophane, and epidote, and accessory albite and carbonate. Nitrogen preferentially partitions into phengite (117-243 ppm) over paragonite (31-118 ppm). Albite also contains some nitrogen (15 ppm). Silicon contents of phengite vary from 3.32 – 3.40 a.f.u. Decrease in silicon is correlated with decrease in nitrogen and boron, and increase in lithium. These trends can be explained by growth of paragonite during retrograde fluid-rock interaction and redistribution of these elements between phengite, paragonite and glaucophane.

Variability in nitrogen concentrations in other samples which have undergone peak or retrograde fluid-rock interaction, and contain only phengite as a nitrogen-bearing phase cannot be explained by redistribution. Different samples display either no change in nitrogen, or addition of nitrogen during fluid-rock interaction, as recorded by different generations of phengite. No correlation between nitrogen contents of the samples and P-T conditions was observed, but this was likely due to the large range of protoliths in this study.

Our results demonstrate that nitrogen behaviour during fluid-rock interaction is complex and can be variable between samples, and that *in situ* data can inform understanding of the processes controlling N distribution.

**References:**

Experimental simulation of geodynamic processes using piston cylinder P-T loop experiments: the subduction P-T path of a natural metapelite sample

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Metamorphic rocks are recorders of geodynamic processes. But how much memory, e.g. which part of the P-T path is actually recorded in the observed mineral assemblages often remains a mystery. On the other hand natural observations show that several stages of mineral growth mostly along the retrograde portion of a subduction P-T path can indeed be preserved [1,2,3]. But can we experimentally simulate polyphase mineral growth along a defined P-T path? Experimental investigations using natural rocks can be seen as a forward modelling technique and thus allow putting constraints on the mineralogical evolution of a rock under defined P and T conditions. For this purpose, simple experiments using natural rocks as starting materials can easily be conducted. The disadvantage of this method lies in the complex chemical compositions of natural rocks and the deviation from chemical end-member systems. Therefore thermodynamic modelling using pseudosections often yields only moderate agreement between observed and calculated phase assemblages.

Theoretically, high-pressure metapelites in the system N(C)KFMASH show complex mineral assemblages during the transition from high-P-T conditions to the retrograde portion of the P-T path and often preserve no mineralogical memory of high-P-T conditions at all [2,3]. To test this observation the experimental simulation of a defined subduction P-T path was done by using a piston cylinder apparatus with an automated P-T control. As starting material a natural muscovite-rich quartzphyllite sample (SP5) with the mineral assemblage garnet + muscovite₁ + chlorite + albite + ilmenite + quartz) with 10% H₂O added was used.

For the P-T loop experiments three different P-T conditions were chosen and run subsequently one after the other representing a P-T loop from a subduction setting. The P-T conditions were: 500°C 1 GPa (stage-1), 600°C 1.8 GPa (stage-2) and 500°C 0.5 GPa (stage-3) and each P-T condition was run for 8 days which results in a total experimental duration of 24 days for the whole P-T loop. The experiment yielded the complex newly-grown mineral assemblage: Amp₁,₂,₃ + Ms₂ + Rt. Ms₂ shows an increase in Si, amp₁ and amp₂ are winchites/barroisites, where amp₂ shows an increase in the Al content and amp₃ is cummingtonite. Glaucophane formed via the reaction: albite + Mg-chlorite = glaucophane + H₂O. Due to the low temperature, too little time and small amounts of fluid, only incomplete mineral Transformations were observed. Ilmenite shows partial transformation into rutile, relict albite is still present and garnet shows tiny resorption rims. The comparison with theoretically calculated phase assemblages using DOMINO-THERIAK is due to the lack of calculated omphacite and garnet only moderate.

This study shows that experimental forward modelling using whole-rock experiments close to the system N(C)KFMASH does indeed provide clues about the mineralogical evolution of a given rock composition that can be attributed to different P-T stages of a given P-T path. On the other hand thermodynamic testing using pseudosections is still hampered by slow kinetics and the complex nature of the bulk composition of the starting material.

References:
Monazite, xenotime and Al$_2$SiO$_5$ polymorphs, the perfect team to characterize polymetamorphism

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Al$_2$SiO$_5$ polymorphs (andalusite, kyanite and sillimanite) are common in aluminous metamorphic rocks, are easily identifiable, crystallize at distinct pressure (P) and temperature (T) conditions, and therefore provide first-order constraints on the metamorphic grade and facies series. The metastable coexistence of all three polymorphs in the northern Canadian Cordillera provides the opportunity to reconstruct the polyphase metamorphic evolution of a peri-Laurentian terrane, the Yukon-Tanana terrane. We used in-situ laser-ablation split-stream (LASS) petrochronology to target monazite and xenotime associated with specific metamorphic index minerals. These data reveal a complex P–T–time (t) path, requiring three P–T loops, and passing through the kyanite, sillimanite and andalusite stability fields over 150 Myr from the Permian to the Early Cretaceous. The earliest preserved metamorphic event reached the kyanite stability field (>600 °C, >0.6 GPa) at ca. 270–240 Ma and was followed by retrograde metamorphism at ca. 240–215 Ma. Renewed garnet growth occurred during a second prograde metamorphic event at ca. 195–185 Ma. Garnet breakdown, probably linked to decompression in the suprasolidus stability field of sillimanite and K-feldspar (>700 °C, <0.7 GPa) occurred at ca. 185–170 Ma. Finally, a third P–T loop is characterized by the growth of andalusite, then cordierite, and reached >600 °C below 0.3–0.4 GPa after ca. 120 Ma. These new P–T–t constraints indicate that the Yukon-Tanana terrane was involved in two separate collisions with adjacent terranes during the Permian–Triassic and the Late Triassic to early Jurassic, followed by an episode of Cretaceous contact metamorphism. Our study illustrates the importance of analyzing petrochronometers in their textural context, especially inclusions in porphyroblasts, and the complementary P–T–t information that can be extracted from monazite and xenotime. LASS petrochronology was decisive to understand the interplay and trace element partitioning between garnet and accessory petrochronometers.
Petrochronologic constraints and P-T-t history of multiple crustal levels of an ancient orogenic plateau, Appalachian orogen, USA

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Orogenic plateaus are formed by a complex interplay of deep and surficial processes, however the former are poorly constrained as the lower levels of extant plateaus are rarely exposed. To better constrain the 4D evolution of orogenic plateaus, we conducted a detailed petrochronologic study of a recently identified ancient analogue in the Appalachian orogen, New England, USA [1]. We constrained P-T-t paths from rocks sampling depths of 10 to 60 km of the “Acadian altiplano”, using multi-scale compositional mapping, in-situ monazite and xenotime petrochronology, major and trace element thermobarometry, and forward and inverse thermodynamic modelling.

Samples from upper mid-crustal rocks (10-15 km) preserve a polyphase record of the Acadian and Neoacadian orogenies. Xenotime and monazite are present in equal abundance, with the latter showing up to eight distinct compositional domains. Thermal peaks ca. 400 and 380 Ma are related to the Acadian nappe phase and Neoacadian plateau formation, respectively, and were followed by slow cooling. Mid-crustal samples (20-25 km depth) record a counter-clockwise P-T path with protracted partial melting during granulite facies metamorphism. Monazite is abundant in the matrix and as inclusion within garnet rims while xenotime is restricted to inclusions within garnet cores. Y zoning in monazite consistently involves high Y cores (400-380 Ma), low Y mantles (380-330 Ma), and high Y rims (330-300 Ma). High Y monazite cores and xenotime inclusions in garnet constrain garnet growth to c. 380 Ma. We interpret that low Y domains record monazite growth in the presence of stable garnet and high Y rims record garnet breakdown during exhumation. This “U-shaped” Y-monazite profile is typical of rocks recording prolonged mid-crustal residence [2]. Lower crustal rocks (~50-60 km) from gneiss domes record a looping P-T path, with eclogite to high pressure granulite facies metamorphism ca. 380 Ma, followed by decompression and re-equilibrium in the mid-crust (~20-25 km). Monazite from these rocks is zoned with increasing Y from core to rim and increasing Eu/Eu*, which we interpret to be associated with decompression, cooling, during two-stages of exhumation. Each crustal level is a characterized by distinct P-T path, compositional zoning in monazite and xenotime, and reaction history. Together, our petrochronologic approach documents the dynamic history of the Acadian altiplano and highlight similarities with features observed in extant plateau. Abundant evidence for protracted partial melt in mid-crustal rocks at 20-25 km depths is absent from rocks just a few km higher, which we speculate may preserve a window into the “bright spots” imaged at similar depths underneath Tibet [3]. All samples show evidence for garnet breakdown and exhumation at c. 340-330 Ma, indicating that plateau collapse was largely synchronous and perhaps driven by plate scale events [4]. Together, these results demonstrate the sensitivity of in-situ petrochronologic methods to reconstruct complex P-T-t paths and suggest that the New England Appalachians may prove an important natural laboratory for studying orogenic plateaus.

References:
Multiple Melt Generations in the Himalaya: Zircon isotope geochemistry

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Prograde metamorphism in orogenic settings results in widespread partial melting and, therefore, decreased mechanical strength of the rocks involved. This has implications for the structure of the mid-crust and its exhumation. Peak temperatures and pressures reached in the Himalayan orogen results in granitic bodies by melting amphibolite-grade pelitic material, both through the presence of aqueous fluid and the dehydration of muscovite [1]. Granites and migmatites with complex cross-cutting and intermingling relationships are found throughout the Greater Himalayan Sequence (GHS), forming some of the highest peaks of the Himalaya. The granites have been dated to the Early and Mid-Miocene, associated with decompression after the onset of exhumation [2]. The age, composition, and textures of the migmatites are, therefore, critical to our understanding the early stages of exhumation in orogenic systems.

Studies of granite pluton formation have developed the idea that plutons are created by the amalgamation of multiple pulses of melt over millions of years [3, 4], with accessory mineral phases capturing trace element and isotopic signatures over millions of years of crystallisation. However, the precise longevity of the process from anatexis through melt extraction, transport and accumulation as large granite plutons is not yet constrained. It is, therefore, important to analyse geochemical signatures in granites, migmatites, and un-melted host rocks to uncover the full story of melt generation events. We present a dataset from the GHS of the Garhwal Himalaya, India, that constrain the regional conditions and timescales of melting episodes, while detailing case-study outcrops of melt relationships.

U-Th-Pb, Hf, and oxygen isotopes, together with trace elements, were analysed in zircon separated from leucogranites, migmatites, and host metasediments using LA-ICP-MS and SIMS. Samples were collected from the Rishi Ganga and Alaknanda valleys in the Garhwal Himalaya. Himalayan-age rim domains were targeted for analysis, identified using cathodoluminescence imagine. Our findings show that in some cases the migmatites formed up to 10 Ma prior to the associated leucogranites, with regional migmatite crystallisation largely constrained to 34-15 Ma, and leucogranites to 22-13 Ma. Measurements of δ18O suggests enrichment of 16O in younger melt bodies, relative to local heterogeneities, while εHf values show little systematic variation with age, suggesting a common source of melt.

References:
Field and petrographic constraints on the structural and metamorphic evolution of the Zanskar Himalaya, Suru Valley, NW India

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The metamorphic rocks of the Greater Himalayan Sequence (GHS) provide a key record of how continental crust accommodates deformation during continental collision. In this study, we focus on the Suru Valley of the western Himalaya, where the GHS is bound to the northeast by the Zanskar Shear zone (ZSZ), and to the southwest by the Main Central Thrust (MCT). This region provides a unique exposure of early widespread lower-temperature, higher-pressure (kyanite-grade) mineral assemblages. This contrasts to other areas of the GHS which equilibrated late in the orogenic cycle, under higher-temperature, lower-pressure (sillimanite-grade) conditions. The aim of the study is to integrate mineral growth and deformation fabric relationships at the macro- to micro-scale, with phase equilibria modelling and geochronology, to quantify the P-T-t-d evolution of the GHS, with the results of the structural analysis the focus of this presentation.

Field and petrographic observations reveal three sets of penetrative planar and/or linear structural elements ($S_1$, $S_2$, $S_3$ and associated $L_1$, $L_2$, $L_3$, and $F_2$). These structural elements are folded by late open NE and SW plunging $F_4$ folds. The dominant $S_2$ fabric comprises a NW- to NE-dipping crenulation cleavage of $S_1$ with locally developed shear structures documenting thrust-sense displacements. $F_2$ are tight to isoclinal, m- to km-scale structures resulting in significant thickening of the GHS. The GHS in the study area displays a complete Barrovian metamorphic sequence from chlorite- to sillimanite-K-feldspar grade. The trace of mapped mineral isograds appear broadly concordant with $S_2$ and are folded by the $F_4$ structures. Peak-pressure and peak-temperature metamorphic minerals display the following relationships to the dominant penetrative fabric. Chlorite is aligned with $S_2$. Biotite is aligned with $S_2$, but at higher grades also overgrows $S_2$. Garnet cores are characterized by an internal fabric comprising spiral or concordant inclusion trails with respect to $S_2$, whereas inclusion-poor garnet rims overgrow $S_2$. Staurolite overgrows $S_2$ and preserves $S_2$ concordant inclusion trails. Kyanite overgrows $S_2$. Sillimanite shows both alignment and misalignment with respect to $S_2$. Taken as a set, these observations suggest that the thermal peak of metamorphism outlasted deformation in the core of the GHS in the Zanskar Himalaya.

Penetrative, top-to-NE, normal shear sense fabrics associated with the ZSZ overprint the compressional fabrics of the GHS. North of Sankoo, the ZSZ is bound by undeformed and deformed Dras Volcanics in the hanging wall and footwall respectively, whereas east of Rangdum the shear zone juxtaposes low-grade metasedimentary rocks of the Tethyan Himalayan Series (THS) in the hanging wall and mixed semipelite, metacarbonate and pelite of the GHS in the footwall.

It is anticipated that forthcoming P-T-t data for peak-pressure and peak-temperature metamorphic assemblages from a broad range of exposed structural levels will help to constrain models for how the continental crust was thickened, metamorphosed, and exhumed in the Zanskar Himalaya, with potential along-strike implications for the evolution of the Himalayan metamorphic core.
Development and Application of High-Resolution Garnet P-T-t paths to Himalayan Tectonics

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Tectonic models as a universal outcome generate predictions regarding the travel-time paths of rocks as they displace due to the application of particular input parameters and boundary conditions. A need for most of these models, either as a constraint for realistic input conditions or to gauge their relevance to a particular natural system, is pressure-temperature-time (P-T-t) paths from individual rock samples that track the conditions they experienced during displacement. This type of information is a valuable addition to microstructural data regarding strain recorded during rock deformation. Zoned garnets have long been used to generate P-T paths. However, low-resolution paths are limited in their ability to test ideas regarding lithospheric response to perturbations. Thermodynamic modelling [1-3] allows the ability to generate high-resolution P-T paths that show the conditions responsible for garnet growth within major Himalayan fault systems exposed across fault systems in central Nepal (Darondi Khola and Marysandi River) and NW India (Bhagirathi River) [4,5]. The Main Central Thrust (MCT) separates lower-grade garnet-bearing schists from the Lesser Himalayan Formation from higher-grade gneisses of the Greater Himalayan Crystallines. MCT footwall P-T paths are consistent with shear zone imbrication and demonstrate consistency in conditions across the footwall at locations ~650 km apart. Lesser Himalayan garnets seem ideally suited for the approach and appear to behave as closed systems with minimal modification since growth. High-resolution paths can significantly increase the understanding of the dynamics of field areas that contain garnet.

Isochemical phase diagrams with garnet core isopleths (colored bars) and P-T paths (black lines) from Himalayan MCT footwall garnets collected from the (a) Bhagirathi River, (b) Darondi Khola, and (c) Marysandi River [see also 4,5].

References:
Unravelling tectono-metamorphic discontinuities in NW Himalaya: consequences for the mid-crust assembly during continental collision

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Tectono-metamorphic discontinuities are abrupt changes of metamorphic, deformation and time path pattern within collisional belts. In the Greater Himalayan Sequence (GHS), an exhumed mid-crust mega tectonic unit in the Himalaya belt, a tectonic-metamorphic discontinuity known as the High Himalayan Discontinuity (HHD) has been mapped in central and eastern Himalaya, but it has never been reported in NW Himalaya. In order to assess the HHD presence in the western portion of the belt, a multidisciplinary approach comprising fieldwork, microstructural analyses, petrology and in situ monazite geochronology was addressed to the GHS in the Alaknanda valley, Garhwal Himalaya (NW India). This applied integrative methodology allowed us to reveal the occurrence of a newly high-temperature shear zone, the Badrinath shear zone (BSZ), within the GHS.

The Badrinath mylonite displays top-to-the-south thrust-sense of shear and affects sillimanite-bearing gneiss showing evidence of partial melting. The data integration allowed us to reconstruct the following model for BSZ development: the pre-mylonitic stage took place during prograde metamorphic path reaching conditions of 700-720°C and 10 kbar during the time interval of 34 and 23 Ma with incipient partial melting, followed by nearly-isothermal decompression triggered by the shear activity between 23-19 Ma, with exhumation rate of ±0.3 cm yr⁻¹. Moreover, the rocks from the lower part of GHS, in the BSZ footwall, experienced metamorphic conditions of c. 700°C and c. 10-11 kbar, the partial melting and exhumation took place later, ~3 Ma after the BSZ.

Such features led us to correlate the BSZ with the High Himalayan Discontinuity (HHD). The BSZ is the first reported HHD branch in NW Himalaya (Garhwal). It corroborates the regional extent of the HHD accomplishing an important role during the GHS exhumation. In the Alaknanda valley, the MCTz and STDS ductile activities in the Alaknanda valley were coeval but only at ~20 Ma, later than the BSZ ductile shear activity, which allowed the earlier exhumation of the upper GHS. These new data point to a shift in time and space of deformation responsible for the mid-crust rocks exhumation within the GHS.
Unravelling the evolution of a major extensional lower crust shear zone from Val d’Ossola (Ivrea-Verbano Zone, Western Alps, Italy)

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The Ivrea Verbanzone (IVZ, Western Alps) is an exhumed section of the pre-Alpine middle to lower continental crust made of (ultra-)mafic rocks intruded into high grade metapelites and metabasites that escaped Alpine subduction. Following the Variscan orogeny, indeed, the IVZ was affected by post-orogenic extension and subsequently, in the Triassic-Jurassic time interval, by a complex and polyphasic episode of rifting stage which resulted in mid lower crustal shear zones [1]. In particular, the Val d’Ossola displays an ideal IVZ section that preserves the main extensional shear zones (i.e., Anzola and Premosello shear zones) showing progressively higher T conditions with increasing crustal depth [2]. While magmatism and amphibolite to granulite metamorphism are constrained between the Carboniferous and Permian times [3], the timing of extensional shear zones activities is still poorly constrained [4]. The present study focuses on the Anzola shear zone, which developed at upper amphibolite facies conditions between metabasites/granulites and metagabbros. In this contribution, we present new microstructural and petrological data with the purpose to reconstruct the Pressure-Temperature-timing-Deformation (P-T-t-D) path of mylonites and surrounding wall rocks (metabasite/granulite and metagabbro). In particular, we focus on the intracrystalline deformation features of the potential geochronometers titanite and zircon. We performed quantitative orientation analysis using SEM-EBSD to characterise their deformation features from different rock types across shear zone and investigate their relationship with isotopic signatures and, possibly age dating. Preliminary zircon data obtained from the mylonitic amphibolites from Anzola [5] revealed a weak or absent intracrystalline deformation and a wide range of U-Pb dates (310-230 Ma), mainly overlapping with the Carboniferous-Permian magmatic and metamorphic events. However, these mylonitic amphibolites contain abundant titanite along the foliation, which shows sigmoidal shapes, slight bent twins and intracrystalline deformation with a maximum orientation change within an individual grain of around 15°. The trace element characterization of titanite grains showed a U concentration ranging from 50 to 150 ppm; we plan to perform U-Pb dating on these intriguing grains. The combination of multidisciplinary approach and different systematics on multiple geochronometers may allow to better constrain the role of the shear zone in the rifting process of the IVZ.

References:
In north-eastern Sardinia, in the southern side of the Posada-Valley which is a km-wide shear zone of regional relevance, we collected garnet-staurolite schists with plurimillimetric garnet and staurolite porphyroblasts. At the outcrop scale the schists appears as silver-coloured, strongly foliated rocks rich in mica characterized by the occurrence of reddish to brownish garnet porphyroblasts up to 0.8-1 cm in size. Garnet crystals are enveloped by the main S2 regional schistosity which is identified by the orientation of white mica and chlorite. The garnet porphyroblasts are characterized by an inclusion-rich nucleus (garnet core) surrounded by a garnet mantle almost free of inclusions. The inclusions within the garnet crystals, which mainly consist of quartz, rutile, ilmenite, chloritoid, mica and zircon, often follow an oriented spiral-shaped and/or sigmoidal arrangement recording an earlier S1 schistosity. Some smaller (less than 0.5 cm) and/or anhedral garnet grains lack the inclusion rich nucleus. The yellowish staurolite porphyroblasts (up to 0.5 cm in size) are often characterized by opaque minerals oriented inclusions. Chloritoid is found as oriented and isolated single crystals within the rock matrix. Paragonite locally grows on chloritoid, when this latter is included in the garnet. Accessory minerals in the schists are apatite and tourmaline. EMP X-ray mapping and rim-core-rim garnet compositional profiles reveal a strong compositional zoning of the garnet components and the occurrence of a very thin (only a few dozens of µm in size) outer garnet rim, not detectable with the polarizing microscope. The garnet core composition ranges between XCa (Ca/(Ca+Mg+Fe+Mn): 0.21-0.27; XMg (Mg/(Ca+Mg+Fe+Mn): 0.01-0.02; XFe (Fe/(Ca+Mg+Fe+Mn): 0.45-0.50; XMn (Mn/(Ca+Mg+Fe+Mn): 0.25-0.30. The garnet mantle is enriched in almandine (XFe 0.55-85), pyrope (XMg 0.018-0.075) and depleted in grossular (XCa 0.06-0.18) and spessartine (XMn 0.05-0.24) components as compared to the garnet core. The narrow outer rim shows an abrupt decrease in grossular (XCa 0.02-0.03) and increase in pyrope content (XMg 0.11-0.13). Plagioclase single crystals in the matrix are oligoclase/albite (Ab ~ 90 mol.%). Staurolite porphyroblasts show XMg ratio of 0.14-0.13 in the core and 0.11-0.10 in the rim. Ti and Mn contents in staurolite is ~ 0.1 and 0.02-0.05 a.p.f.u., respectively. Chloritoid, independently from its microstructural position (i.e. inside the garnet or in the rock matrix) shows XMg ratio of 0.12-0.13. Biotite in the matrix has XMg ratio of 0.47. White mica shows different composition based on the microstructural position: white mica included in garnet has Si (a.p.f.u.) 6.38 and XMg 0.54, white mica single crystals in the matrix shows Si 6.11 a.p.f.u. and XMg 0.47, white mica in the micaceous layers has Si 6.04 a.p.f.u. and XMg 0.40. Chlorite shows XMg ~ 0.4. Monazite in situ dating with EMP yielded ages comprised between 417 and 322 Ma (average 377 Ma) for monazite included in garnet and 402-330 Ma (average 357 Ma) for monazite in the rock matrix. Small rutile grains preserved in garnet contain up to 0.02 wt.% zirconium, whereas the rare rutile grains in the rock matrix have undetectable zirconium content. Application of the Zr-in-rutile thermometer, following the calibration after [1], to 35 rutile grains included in garnet gives an average temperature of 554°C. Preliminary results on thermodynamic modelling suggest that the schist underwent a clockwise P-T path with a prograde portion that reached ca. 1.0 GPa peak pressure and temperature up to 600°C. The rock underwent later low-grade re-equilibration and mylonitization.

References:
Metamorphic and structural data of the Monte Filau Orthogneiss, SW Sardinia (Italy)

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The Monte Filau Orthogneiss represents the southernmost metaigneous body cropping out in the External Zone of the Variscan chain of Sardinia. It derives from an Ordovician granitoid intruded in the Monte Settiballas Micaschist at about 460 Ma. Three different petrographic facies can be distinguished in the orthogneiss: (i) a dark, biotite-rich facies, (ii) a leucocratic, fine-grained facies and (iii) a leucocratic, fine-grained facies (quartz + plagioclase + K-feldspar + muscovite + biotite ± garnet ± sillimanite ± andalusite). The Monte Filau Orthogneiss shows a polyphasic deformation. The first schistosity is recognizable in the field only in the eastern part of the dome and is evidenced by the orientation of mm-thick quartz-feldspar-bearing porphyroblasts or biotite crystals. The main structure in the field is a N-S striking gneissic pervasive foliation dipping toward West and East in the western and eastern part of the dome, respectively. The foliation is marked by a mm-thick quartz-feldspathic layering that changes to a biotite-bearing gneissic structure in the biotite-rich facies and near the contact with the andalusite-bearing micaschists. In the leucocratic, fine-grained facies the foliation is poorly recognizable except for andalusite-bearing facies in which it is marked by the orientation of andalusite crystals. The NNW-SSE striking mineral lineation gently plunging toward north are highlighted by orientation of biotite on the foliation planes. Late deformational structures include asymmetric folds, shear bands, transposition of mineral lineation and NS striking upright folds. Sillimanite, garnet and andalusite were observed mainly in the leucocratic fine-grained facies. Sillimanite in the fibrolite variety as well as andalusite were observed enclosed in the coarse-grained muscovite. Garnet has been observed as isolated single crystals and in clusters of small crystals oriented along the main schistosity. Worthy of note is the occurrence of dark spindles (term after [1]) up to half a centimeter mainly composed of quartz, feldspar, coarse-grained muscovite and andalusite. In the Western side the gneissic foliation is overprinted by low - temperature (greenschist facies) mylonitic fabric characterized by new growth of quartz, albite, muscovite, and chlorite. In conclusion, the history of Monte Filau Orthogneiss consists of different stages of metamorphic evolution and deformatve events recorded in different portion of the orthogneiss. A high-grade metamorphic stage, with P-T conditions P= 3-5 kbar and T near 700 °C, and a later stage under low-temperature conditions (T ~ 400°C) were recognized. Our data support a continuous evolution from amphibolite to greenschist facies with local preservation of high metamorphic grade structures, possibly being consistent with an almost completely Variscan history.

References:
Petrogenesis of the Kennack gneiss and other felsic units within the Lizard ophiolite, Cornwall, UK

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The Kennack gneiss is an enigmatic lithology found along the basal thrust of the Lizard ophiolite, Cornwall. It contains distinct felsic and mafic bands that show complex structural relationships: in many exposures, these layers appear as a typical banded gneiss and fragments occur as raft-like macro-inclusions surrounding peridotite, although in other cases, either (or both) components appear to locally intrude the surrounding peridotite, inferring that they were (partially) molten. These relationships have been used to suggest that the Kennack gneiss may be a migmatite derived from partial melting underlying metamorphic sole [1], a co-mingled and mixed intrusion of two discrete magmas of felsic and mafic composition [2][3], or a composite intrusion of two discrete magmas [4]. Here, we present preliminary results from field investigation and laboratory analysis of Kennack gneiss components and nearby felsic dykes within the Lizard ophiolite. Meter-scale field mapping indicates that the felsic component of the gneiss is intrusive to the mafic component. Complex field relations, indicating the mafic was intruded in part the liquid state and in part the solid state, suggests there were multiple stages of magmatism. Bulk-rock geochemical compositions from mafic and felsic components are consistent with formation at a volcanic-arc. The composition of mafic component is calc-alkaline, suggesting that it is derived from a mantle wedge. Conversely, the peraluminous composition of the felsic component, alongside a k-feldspar-rich composition, suggests a crustal sedimentary source. Meanwhile, there appear to be significant geochemical disparities between the felsic component of the gneiss and nearby felsic intrusions, indicating they are unrelated. Future work will involve performing thermobarometry on the felsic and mafic components to determine their temperature and pressure conditions of metamorphism, and U-Pb geochronology will constrain the age of formation. These results will be combined with published age data to produce a new model for metamorphism of the Kennack gneiss that integrates with recent work by our research group on the formation and emplacement of the Lizard ophiolite and surrounding units in southeast England.

References:
Permian nappe tectonics and high-grade metamorphism related to Gondwanide Orogeny in northern Patagonia terrane

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The focus of this contribution is to characterize a sequential order of deformational structures and associated metamorphic conditions of the igneous-metamorphic basement rocks from northern Patagonia terrane (41°28’30”S-65°40’30”W). Based on field mapping, mesoscopic structures are analysed to evaluate progressive and polyphasic deformation, developed under regional high-grade metamorphism.

Three continuous deformational phases are recognized. During D₁ phase, the formation of overturned tight F₁ folds is associated with penetrative axial plane foliation S₁. It exhibits P-T conditions close to the baric peak, and likely represents the progressive metamorphic stage associated with syn-kinematic growth of garnet-kyanite porphyroblasts in meta-pelites. D₂ phase is recorded as either shear bands S₂ transposition or mylonitic foliation, coeval with polymorphic transformation of kyanite to sillimanite owing to thermal peak. A nappe system related to kilometer-scale El Jagüelito ductile shear zone characterizes the large-scale D₂ structure of the investigated area. D₃ phase is distinguished by refolding of the former fabric and formation of either kink-bands or crenulation cleavage S₃ of the S₁-S₂ foliation planes, under retrogressive metamorphic conditions. The nappe system exhibit a top-to-the S/SW tectonic transport, and the El Jagüelito shear zone served as a right lateral ramp in the exhumation process among D₂-D₃ events.

Petrographic analyses of metamorphic mineral assemblages and reaction textures combined with conventional geothermobarometric estimates and a pseudosection records the pressure-temperature conditions of metamorphism among D₁-D₃ events. In situ electron probe Th-U-Pb monazite dating of 272, 260, and 251 Ma constraints the main tectono-metamorphic event to Late Permian Gondwanide Orogeny.

New results combined with existing geological and geochronological constraints allow inferring a clockwise P-T-D-time evolutionary path within the kyanite-sillimanite stability fields. Comprehensive regional comparison of the large-scale structural framework is indicative of an ongoing oblique subduction beneath the proto-Andean margin of Gondwana in the NE direction. This continental subduction and exhumation lasted at least 20 million years, nearly the entire Guadalupian-Lopingian series, producing transpression and metamorphic conditions of amphibolite-to-granulite facies, in medium- to high-pressure regimes, although the studied area occur in a back-arc to intracontinental settings. Geotectonic implications also includes a long-lived tectono-metamorphic history of the El Jagüelito shear zone, which was formed during Early Paleozoic and successively reactivated during Permian and Jurassic times.
Petrological modelling of Garnet-Amphibolite from Ardalanish Bay, Ross of Mull: New insights into a crustal thickening event affecting the Moine

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The Moinian super group, exposed on the Ross of Mull, is one of the most famous examples of polymetamorphism and represent a N–S trending inlier approximately three km thick that is positioned structurally above the inferred projection of the Moine Thrust, and bounded to the west by the Ross of Mull pluton and to the east and north by Tertiary lavas. Despite covering such a small geographic extent, the Moines on the Ross of Mull provide insight into mountain building processes not seen elsewhere in the Scottish Caledonides, as they spectacularly preserve a regional kyanite-grade metamorphic event associated with crustal thickening that is overprinted by a Caledonian-aged sillimanite- andalusite-grade contact metamorphic event related to the intrusion of the Ross of Mull pluton at ca. 414 Ma. Although the timing and conditions of contact metamorphism are well described and studied, the nature and timing of the earlier regional kyanite grade event remains poorly understood. The best constraints remain ~8 kbar and 600–650 °C, although there is some ambiguity in the pressures estimates. Fresh garnet amphibolite that represents mafic dykes crop out at Ardalanish Bay ~700 m to the east of the Ross of Mull pluton and provide an opportunity to precisely constrain the P−T conditions and timing of regional kyanite-grade metamorphism in the Moine. Adjacent garnet-amphibolite dykes display almost identical peak Grt–Bt–Amph–Rt–Ilm–Sph–Qz–(L) assemblages with minor retrograde epidote and plagioclase. Samples display similar garnet chemistry and garnet modes (~10%) with only slight differences in biotite and ilmenite mode, but have noticeably different garnet crystal size distributions. Equilibrium phase diagram modelling in NCKFMSHTO using Dataset 62 and the mafic melt models and Dataset 55 and conventional thermobarometry suggest garnet grew at P−T conditions of ca. 10–11 kbar and 640–740 °C and was followed by cooling at elevated pressure, prior to intrusion of the Ross of Mull Granite. Our modelling suggests the difference in garnet crystal size distributions between adjacent metabasic dykes is primarily controlled by bulk composition, namely CaO and MnO. This subsequently affects the modal proportion of ilmenite predicted which may enhance garnet nucleation. The similar chemistry (XMg [Mg/(Mg+Fe)] ~0.83, Grs [Ca/(Mg+Fe)2+Ca] ~0.26–0.28) in both large and small garnets suggest larger cm sized garnets form from coalescing of smaller garnets. The age of this kyanite-grade metamorphic event remains enigmatic and there are two distinct hypotheses. 1) The age of kyanite-grade metamorphism is Knoydartian, in which case the deformation and metamorphism is unrelated to the underlying Moine Thrust. 2) Alternatively, regional metamorphism is Caledonian-aged, in which case it requires a geodynamic process to explain rapid decompression from ca. 11 to 4 kbar. One such idea could involve extrusion of the Moines towards the west above the underlying Moine Thrust synchronous with normal faulting on a roof shear zone prior to the onset of extensional collapse of the Scottish Caledonides and granite intrusion at ca. 414 Ma. Future work will therefore aim to constrain the timing of garnet growth using Lu–Hf geochronology to directly date this crustal thickening event and test geodynamic models.

Tectonic evolution of the late Paleozoic basement in western Patagonia region (Argentina-Chile)

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Patagonia constitutes a vast area located in the southern extreme of the South American Continent, where the igneous-metamorphic basement presents a complex evolution during the Paleozoic. The oldest outcrops are in the northeastern region near the Atlantic Ocean and correspond to the Cambrian - Ordovician Orogens [1,2]. In contrast, its western region comprises basement units of Silurian – Devonian ages, showing that orogen-development processes migrated towards the southwest of Patagonia [3,4,5]. The last widespread igneous-metamorphic events record the Late Paleozoic Gondwanide Orogeny and are extensively distributed along the Patagonia's boundaries [2,6,7,8]. However, in the western boundary of the Patagonian region, only a few P-T-t path reconstructions were made for the late Paleozoic metamorphic basement [6,7,9,10]. These evolutionary P-T-t models were linked with the subduction of the Proto-Pacific Ocean plate along an active continental margin in southwestern Gondwana. The present contribution aims to review the different geodynamic conditions of the western Patagonia region and establish their relationship with the paleotectonic evolution during the late Paleozoic times.

The late Carboniferous metamorphic complexes exposed at the Andean Cordillera in western Patagonia achieve blueschists-amphibolite facies conditions developing HP-LT progressive metamorphic paths [7,9,10]. The uplift beginning of these accretionary prism-arc basements was coeval with the arc migration throw inboard the continent during early Permian times [6,7]. In this extra-Andean region, stromatic migmatites attained MP-HT conditions at the beginning of the Permian magmatic arc development [6,11]. Finally, the magmatism migration continued far inside the continent during the rest of the Permian period [2,11]. Further P-T-t estimations of these basement regions will improve the knowledge of the late Paleozoic evolution in the Patagonia region and its relationship with the paleotectonic subduction process.

References:
The lawsonite-glaucophane blueschists of Elba and their significance for the Northern Tyrrhenian Sea

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The Northern Tyrrhenian Sea is a key area in the Northern Apennines, classically interpreted as documenting the transition from contractional tectonics to back-arc extension [1]. Exhumed metamorphic complexes preserve high pressure-low temperature (HP-LT) assemblages that formed during early subduction and continental collision in the region. The lack of precise P-T and geochronological constraints on HP-LT rocks, however, hinders the understanding of the exhumation mechanisms and early tectonic history of the Northern Tyrrhenian Sea.

Here, we present a detailed study of lawsonite-glaucophane blueschists that are exposed on the Isle of Elba, in the middle of the Northern Tyrrhenian Sea. HP-LT parageneses are preserved in metabasite bodies and associated metacarbonatic rocks that occur as lenses in Oligocene foredeep deposits. New geochemical and petrological investigations on associated metabasic – metasedimentary rocks, based on mineral and bulk-rock chemistry coupled with P-T and P-T-X(Fe₂O₃) pseudosection modelling using PERPLE_X, show that the HP-LT rocks of Elba record peak P-T conditions of 1.5–1.8 GPa and 320–370°C and nearly isothermal decompression to P ~ 0.2 GPa. During exhumation, peak metamorphic assemblages were overprinted and partially obliterated by epidote-blueschist and, subsequently, albite-greenschist facies metamorphic assemblages. Available geochronological constraints indicate that exhumation occurred over a period of time of 15 Ma between the early Miocene (20-19 Ma) and the late Miocene (6 Ma) with exhumation rates around 2.5-3.7 km/Ma.

Based on this study, we propose that continent-derived units were brought to greater depths than previously reported in the Northern Apennines and that rapid decompression occurred along ‘cold’ and nearly isothermal paths, compatible with syn-orogenic exhumation.

References:
P-T evolution of the Proterozoic aluminous granulites from the western East European Craton, West Lithuania

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The crystalline crust of Lithuania is made of crustal fragments (terranes) that were subsequently amalgamated during the 1.90-1.75 Ga Svecofennian orogeny [1]. Lack of knowledge on metamorphic pressure-temperature (P-T) conditions for the high-grade events [2; 3] in the West Lithuanian granulite domain (WLG) prevents effective evolutionary reconstructions and limits an insight into the tectonic regimes. In this study, we investigated aluminous granulite facies rocks with the assemblages of garnet, plagioclase, K-feldspar, ilmenite, magnetite, hercynite, ± biotite, ± quartz, ± cordierite, ± sillimanite and monazite. The rocks are texturally and mineralogically heterogeneous and display evidence of a variable degree of partial melting. We use microstructural and mineral chemical data in combination with calculated isochemical phase diagrams to obtain qualitative constraints for the better understanding of the P-T paths and geological evolution of the area. Pseudosections were constructed in the MnO-Na₂O-CaO-K₂O-FeO-MgO-Al₂O₃-SiO₂-H₂O-TiO₂-O₂ (MnNCKFMASHTO) system using whole-rock composition. The thermodynamic modelling is challenging because of the mentioned heterogeneous nature of the rocks that affect the bulk composition. Our results indicate peak metamorphic pressures of 4.0-7.5 GPa and temperatures of 750-810°C. P-T conditions were constrained using inferred mineral assemblages and near homogenous garnet core compositions. A subsequent decompression path is suggested by the recognized garnet consuming reactions, formation of cordierite coronas and cordierite-spinel symplectites.

References:
Medium-high grade igneous-metamorphic basement unit in Central Patagonia, Argentina at its relation with the Terra Australis Orogen.

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During the Late Neoproterozoic to middle Paleozoic time span, the southwestern margin of Gondwana has been exposed to protracted subduction [1,2,3,4], which has been considered as part of the widespread Gondwanan Terra Australis Orogen (TAO) [2]. In southwestern Gondwana, the TAO comprises a series of accretionary systems which are associated with crustal extension and back-arc basin development [2]. This tectonic setting alternates with sporadic contractional episodes related with increased plate coupling, accretion of oceanic material, or collision of allochthonous/para-autochthonous crustal blocks [1,2,3,4].

In this context, the Patagonian continental block has been considered as a peri-Gondwanan block, accreted either in Early or Late Paleozoic times [5,6,7]. In recent years, compelling evidence points out to an Early Paleozoic accretion of the northern part of Patagonia [7,8], within the tectonic framework of TAO. However, the Middle to Late Paleozoic tectonic history of central and southern Patagonia, the tectonic setting of Gondwanide orogeny, and therefore the proper assessment of the culmination of TAO in this area are yet a matter of debate [9,10].

In the past decades, a Middle-Late Paleozoic igneous-metamorphic belt was described in Central Patagonia[5,6], a key area for integrating central and southern Patagonia, and its precise location, crossing this area with a ~NNW-SSE structural trend, was defined by geophysical means [9]. This belt comprises a series of fault-controlled basement blocks, formed by medium-high grade metamorphic complexes and coeval magmatism [5,10,11]. Recently, the Lagunita Salada Igneous-Metamorphic Complex was defined in this area. The regional metamorphism of this complex attained upper amphibolite-lower granulite facies, constrained by Th-U-Pb EPMA monazite ages between ca- 379-320 My [12]. Based on dated syn- and post-tectonic granitoid intrusions in the area an isotopic system re-opening could not be discarded for the ~320 Ma isochron monazite model age. Moreover, a magmatic lull of ~20 My coeval or slightly posterior to the medium-high grade metamorphism [12], could present important implications for the tectonic regime for the the TAO in this area, previous to the syn- to posttectonic Upper Carboniferous – Early Permian magmatism and the initiation of Gondwanide orogeny in southwestern Gondwana.

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