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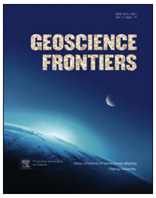

Focus paper

The contribution of metamorphic petrology to understanding lithosphere evolution and geodynamics

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ABSTRACT

In the early 1980s, evidence that crustal rocks had reached temperatures >1000 °C at normal lower crustal pressures while others had followed low thermal gradients to record pressures characteristic of mantle conditions began to appear in the literature, and the importance of melting in the tectonic evolution of orogens and metamorphic–metasomatic reworking of the lithospheric mantle was realized. In parallel, new developments in instrumentation, the expansion of *in situ* analysis of geological materials and increases in computing power opened up new fields of investigation. The robust quantification of pressure (P), temperature (T) and time (t) that followed these advances has provided reliable data to benchmark geodynamic models and to investigate secular change in the thermal state of the lithosphere as registered by metamorphism through time. As a result, the last 30 years have seen significant progress in our understanding of lithospheric evolution, particularly as it relates to Precambrian geodynamics.

Eoarchean–Mesoarchean crust registers uniformly high T/P metamorphism that may reflect a stagnant lid regime. In contrast, two contrasting types of metamorphism, eclogite–high-pressure granulite metamorphism, with apparent thermal gradients of 350–750 °C/GPa, and granulite –ultrahigh temperature metamorphism, with apparent thermal gradients of 750–1500 °C/GPa, appeared in the Neoarchean rock record. The emergence of paired metamorphism is interpreted to register the onset of one-sided subduction, which introduced an asymmetric thermal structure at these developing convergent plate margins characterized by lower T/P in the subduction channel and higher T/P in the overriding plate. During the Paleoarchean to Paleoproterozoic the ambient mantle temperature was warmer than at present by ~300–150 °C. Although the thermal history of Earth is only poorly constrained, it is likely that prior to ca. 3.0 Ga heating from radioactive decay would have exceeded surface heat loss, whereas since ca. 2.5 Ga secular cooling has dominated the thermal history of the Earth. The advent of paired metamorphism is consistent with other changes in the geological record during the Neoarchean that are best explained as the result of a transition from a stagnant lid to subduction and a global plate tectonics regime by ca. 2.5 Ga. This interpretation is supported by results from 2-D numerical experiments of oceanic subduction that demonstrate a change to one-sided subduction is plausible as upper mantle temperature declined to <200 °C warmer than at present during the late Neoarchean–Paleoproterozoic. This is the beginning of the Proterozoic plate tectonics regime.

At 1.0 Ga the ambient mantle temperature was still ~150–100 °C warmer than at present. Continued secular cooling caused a transition to cold subduction registered in the crustal record of metamorphism by the first appearance of blueschist and high to ultrahigh pressure metamorphism during the Neoproterozoic. Results of 2-D numerical experiments of continental collision demonstrate a transition from

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shallow to deep slab breakoff associated with stronger crust–mantle coupling that enabled continental subduction to mantle depths as upper mantle temperature declined to <100 °C warmer than at present during the late Proterozoic. This is the beginning of the modern plate tectonics regime.

1. Introduction

On contemporary Earth, regional metamorphism is associated with geodynamic settings of lower or higher than average heat flow, such as subduction zones and arc–back arc systems, or is related to tectonic processes that disrupt the steady-state thermal structure of the lithosphere by thickening or thinning, such as occurs in orogenic hinterlands and collisional mountain belts or during orogenic collapse and regional extension (Brown, 2008, 2009). In addition, the long-term cooling of the lithosphere drives garnet-producing metamorphic reactions, which decreases the buoyancy of crustal roots and enhances lithosphere stability (Fischer, 2002). To extend this understanding of the relationship between geodynamics and metamorphism back in time, we use the forensic methods and techniques of metamorphic petrology.

Thus, metamorphic petrology is concerned with decoding the mineralogical and microstructural record of burial/heating and exhumation/cooling imprinted on pre-existing sedimentary, igneous and metamorphic rocks by processes such as subduction, accretion, trench advance or retreat, collisional orogenesis and orogenic collapse. As petrologists, we address multiple scales of activity, from the pressure (P)–temperature (T)–time (t) evolution of a single rock to the evolution of P–T in space and time. Both subduction/accretion and collisional orogenesis/orogenic collapse cause perturbations of steady-state geotherms on time scales and length scales constrained by the mechanical properties of the lithosphere, which vary with composition, temperature, fluid/melt presence/absence, and strain rate. Thus, by determining quantitative P–T–t paths petrologists make available information to parameterize subduction zone processes and collisional orogenesis. Inverting this P–T–t information, provides constraints on the geodynamic and metasomatic processes involved, and consequently advances understanding of lithosphere evolution and geodynamics.

Although mobile-lid plate tectonics (hereafter “plate tectonics”) has provided us with a context to understand metamorphism and its relationship to tectonics at least as far back as the dawn of the Phanerozoic (Brown, 2008, 2010b), during the Precambrian geodynamics may have been different (Sizova et al., 2010, 2014). For example, a strong case has been made for a stagnant-lid plate tectonics regime on the early Earth (Debaille et al., 2013; Griffin et al., 2013; O’Neill et al., 2013; hereafter “stagnant lid”). In addition, Earth’s mantle was hotter and Moho temperatures were higher in the past, and in the Archean conditions were probably appropriate for lithosphere foundering by Rayleigh–Taylor instabilities (Jull and Kelemen, 2001; Toussaint et al., 2004), which may have played a much more important role in lithosphere evolution on the early Earth than on contemporary Earth (Johnson et al., 2014).

In the first section of this paper I review examples of major discoveries in metamorphic petrology and advances in instrumentation and methods during the last 30 years. This provides a perspective for the second section in which I review evidence from the crustal record of metamorphism and recent results from geodynamic modeling to investigate the major geodynamic transitions in Earth evolution. The first of these concerns the transition from an Archean stagnant-lid regime to a Proterozoic plate tectonics regime, as evidenced by the appearance of paired metamorphism, whereas the second concerns the Cryogenian to Cambrian transition from the Proterozoic plate tectonics regime to the modern plate tectonics regime characterized by cold subduction, as evidenced by the appearance of blueschist and ultrahigh-pressure metamorphism in the geological record.

2. The state of the art in metamorphic petrology

2.1. Brave new world

It is now 30 years since the discovery that some lithospheric materials record evidence of metamorphism at pressures characteristic of mantle conditions (e.g. Chopin, 1984, 2003; Dobrzhinetskaya et al., 2011). Just a few years earlier, persuasive evidence had appeared in the literature demonstrating that some crustal rocks registered temperatures >1000 °C over large areas at ‘normal’ lower crustal pressures (e.g. Ellis, 1980; Harley, 1998, 2008; Kelsey, 2008). Although both of these statements appear to be broadly correct, it is wise to be circumspect of extreme values in case the recorded pressure was not lithostatic (Moulas et al., 2013) or where the calculated temperature approaches or exceeds the liquidus for the continental crust (~1100 °C). Also during the same period, the realization that melting and melt drainage and migration might play an important role in crustal deformation was becoming widespread (e.g. Hollister and Crawford, 1986; D’Lemos et al., 1992; Brown, 1994, 2010a). Furthermore, it became clear that much of the underlying mantle has undergone dynamic reworking (Mercier and Nicolas, 1975), including metasomatic modifications (Thompson, 1992). This revelation opened both the mantle (Tirone et al., 2009; Holland et al., 2013), including the deep mantle (Ganguly et al., 2009), and subducted lithospheric slabs (Hacker et al., 2003a) to study using the methods of metamorphic petrology.

These fascinating developments during the past 30 years have not only changed our perception of the field of metamorphism but also of the role that metamorphic petrology can play in understanding orogenesis. But how have these developments helped us to understand the evolution of the lithosphere and geodynamics during the Precambrian in relation to secular change?

2.2. Metamorphism and tectonics

In addressing the issue of metamorphism and tectonics, both regional and global scales of interactions are of interest. At the regional scale, we are concerned with differences from terrane to terrane that enable us to distinguish the particular combination of tectonic events responsible for the metamorphism of each terrane, and which inform us about tectonic interactions at the terrane scale. At the global scale, we are concerned with similarities in styles of metamorphism and relationship to plate tectonic setting, which relationships are likely to reflect global geodynamic processes.

The asymmetry in the thermal structure characteristic of one-sided subduction creates contrasting thermal environments—lower T/P in the subduction zone and higher T/P in the arc–backarc/orogenic hinterland—that are registered in the rock