Metamorphic geology: progress and perspectives

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Our dynamic planet Earth has been in constant evolution since its accretion and formation about 4.56 billion years ago as a rocky planet in our solar system. Since the onset of plate tectonic processes, migration and collision of rigid tectonic plates, driven by mantle convection, have promoted intense formation and reworking of continental and oceanic crust. Orogenic belts, forming along convergent plate boundaries, are unique natural laboratories for Earth scientists, as they are the loci of interactions between tectonic, magmatic and metamorphic processes. As metamorphic geologists, our main goal is to develop and apply reliable methods to investigate the textural and mineralogical metamorphic rock records.

By definition, a metamorphic rock is the product of the transformation of a protolith that can either be sedimentary, magmatic or metamorphic due to changes in physical and chemical conditions. Therefore, a metamorphic rock may contain a wealth of information related to its protolith and/or the preservation of disparate rock records from several partial re-equilibration stages of a single or multiple metamorphic cycles. Because of this complexity, only snapshots of the cumulative processes are preserved in the mineral assemblages, chemistry and microstructures. It is thus essential to study rock samples that best preserve this fragmented metamorphic record, and develop the best petrological tools for analysing them. This naturalist and analytical approach is supplemented by the input of experimentalists and modellers to quantify the physical and chemical conditions of metamorphism and test conceptual models.

This Special Publication reflects the variety of novel techniques and approaches used to investigate metamorphic processes. It encompasses a wide range of metamorphic topics that include state-of-the-art methods on deciphering the complex polyphase nature of metamorphic geology. In this introduction, we have tried to describe each chapter in a larger context, including for instance the evolution of analytical and modelling techniques, new trends in metamorphic petrology, and some brief comments on future directions in the field.

Metamorphic geology: an evolving discipline

The present book finds its predecessor in *Evolution of Metamorphic Belts* (Daly *et al.* 1989). Reading reveals some interesting aspects on the evolution of metamorphic geology in the past 30 years. Two main aspects are discussed below: the evolution of the petrological models and an incredible increase in the amount of geochemical data.

Thermobarometry: petrological modelling of phase relationships

The chapters in Daly *et al.* (1989) describe the modelling techniques that were used at that time to

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decipher pressure–temperature–time (*P–T–t*) histories of metamorphic rocks and metamorphic belts. Inverse modelling in the form of exchange thermometry and net-transfer equilibria has been extensively used since the late 1960s, although many of them were either based on inaccurate thermodynamic data or applied outside their validity range (Essene 1989). The widely accepted practice of estimating *P–T* conditions from separate reactions was generally leading to errors and misinterpretation of *P–T* paths, especially if post-peak modifications via retrograde reactions are involved (e.g. Aranovich & Podlesskii 1989). Forward modelling of phase relationships via petrogenetic grids was restricted to a few simple chemical systems and, as noticed by Essene (1989, p. 12):

> It [was] generally [considered to be] safer to select an experimentally reversed univariant equilibrium in a chemical subsystem that is buffered by mineral assemblages in the rock under study […] than to rely quantitatively on complex petrogenetic grids.

At the same time, Spear (1989) was introducing the concept of relative thermobarometry – based on differential forms of the equilibrium constants, a variant of the Gibbs method (Spear 1988). This original approach, if based on an internally consistent database (e.g. Berman 1988; Holland & Powell 1988, 1998, 2011), permits the production of isopleth maps of mineral compositions, moles and equilibrium constants for a given bulk-rock composition, as well as forward models along *P–T* trajectories predicting the growth zoning of metamorphic minerals (see Spear 1989, fig. 3c). Since that time, isopleth thermobarometry has become a powerful aid in the interpretation of complex reaction histories and mineral zoning (Evans 2004; Tinkham & Ghent 2005; Gaidies *et al.* 2008; Moynihan & Pattison 2013; Lanari *et al.* 2017). This major development is being used routinely in modern petrological studies as isopleth maps can be readily obtained within a couple of minutes (or hours) for simple (and complex) rock systems and any thermodynamic database using a Gibbs energy minimizer such as Theriak-Domino (de Capitani & Brown 1987; de Capitani & Petrakakis 2010) or Perple_X (Connolly & Kerrick 1987; Connolly 2005), or using a phase-equilibrium calculator such as Thermocalc (Powell & Holland 1988, 2008) or Gibbs (Spear 1988). In his paper, **Tropper (2018)** uses an unconventional method to determine the accuracy of the phase diagrams. Natural rocks were used as the starting material in experiments to forward model the stable mineral assemblage, mineral modes and compositions at given pressure and temperature conditions, with rather satisfactorily results. Despite only partial equilibration being achieved in the experimental products, as illustrated by the presence of unreacted relicts (garnet, quartz), the mineral assemblages and a few key isopleths, such as the Na and Ca in plagioclase, Ti in biotite or X_{Mg} in cordierite observed in metapelites from the South Alpine domain (northern South Tyrol, Italy), are reasonably reproduced in the experiments. This is not the case for the isopleths obtained using thermodynamic models based on the bulk-rock compositions, suggesting that kinetics and/or fractionation effects may play a significant role (Rubie 1998; Pattison *et al.* 2011; Carlson *et al.* 2015; Lanari & Engi 2017; Spear & Pattison 2017; Lanari & Duesterhoeft in press).

Geochemical data: from small to large datasets

Another important change in metamorphic studies is related to the amount and quality of geochemical data available in present-day research. The number of analytical instruments (scanning electron microscopy (SEM), electron probe microanalyser (EPMA), Raman spectroscopy, laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), secondary ion mass spectrometry (SIMS/SHRIMP), Fourier transform infrared spectroscopy (FTIR), etc.) and their increasing precision fundamentally changed the way petrologists and geochronologists deal with the available geochemical information to investigate rocks and their metamorphic history. We estimate that the total number of EPMA analyses used in the 55 chapters of the book from Daly *et al.* (1989) to be around 2000, among which only Burton *et al.* (1989) reported core to rim compositional zoning profiles of two garnet grains. Between 40 and 50 Ar–Ar or K–Ar spectra, laser and spot analyses by SIMS were reported in the entire book. Today, the situation has changed dramatically in that much larger datasets are used to support models and interpretations. Many petrological studies include, for instance, core to rim compositional zoning profiles combined with semi-quantitative X-ray maps, providing a more detailed investigation of the compositional variability of minerals. Nowadays, X-ray maps can be quantified (calibrated like single-spot analysis), allowing the compositional variability of mineral phases to be analysed continuously in two dimensions. In their paper, **Lanari *et al.* (2018)** show how quantitative compositional mapping has impacted mineralogical and petrological studies over the past half-century. The authors present a new calibration technique for electron probe microanalyser (EPMA) X-ray maps, which has been incorporated into the computer software XMapTools (Lanari *et al.* 2014). Such data visualization tools are important as a set of maps typically contains between 200 000 and 1 000 000 spatially resolved fully quantitative chemical analyses. This paper by **Lanari *et al.* (2018)** illustrates how technological evolution has caused an exponential increase in the amount of data available and also shows how important the tools facilitating data processing and data handling are. It is not only the quantity of data that is important, but also the quality of the reporting and the analysis.

Are more high-resolution data improving our geological understanding of metamorphic rock evolution? Of course, it depends on the quality of the data and our capability to interpret this geological record. Two papers illustrate how large geochemical datasets are used to decipher the metamorphic evolution. The first example is presented in the article by **Martin (2018)**, who uses quantitative compositional X-ray mapping to investigate the compositional variability of symplectite assemblages in eclogite from the Western Gneiss Region of Norway. This large geochemical dataset (corresponding to several million point analyses), used in conjunction with multi-equilibrium models, enabled the *P–T* conditions of symplectite formation to be unravelled and the influence of external fluid on the progressive retrogression of mafic eclogite to be discussed. A critical aspect concerns the evolution of the chemical composition of amphibole in each microstructural domain of a suite of samples showing different degrees of retrogression. The reconstruction of the crystallization sequence shows that the presence of a corona around garnet (kelyphite in **Martin 2018**) is indicative of interactions with external fluids during retrogression. The second example is presented in the paper by **Hyppolito *et al.* (2018)**, who combine quantitative major element mapping by EPMA and trace element mapping by LA-ICP-MS to retrieve garnet growth and resorption pulses in amphibolitized eclogites from the Diego de Almagro Metamorphic Complex (Chile). These highly resolved microchemical investigations have led to a relatively detailed model for the partial re-equilibration of these eclogites under amphibolite-facies conditions, interpreted as a process that is enhanced by locally derived aqueous fluids and mainly controlled by short-scale dissolution–transport–precipitation. The study of **Hyppolito *et al.* (2018)** is a state-of-the-art example on how a large amount of data may contribute in a powerful way to our conceptual models; in this case, re-equilibration processes.

New strategies and trends in metamorphic geology

In the Special Publication *The Earth Inside and Out: Some Major Contributions to Geology in the Twentieth Century* (Oldroyd 2002), Touret & Nijland (2002) defined three major trends in metamorphic petrology: (i) *mineralogical petrology* concerned with the determination of *P–T* conditions of metamorphic minerals; (ii) *chemical (or geochemical) petrology* to determine the time factor; and (iii) *structural petrology* for the reconstruction of the kinematics of the rock evolution and the investigation of global tectonics. Although these trends are still valid, the papers compiled in this Special Publication demonstrate that some boundaries have shifted and new trends have emerged. The development and evolution of new analytical techniques, applied at high resolution, have triggered the imagination of Earth scientists and have impacted the way they practice metamorphic petrology and geochronology.

Petrochronology: the full integration of geochronology, geochemistry and metamorphic petrology

What does the age of a metamorphic rock mean? Could one say that a metamorphic rock has a single age? These questions might have been rather odd in the 1980s but the last couple of decades have seen the emergence of new high-resolution and *in situ* analytical and theoretical techniques to link ages with temperature, pressure and/or mineral reactions, and with petrological evolution (Kohn 2016; Kohn *et al.* 2017). This integrative approach referred to as ‘petrochronology’ focuses on the rate of the processes rather than on the determination of absolute ages (Engi *et al.* 2017).

A key aspect of petrochronology is to apply geochemical correlation methods that link time (ages and rates) obtained from accessory minerals (such as monazite, zircon or rutile) to petrogenetic processes (e.g. crystallization or re-equilibration) and their conditions determined from major rock-forming mineral assemblages largely involving garnet (Hermann & Rubatto 2003; Baxter *et al.* 2017). If the partitioning relationships between the two phases are known for diagnostic trace elements, it is possible to test whether two specific growth zones co-existed in equilibrium (or not) at any stage of the *P–T* history. In their paper, **Warren *et al.* (2018)** investigate monazite and garnet in six amphibolite-facies metapelites from Bhutan, and propose that the core of the matrix monazite may have formed in equilibrium with the rim of garnet. The obtained rare earth element (REE) partitioning coefficients between monazite and garnet differ partly from previous studies, up to one order of magnitude lower for the heavy (H)REE (see **Warren *et al.* 2018**, fig. 9). These results show that several underestimated factors, such as the presence of melt or different stable mineral assemblages, may influence garnet–monazite partitioning behaviour. Caution is therefore urged in applying garnet–monazite REE trends to ‘prove’ equilibrium when linking monazite ages to metamorphic stages.

Mineral chemical correlation is critical to ensure that two minerals, a chronometer and a geothermobarometer, formed in equilibrium – the textural correlation methods alone can lead to erroneous interpretations. In the paper by **Pownall *et al.* (2018)**, the authors investigate several major and accessory minerals of garnet–silimanite granulites exposed in the island of Seram (eastern Indonesia). The large variety of analytical and theoretical techniques employed have led to a fairly precise metamorphic history of these polycyclic rocks, which were first deposited in the Late Triassic, metamorphosed under amphibolite-facies conditions at *c.* 200 Ma and, finally, involved in the ultrahigh-pressure (UHP) event at 16 Ma caused by extensional exhumation of hot mantle rocks behind the rolling-back Banda Arc. A major finding of this study is that zircon shielded within garnet was not affected by the ultrahigh-temperature (UHT) episode. The age distribution between peak zircon and retrograde monazite suggests that UHT conditions have been very short lived and exhumation of the granulite complex was very rapid.

Combining physical and chemical modelling at all scales

In the mid-1980s, the discovery of coesite inclusions in garnet porphyroblasts of continental rocks (Chopin 1984; Smith 1984) demonstrated that the buoyant continental crust can be subducted to mantle depths. The *P–T–t* paths retrieved by the petrochronological studies have challenged modellers who tried to reproduce these trajectories in dynamic thermomechanical models. The remaining differences may reflect the neglect of key processes such as shear heating, the influence of phase transitions on rock properties or the evolution and migration of fluids (see Engi *et al.* 2017 and references therein). Interestingly, these processes can be partly quantified by chemical modelling based on equilibrium thermodynamics (Connolly 2005, 2009; Duesterhoeft *et al.* 2014). This integration of physical and chemical processes has been a hot topic in the last decade (Fullea *et al.* 2009; Siret *et al.* 2009; Zunino *et al.* 2011; Duesterhoeft & de Capitani 2013). In their paper, **Riel *et al.* (2018)** present a modelling tool, STyx, coupling melt (two-phase) flow, heat flow and petrological calculations, and which aims to link physical and chemical processes in partially molten crust. Several models representing a magmatic event affecting an amphibolitic lower arc crust were produced to quantify the relative contribution between partial melting of the pre-existing crust and fractional crystallization from mantle-derived hydrous magma. This study shows that mantle-derived magmas are the main contributor to the extracted products, whereas the effects of partial melting in the pre-existing crust are rather limited. This tool opens up new directions of research in which to model the effects of complex fluid–rock interactions at high-grade conditions.

Melt inclusions

An illustrative example of the kind of multidisciplinary approach required to unravel the complexity of natural metamorphic samples is provided in the paper by **Ferrero *et al.* (2018)**, who investigate melting processes via the study of melt inclusions. These ancient droplets of melt are commonly preserved in a major metamorphic mineral – garnet – as crystallized aggregates of quartz + feldspar(s) + OH-bearing phase(s) known as nanogranitoids (Ferrero *et al.* 2012; Cesare *et al.* 2015; Ferrero & Angel 2018). The presence of melt inclusions provides qualitative constraints, such as the presence of a melt phase during metamorphism, as well as quantitative constraints for the melt composition in both major and trace elements. In this paper, **Ferrero *et al.* (2018)** have compiled results from the literature and, in conjunction with new data and observations, show that the presence of melt inclusions is more the rule than the exception in high-grade metamorphic rocks from the Bohemian Massif. Some inclusions were linked to the UHP stage, demonstrating that these rocks experienced partial melting during the early stage of exhumation that followed continental subduction. In addition, the experimental re-homogenization of nanogranitoids provides microstructural criteria that allow the conditions at which melt and host are mutually stable to be assessed.

Exploring the lower limit of metamorphism

The metamorphic phase transformations and the processes driving these changes remain poorly understood at low-grade conditions (<350°C) compared to metamorphism at higher *P–T* conditions. One reason for this lack of knowledge is that most metamorphic petrologists have traditionally investigated changes taking place at high *P–T* conditions, where equilibrium thermodynamics can be applied with a higher level of confidence (Robinson & Merriman 2009). Investigating low-grade metamorphism is challenging, requiring alternative strategies and complex petrological models (Schiffman & Day 2009; Lanari *et al.* 2012; Cantarero *et al.* 2014, 2018; Scheffer *et al.* 2016; Vidal *et al.* 2016). In their paper, **Cárdenes *et al.* (2018)** explore unconventional proxy methods to quantify the degree of metamorphism in low-grade samples. The authors have investigated the size distribution of framboidal and euhedral microscopic crystals of pyrite in metapelites that experienced different grades of low-temperature metamorphism. The size distribution was obtained using high-resolution X-ray tomography and compared with the results of traditional thermometers. Whereas new generations of pyrite form along with increasing grade of metamorphism, the maximum size of the crystals also increases. This study demonstrates how complex the investigation of samples is at the transition between diagenesis and low-grade metamorphism.

The development of sophisticated techniques for the investigation of low-grade metamorphism opened up new avenues. In the paper by **Grosch (2018)**, the author has combined a wide range of petrological and modelling techniques to unravel the metamorphic history of Archean rocks from the Barberton Greenstone Belt, recording very low-grade to upper-greenschist facies conditions. Such studies aim to identify evidence of metamorphism and metasomatism, processes providing critical information for assessing the tectonic settings, and crustal hydrothermal environments on the early Earth (e.g. Grosch *et al.* 2012). The author combined empirical chlorite thermometry with inverse thermodynamic models of chlorite and white mica, in conjunction with Raman thermometry on carbonaceous material and oxygen stable isotope analysis. Seawater hydrothermal alteration zones were successfully distinguished from tectonic and contact metamorphic processes. An important finding of this work is that an early form of plate tectonics was already active *c.* 3225 myr ago.

The role of metamorphic fluids in the formation of ore deposits

Many ore deposits are hosted by metamorphic rocks or involve metamorphic fluids caused by the breakdown of volatile-bearing minerals. Metamorphic brines and fluids have a high ore-forming potential as they can carry a significant amount of metal in solution (Yardley & Cleverley 2013). In their paper, **Ni *et al.* (2018)** investigate a large Pb–Zn deposit in the West Qinling Orogen in central China that was previously classified as having a sedimentary or hydrothermal origin (SEDEX for sedimentary exhalative). This type of deposit is among the world's most important source of Pb and Zn. Combining fluid-inclusion petrology, microthermometry, Raman and Pb isotope analysis, the authors showed that the Changba–Lijiagou ore deposit results from a multi-stage process: an early primary marine sedimentary mineralization and a late stage of metamorphic superimposition. Primary fluid inclusions in quartz were eliminated during the late Triassic episode of regional metamorphism and replaced by CO_2–CH_4-rich inclusions, which are symptomatic of a metamorphic fluid.

In the paper by **Abu-Alam *et al.* (2018)**, the authors demonstrate the link between active tectonism and ore-carrying fluids. In their study, they have performed a detailed investigation of orogenic gold ores of the Arabian–Nubian Shield that are linked to a large fault system. The analysis of fluid inclusions from four ore deposits indicates that the gold was precipitated from metamorphic fluids at shallow- to medium-crustal levels. Petrological modelling was applied to model the amount and composition of fluid released by the metamorphic rocks (meta-ophiolites and metasediments) during prograde metamorphism. The largest amount of fluid production is predicted to occur at the greenschist–amphibolite-facies transition, allowing effective gold mobilization from the deeply seated host ophiolite in the host rock, and vertical transport via the brittle fault system.

From mineral scale to tectonic processes

Research into the orogenic processes that shaped the continental crust has a long-standing tradition in metamorphic geology. Metamorphic data are critical in this endeavour as they can be used to quantify tectonic and geodynamic processes: their potential application in tectonic and geodynamic reconstructions is clearly illustrated throughout the whole book.

In the paper by **Waters *et al.* (2018)**, microscale observations are used to characterize large-scale tectonics. Here, **Waters *et al.* (2018)** have integrated microscale observations with petrological and field structural data to constrain the thermal structure and large-scale behaviour of the South Tibetan Detachment, a major shear zone in the Himalayan belt. This study uses a series of samples collected by L.R. Wager in 1933 during the British expedition to Mt Everest. The authors characterize the evolution of the metamorphism and microstructures along four new profiles, each of them over a north–south distance of 35 km across the shear zone. Mineral assemblage and thermobarometry, as well as quartz deformation regimes, determined through recrystallization microstructures of quartz both suggest high thermal gradients within the shear zone of up to 200°C km^{-1}. The authors explain the formation and preservation of these high gradients by a combination of high strain rates with a component of vertical shortening over a short period of time (<18 myr) and a contribution of latent heat from the emplacement of magmatic bodies. Interestingly, viscous heating can generate anomalies of the order of 12°C km^{-1} in the shear zone, and is therefore not capable of generating the steep gradients captured by the rock record.

Metamorphic isograds have, since the seminal work of Barrow (1893) on the Scottish Highlands, been a crucial concept that have helped generations of metamorphic petrologists to decode the history of metamorphic terranes. In his paper, **Gervais**

(2018) has revisited the isograd concept by investigating the textural relationships in metapelites from the west flank of the Frenchman Cap dome in the Canadian Cordillera. In this area, four metamorphic isograds (kyanite-in, sillimanite-in, muscovite-out and kyanite-out), each of them corresponding to a line on the map across which there is a change in metamorphic mineralogy, were mapped along a distance of *c.* 5 km. The author shows that three main modes of formation can be proposed for these isograds: the prograde isograd (e.g. muscovite-out and kyanite-in) corresponds to a prograde net-transfer metamorphic reaction; the retrograde isograd (e.g. sillimanite-in) is related to a new mineral forming under exhumation and cooling; and the structural isograd (e.g. kyanite-out) is marked by a structural discontinuity. In this example, the four isograds formed at different times via different petrological and/or tectonic processes, thus providing a powerful caveat for petrologists: the main conclusion of the author is that interpreting isograds according to the classical definition – without a descriptive definition – can lead to problematic and unrealistic tectonic models.

One of the main tasks of metamorphic geology is to reconstruct detailed pressure–temperature–deformation paths. In their paper, **Plissart *et al.* (2018)** combine a detailed petrostructural study of the Alpine Upper Danubian–Balkan basement to unravel the fragmentary Variscan history of this region spreading across Romania, Serbia and Bulgaria. Two main deformation phases were documented and interpreted as reflecting two different tectonic regimes: a right-lateral-dominated shear thrust in the eastern part of the region linked to the obduction of an ophiolitic slice (D_1); and sinistral transpression recording the collisional event (D_2). One unit, the Corbu metasediment, was selected to forward model garnet growth and the corresponding evolution of the reactive bulk composition. Inverse thermometry allowed the *P–T* conditions of the retrograde conditions to be constrained. The detailed pressure–temperature–deformation (*P–T–D*) path shows that the D_2 phase includes a stage of prograde garnet growth, up to the peak conditions of 600°C and 5.2 kbar, as well as a re-heating event that took place at shallower levels and was likely to have been caused by Carboniferous syntectonic intrusions.

The Earth is a continuously evolving system, and especially in Precambrian rocks. In their paper, **Wang *et al.* (2018)** report on a new occurrence of Neoarchean–early Paleoproterozoic high-pressure (HP) granulites in Eastern Hebei, North China Craton. High-pressure granulites are important markers for tectonic secular changes, as they require burial either via crustal thickening and/or subduction. The authors investigated garnet–clinopyroxene and two-pyroxene granulites occurring as supra-crustal lenses/slivers within the tonalite–trondhjemite–granodiorite gneisses by combining petrography, mineral chemistry, thermobarometric calculations, bulk-rock elemental and Nd isotopic geochemistry with *in situ* zircon U–Pb dating by ion probe. They demonstrated that the magmatic protolith of the HP granulites are island-arc andesites erupted during the Neoarchean. Such magmatism coupled with collisional metamorphism is analogous to modern plate tectonic settings.

One of the next challenges for the geodynamicists is the analysis of large metamorphic datasets. Integrating the large variety of petrochronological data into consistent tectonic and geodynamic models can strengthen our understanding of the formation of metamorphic belts. In the paper by **Oh & Lee (2018)**, the authors have tracked the systematic changes in the metamorphic record and the distribution of the post-collisional igneous rocks along the Permo-Triassic Qinling–Sulu–Odesan belt located between the North China Craton and South China Craton. The authors have interpreted the variation in the peak-pressure conditions along the belt as being a result of the geometry of the continental margin. The amount of subducted oceanic slab increases westwards, resulting in lower peak-pressure conditions for continental subduction and a decrease in the depth at which slab break-off occurs. This study demonstrates that the geometry of the continental margin entering subduction strongly dictates the *P–T–t* trajectories followed by the subducted rocks. Similar conclusions were reached based on the petrochronological record of HP–UHP rocks for other metamorphic belts such as the Western Gneiss Region of Norway or the Himalayas (Hacker *et al.* 2010; Lanari *et al.* 2013).

Open questions and evolving perspectives

It is remarkable to see how some basic problems have remained at the core of metamorphic petrology. In the Special Publication entitled *What Drives Metamorphism and Metamorphic Reactions?* (Treloar & O'Brien 1998*a*), Treloar & O'Brien (1998*b*, p. 4) noted:

> [T]hat all of our major findings of the last 25 or so years, albeit based on analytical data and integrated into the modern Plate Tectonic paradigm, do not necessarily tell us more about 'What Controls Metamorphism' than our predecessors would have concluded.

This conclusion is, to some extent, still valid today but our Special Publication also emphasizes the evolution of our understanding of some critical metamorphic processes in the last couple of decades. New ideas have been explored, notably to investigate the role of seismic activity in initiating and facilitating metamorphism (e.g. Putnis *et al.* 2017 and references therein) or the importance of aqueous solutions in nanopores in driving metamorphism (Plümper *et al.* 2017). In the following, a few open questions that we think are important are briefly discussed.

The increasing role of fluids

If fluid is not present, element transfer is very limited in metamorphic rocks (e.g. Carlson 2010); being insufficient in most cases to form new minerals that are predicted to be stable by equilibrium thermodynamics (Rubie 1998). How are the reactive fluids transferred away from the fractures and veins? Is microcracking and grain-boundary dilation the main process, as suggested by Barker & Zhang (1998) in a previous Special Publication (Treloar & O'Brien 1998*a*), or is this transport more often pervasive through the entire rock (Putnis & John 2010)? Clearly, geochemical evidence can be used to identify micro-chemical and microstructural evidence of fluid–mineral reactions and to quantify the extent of re-equilibration (Airaghi *et al.* 2017; **Hyppolito *et al.* 2018**; **Lanari *et al.* 2018**). Then the question of what initiates, drives and stops re-equilibration can be addressed in a different way.

Element transfer during prograde metamorphism

Is metamorphism largely isochemical as supposed in most of the petrological models based on bulk-rock compositions or does element transport via aqueous fluids matter? This question remains largely unsolved and divides the community. In the paper by **Likhanov (2018)**, the author investigated several metapelite samples from the Garevka Complex in the Yenisey Ridge (Siberia, Russia). Detailed chemical analysis of garnet was combined with inverse thermobarometry to reconstruct multiple stages of garnet growth and to unravel the associated reaction sequence. The mass balance of these mineral reactions was then compared to the observed mineral modes to test if the rock behaved as a closed or open system for element exchanges. The author concludes that prograde metamorphism was, in this example, largely isochemical for the major elements, in contrast to trace elements (especially HREE) that behave in a more complex fashion.

Hydration and stress generation

What is the structural and chemical evidence for mass and/or volume loss in metamorphic rocks? This question, largely inspired by Vernon (1998), is still a matter of debate today. An excellent illustration of the problem is presented in the paper by **Centrella (2018)**. In the Lindås Nappe of the Bergen Arcs (Norway), Neoproterozoic granulites were partially transformed into eclogite and amphibolite during the Caledonian Orogeny. The spatial relationships between granulite, amphibolite and eclogite are complex, preventing a relative sequence to be established. Petrochronology does not help much in this case as the ages of the eclogite and amphibolite stages are coeval within uncertainty. The isochemical transformations of granulite into amphibolite and eclogite caused major density changes. The decrease in density from granulite to amphibolite requires either an increase in volume, assuming a closed system, or a significant loss of mass, assuming open-system behaviour. Several lines of evidence reported by **Centrella (2018)** point towards an unexpected scenario. In a closed system, deviatoric stress is generated by the hydration of the granulite and this may influence the local mineral assemblage that would record higher pressures. These bring an additional piece to the puzzle of possible grain-scale pressure variations recorded in metamorphic rocks (Tajčmanová *et al.* 2014, 2015; Centrella *et al.* 2018).

Links between metamorphism and short-term tectonics

It is now well recognized that earthquakes and aftershocks, produced by frictional failure, are not restricted to the seismogenic upper crust (*c.* <15 km and T <450°C) but can occur in, or penetrate into, the middle–lower crust of all collisional settings. For instance, the 2015 $M_w = 7.8$ Gorka earthquake in India located at a depth of 10–15 km has induced aftershocks down to 30 km (McNamara *et al.* 2017). In a similar way, the beginning of the twenty-first century saw the major discovery of slow earthquakes characterized by slow slip events accompanied by non-volcanic tremor and deep low- to very low-frequency earthquakes in subduction zones around the Pacific Ocean at depths of >30–45 km (Cascadia, Alaska, Mexico, Costa Rica, Japan) (Ohmi & Obara 2002; Rogers & Dragert 2003; Nadeau & Dolenc 2005; Schwartz & Rokosky 2007) and along the deep extension of the strike-slip plate boundary of the San Andreas Fault at depths of >20 km (Nadeau & Dolenc 2005; Shelly 2010).

To better understand the mechanics of brittle failure in the ductile realm, field geologists (mostly structural geologists) have looked for the rock record of earthquakes in the deep metamorphic crust. But because the main factors controlling the rock rheology includes, in addition to mechanical parameters (strain rate and deviatoric stress), temperature, chemical composition, water activity and pore-fluid pressure, metamorphic petrologists are becoming more involved in the quest for the rock record of deep seismicity. Pseudotachylite is probably the most reliable indicator of palaeo-earthquakes. To discuss the deformation mechanisms that control pseudotachylite development, it is first critical to establish via thermodynamic modelling the *P* (depth)–*T* conditions of formation (Hawemann *et al.* 2018). The rock record and mechanics of non-volcanic tremors are currently being investigated by studying exhumed geological exposures of shear zones (e.g. Fagereng & Sibson 2010; Fagereng *et al.* 2014; Hayman & Lavier 2014). It appears that shear zones are characterized by the concomitant activation of ductile and brittle deformation, as well as significant metamorphic reactions due to synkinematic fluid percolation. This observation raises the question of the role of chemical processes in the mechanics of deep seismicity.

Conclusion

In conclusion, metamorphic geology is an all-encompassing discipline that borrows heavily the approaches and techniques from a broad range of disciplines – from material science to mathematics – and in return delivers new insights based on the investigation of natural materials; and sometimes new problems. The discipline is rapidly evolving, and this Special Publication aims to provide a snapshot of its state in the second decade of the 2000s. The fundamental question remains: what drives changes in nature? The tumultuous development of technology and computational power will surely bring new exciting ideas on the stage in the next years. In the words of T. S. Elliott (from his poem *Little Gidding*), as metamorphic geologists 'We shall not cease from exploration / And the end of all our exploring / Will be to arrive where we started / And know the place for the first time'.

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