GEODYNAMIC REGIMES AND TECTONIC SETTINGS FOR METAMORPHISM: RELATIONSHIP TO THE SUPERCONTINENT CYCLE

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Abstract

Metamorphism associated with orogenesis provides a mineral record that may be inverted to yield ambient apparent thermal gradients. On modern Earth, tectonic settings with lower thermal gradients are characteristic of subduction zones whereas those with higher thermal gradients are characteristic of backarcs and orogenic hinterlands. The duality of thermal environments reflects the asymmetry of one-sided subduction, which is the hallmark of modern plate tectonics; a duality of metamorphic belts is the characteristic imprint of one-sided subduction in the geological record. Apparent thermal gradients derived from inversion of age-constrained metamorphic P-T data may be used to identify tectonic settings of ancient metamorphism and to evaluate Precambrian geodynamic regimes. The Neoarchean records the first occurrences of granulite facies ultra-high temperature metamorphism (G-UHTM) and medium-temperature eclogite-high-pressure granulite metamorphism (E-HPGM), signifying a change in geodynamics that generated sites of higher and lower heat flow than those implied by apparent thermal gradients recovered from the older geological record. G-UHTM is dominantly a Neoarchean-Cambrian phenomenon inferred to have developed in settings analogous to backarcs and orogenic hinterlands. In addition to Proterozoic occurrences, E-HPGM is common in the Paleozoic Caledonides and Variscides, and is inferred to record subduction-to-collision orogenesis. The occurrence of G-UHTM and E-HPGM belts since the Neoarchean signifies a change to one-sided subduction of oceanic lithosphere, possibly beginning as early as the Paleoproterozoic, and widespread transfer of water into the upper mantle. This change registers the beginning of a 'Proterozoic plate tectonics regime' that evolved during a Neoproterozoic transition to the 'modern plate tectonics regime' characterized by colder apparent thermal gradients and deep subduction of continental crust. The age distribution of metamorphic belts is not uniform, recording amalgamation of continental lithosphere into supercratons or supercontinents.

Keywords: Geothermal gradients, metamorphism, plate tectonics, supercontinents

1. Introduction

The plate tectonics revolution provided a paradigm to understand the Cenozoic-Mesozoic tectonics of the lithosphere – the strong outer layer of Earth above the softer asthenosphere – which led to debate about when Earth first adopted plate tectonics. Consensus is emerging that Earth had (partially or completely) adopted plate tectonics by sometime in the Archean (Brown, 2006, 2007a, b, 2008), although there are those who argue for (some form of) plate tectonics as early as the Hadean (Davies, 2006) —
consistent with the null hypothesis that plate tectonics was the mode of convection throughout Earth history – and those who argue against world-wide modern – style subduction before the Neoproterozoic (Stern, 2007) – requiring an alternative hypothesis to plate tectonics for the Hadean to Mesoproterozoic interval. From a geological perspective, we may break into several components the question of when plate tectonics began on Earth. We may ask: when did the lithosphere first behave as a mosaic of plates – torsionally-rigid lithosphere elements bounded by zones of plate generation, plate destruction or transform displacement – and how far back in time may we identify independent horizontal motions from different cratons; and, when in the rock record do we first identify zones of convergence and subduction of oceanic lithosphere (e.g. Davies, 1992)? However, care is required – what imprint in the geological record do we take to answer each of these questions (Cawood et al., 2006)?

2. The Hallmark of Plate Tectonics

In the early days of plate tectonics, the relationship between plate tectonics and metamorphism was addressed by Miyashiro (1972). The first record of blueschist facies metamorphism occurs in the Neoproterozoic, and this is commonly taken as one indicator of the beginning of the modern style of subduction (Stern, 2005). However, due to secular cooling, Brown (2006, 2007a) asked whether plate tectonics on a warmer Earth might have left a different imprint in the ancient rock record. To answer this question, it is necessary to establish the distinctive characteristics of plate tectonics that might be preserved in the rock record. Brown (2006, 2007a) argued that the definitive hallmark of plate tectonics is a duality of thermal environments at convergent plate margins (the subduction zone and the arc-backarc or orogenic hinterland), the asymmetry of which is a direct consequence of one-sided subduction (Gerya et al., 2008). The imprint of this hallmark in the rock record is registered as the contemporary occurrence of spatially distinct contrasting types of metamorphism.

Metamorphic rocks record evidence of change in pressure and temperature with time – commonly expressed as a P-T-t path – or burial and exhumation in the thermal environment(s) in which the mineral assemblage(s) equilibrated (e.g. Brown, 1993, 2001). In effect, the P-T-t path records the changing spectrum of metamorphic (transient) geotherms characteristic of a particular tectonic setting. Different settings are characterized by different ranges of dT/dP and register different metamorphic imprints in the rock record.

Early plate-like behavior may have allowed crust to float, forming thick stacks above zones of boundary-layer downwelling, or, for a slightly cooler Earth, forming thick stacks above zones of 'sub-lithospheric' subduction (Davies, 1992). However, these behaviors are unlikely to have created dual thermal environments at the site of tectonic stacking, although thickening (with or without delamination of eclogite sinkers) could have induced melting deep in the stack generating tonalite-trondhjemite-granite-type magmas (Foley et al., 2002, 2003). Therefore, in principle, the metamorphic imprint imposed by either of these behaviors during the early
part of Earth history should be distinguishable from that imposed by one-sided subduction and plate tectonics sensu stricto. Another challenge is to assess whether once plate tectonics was established it was maintained to the present day or whether geodynamics on Earth alternated between plate tectonics and some other mode (Sleep, 2000) or was episodic (O’Neill et al., 2007) or intermittent (Silver and Behn, 2008), particularly in the Mesoarchean to Mesoproterozoic interval.

In this chapter, I review metamorphism in relation to different types of orogenic system as recorded in the Phanerozoic record before extending the analysis back through most of the Precambrian using a published dataset compiled in 2005 (Brown, 2007a). I discuss the implications of these data in relation to dual thermal environments as the hallmark of plate tectonics and identify when the imprint of this distinctive feature first appears in the rock record (cf. Brown, 2006). Finally, I evaluate the age distribution of metamorphism since the Neoarchean and consider how this relates to the supercontinent cycle (cf. Brown, 2007b, 2008).

3. Earth in the Phanerozoic Eon

Currently, there are two main zones of subduction into the mantle (Collins, 2003) — the circum-Pacific and the Alpine-Himalayan-Indonesian subduction systems — and two major zones of upwelling or superswells (Montelli et al., 2006; Tan and Gurnis, 2007) — under southern Africa and the South Pacific — which define a simple pattern of long-wavelength mantle convection. The Phanerozoic has been distinguished by rearrangement of the continental lithosphere during the final steps in supercontinent assembly and the early stages of supercontinent breakup. The formation of Eurasia and its linking to Gondwana to form Pangea involved successive subduction-to-collision orogenic systems — the Appalachian/Caledonian-Variscide-Altaid and the Cimmerian-Himalayan-Alpine orogenic systems — within a single (Pangean) convection cell, whereas a complementary (Panthalassan) convection cell, centered on the South Pacific superswell, is composed of ocean lithosphere and defined at its outer edge by circum-Pacific accretionary orogenic systems (Collins, 2003). The Panthalassan cell was established by the end of the Neoproterozoic, centered on the former Rodinia and reflecting enhanced heat flux associated with the slab graveyard due to Rodinia assembly. It reached a maximum around the Devonian-Carboniferous boundary, and has been in decline since the Pangean cell began expanding in the Jurassic, centered on the former Gondwana and reflecting enhanced heat flux associated with the slab graveyard due to Gondwana assembly.

3.1. Orogenic systems

The Circum-Pacific and Cimmerian-Himalayan-Alpine orogenic systems define two orthogonal great circle distributions of the continents, which may reflect a simple pattern of mantle convection. This inference is supported by a variety of geophysical data (Richards and Engebretson, 1992). Along each great circle the convergent plate margins are characterized by a different type of orogenic system, which has been the situation during at least the Cenozoic and Mesozoic Eras (Zwart, 1967; Maruyama, 1997; Ernst, 2001; Liou et al., 2004). These types are accretionary orogenic systems [variants have been called
'Pacific-type' (e.g. Matsuda and Uyeda, 1971) or 'Cordilleran-type' (e.g. Coney et al., 1980), which form during ongoing subduction, as exemplified by the Phanerozoic evolution of the Pacific Ocean rim, and collisional orogenic systems [sometimes called 'Himalayan-type' (Liou et al., 2004) or 'Turkic-type' (Sengör and Natali'n, 1996)], in which an ocean is closed and arcs and/or allochthonous terranes and/or continents collide, as exemplified by the Tethysides.

Accretionary orogenic systems vary according to whether the over-riding plate is retreating, neutral or advancing (e.g. the Tasmanides versus the South American Cordillera), and whether suspect terranes, some of which may be far-traveled (cf. Coney et al., 1980; Johnston and Borel, 2007), become accreted to the over-riding plate (e.g. the North American Cordillera). For Turkic-type orogenic systems, Sengör and Natali'n (1996) argued that the pre-collision history of one or both of the colliding margins might involve the growth of large accretionary orogenic systems, with significant juvenile arc magmatism. Nonetheless, a distinction between the accretionary and the collisional phases of an orogenic system remains useful because some accretionary orogenic systems exist for hundreds of millions of years without disruption by collision. In addition, other accretionary orogenic systems have the continuity of subduction interrupted – but not necessarily terminated if a new trench is formed outboard of the collider – by subduction of ocean floor debris or an oceanic plateau or non-terminal collision and suturing of allochthonous terranes or arcs (e.g. Cloos, 1993; Collins, 2002).

Major mountain belts of the Circum-Pacific orogenic systems are located in subduction zone backarcs, which are characterized by high heat flow (greater than 70 mWm$^{-2}$ for continental crust with average radiogenic heat production) and uniformly thin and weak lithosphere over considerable widths (Hyndman et al., 2005a). Subduction zone backarcs are hot due to shallow convection in the mantle wedge consequent upon a reduction in viscosity induced by water from the underlying subducting plate. Moho temperatures in subduction zone backarcs are 800-900°C and lithosphere thicknesses are 50-60 km, compared to 400-500°C and 200-300 km for cratons (Hyndman et al., 2005a); the difference results in backarc lithosphere being at least an order of magnitude weaker than cratons. Parameters such as the contemporaneous surface heat flow cannot be measured directly in ancient orogens, so we must look to the metamorphic record for information. Also, thermal expansion due to the high lithosphere temperatures is argued to account for about 2500 m of elevation in subduction zone backarcs without significant crustal thickening (Hyndman et al., 2005b), which may be recorded in ancient orogens as variation in the pressure field. Most Circum-Pacific mountain belts are broad zones of long-lived tectonic activity because they are sufficiently weak to be deformed by the forces developed at plate boundaries; complex deformation histories in these orogenic systems likely relate to changing dynamics along the convergent boundaries (Dewey, 1975). In accretionary orogenic systems characterized by accumulation of suspect terranes, former backarcs continue as a locus of deformation during terrane suturing because they remain weaker than the hinterland.

Shortening and crustal thickening in large hot orogenic systems, such as the
Himalayan orogenic system and the South American Cordillera, appears to be accommodated mostly in the weak lower crust (Beaumont et al., 2006; Sobolev and Babeyko, 2005). The upper crust may be uplifted as a plateau, which may be underthrust by the adjacent stable craton, and the upper crust may remain largely undeformed internally with deformation localized into high-strain belts.

3.2. The metamorphic realm

The metamorphic realm traditionally is divided into facies, each represented by a group of mineral assemblages associated in space and time that are inferred to register equilibration within a limited range of P-T conditions (Fig. 1a). Some rocks characteristic of the granulite facies record temperatures greater than 1,000°C at pressures of 0.5-1.2 GPa [ultrahigh-temperature metamorphism (UHTM); e.g. Harley, 1998; Brown, 2007a], whereas some eclogite facies rocks record pressures greater than 5 GPa at temperatures of 600-1,000°C, and in one case mineralogical evidence suggests pressures of at least 10 GPa [ultrahigh-pressure metamorphism (UHPM); e.g. Chopin, 2003; Liu et al., 2007; Brown, 2007a]. The transition between these two is referred to as medium-temperature eclogite - high-pressure granulite metamorphism (E-HPGM; e.g. O’Brien and Rötzer, 2003; Brown, 2007a). On modern Earth, the different metamorphic facies series leading to granulite - ultrahigh temperature metamorphism (G-UHTM), medium temperature eclogite - high pressure granulite metamorphism (E-HPGM) and high pressure metamorphism - ultrahigh pressure metamorphism (HPM-UHPM) are generated in different tectonic settings with contrasting thermal regimes at convergent plate boundary zones (Brown, 2006, 2007a).

Recently, Stüwe (2007) has introduced an alternative division of P-T space based on whether thermal conditions implied by the peak metamorphic mineral assemblages in orogenic crust were warmer or cooler than a normal (conductive) continental geotherm (Fig. 1b). On this diagram we may distinguish P-T fields that are reached as a function of different tectonic processes. For conditions warmer than a normal continental geotherm, a thermal gradient of approximately 1,000°C/GPa is the practical limit for a conductive response (based on the extreme condition of the Moho resting directly on the asthenosphere). Metamorphic belts that record apparent thermal conditions hotter than this limit (I use the term 'ultra-high temperature' for this P-T field) require a component of intracrustal advection-driven heating, perhaps in an arc or due to thinning the sub-crustal lithospheric mantle (e.g. Sandiford and Powell, 1991), consistent with the subduction zone backarc model discussed above (Hyndman et al., 2005a, b). For thermal conditions cooler than a normal continental geotherm, Stüwe (2007) suggests a two-fold division into a 'cooler than normal' (note, Stüwe used "colder") and an 'ultra-low temperature' P-T field. The cooler than normal P-T field is a thermal regime that may be reached by whole lithospheric thickening to the potential energy limit for equilibrium with normal plate tectonic driving forces (about double normal thickness crust or half the normal thermal gradient), P-T conditions that do not necessarily reflect thermal regimes attendant with subduction or that require unusually rapid exhumation (cf. Sandiford and Dymoke, 1991). In contrast, the ultra-low temperature P-T field may only be reached by processes other than normal crustal thickening; subduction is one possible process
Metamorphism and Geodynamic Regimes

4. Earth in the Archean and Proterozoic Eons

4.1. Metamorphic regimes through Earth history

Metamorphic belts are classified into three types according to the characteristic metamorphic facies series recorded by the belt, as follows (Fig. 2a; data from Brown, 2007a): HPM-UHPM, characterized by lawsonite blueschist to lawsonite eclogite facies series rocks and blueschist to eclogite to ultrahigh-pressure facies series rocks, where T plotted in Fig. 2a is that registered at maximum P; E-HPGM, characterized by eclogite facies series that reach peak P-T in the high-pressure granulite facies (O'Brien and Rötztler, 2003), where maximum P and T generally are achieved approximately contemporaneously (Fig. 2a); and, G-UHTM, characterized by granulite facies series rocks that may reach ultrahigh-temperature metamorphic conditions, where P plotted in Fig. 2a is that registered at maximum T. The P-T value for each terrane in Fig. 2 records a point on a metamorphic (transient) geotherm, and different apparent thermal gradients are implied by each type of metamorphism. These apparent thermal gradients are inferred to reflect different tectonic settings. HPM-UHPM is characterized by apparent thermal gradients of 150-350°C/GPa (approximately equivalent to 4-10°C/km), and plots across the boundary between the "cooler than normal" and "ultralow temperature" fields. About half of these terranes require a process other than simple thickening to achieve such cold gradients. We
know from the global context that all of these terranes were associated with subduction, so it is likely that subduction was the process that created the ultra-low temperature environment. E-HPGM is characterized by apparent thermal gradients of 350-750°C/GPa (10-20°C/km), and plots across the normal continental geotherm but mostly in the field where heating is a conductive response to thickening. G-UHTM is characterized by apparent thermal gradients >>750°C/GPa (>>20°C/km), and mostly plot across the boundary into the field which requires an advective component of heating. Figure 3 illustrates apparent thermal gradient, which is inferred to relate to tectonic setting, plotted against age of peak metamorphism for each belt. Each type of metamorphism has a distinct range of apparent thermal gradient, as expected from Fig. 2, and UHPM is restricted to the late Neoproterozoic and Phanerozoic. However, what is now clear is the dual nature of the thermal regimes represented in the metamorphic record since the Neoarchean. The Neoarchean to Neoproterozoic interval is characterized by G-UHTM and E-HPGM, whereas the late Neoproterozoic and the Phanerozoic are characterized by HPM-UHPM and E-HPGM, with only sporadic examples of G-UHTM post-Cambrian.

Although patterns based on first occurrences may be challenged by new discoveries, analysis of the data in Fig. 3 provides a set of compelling first-order
observations from which to argue that the modern era of ultra-low temperature subduction began in the Neoproterozoic, as registered by the occurrence of HPM-UHPM, but that ultra-low temperature subduction alone is not the hallmark of plate tectonics. In contrast, G-UHTM and E-HPGM are present in the exposed rock record back to at least the Neoarchean, registering a duality of thermal regimes, which has been argued to represent the hallmark of one-sided subduction and plate tectonics (Brown, 2006, 2008). Based on this observation, plate tectonics processes likely were operating in the Neoarchean as recorded by the imprints of dual types of metamorphism in the rock record, and this may manifest the first record of global one-sided subduction on Earth.

Fig. 3. Apparent thermal gradient in °C/GPa plotted against age of peak metamorphism in Ma (data from Tables 1-5 of Brown, 2007a) for the three main types of metamorphic belt - G-UHTM (circles), E-HPGM (diamonds) and HPM-UHPM (squares) for two time intervals, a. Phanerozoic and Neoproterozoic, and b. Mesoproterozoic to Neoarchean.
The distribution of these types of metamorphism throughout Earth history is displayed in Fig. 4, together with intervals of supercontinent amalgamation. Changes in the metamorphic record broadly coincide with the transitions from the Archean to Proterozoic and Proterozoic to Phanerozoic Eons, and imply a different style of tectonics in the Archean in comparison with the Proterozoic and in the Proterozoic in comparison with the Phanerozoic. Overall, the restricted time span of different types of metamorphism through Earth history and the periods of metamorphic quiescence during the Proterozoic Eon suggest a link with the supercontinent cycle and major events in the mantle.

4.1.1. Caveats

There are several caveats about possible bias in this record. It is commonly argued that going back through time increases loss of information by erosion of the older record. However, the data in Figs. 3 and 4 plot in particular periods and there is a clear distinction between the pre-Neoproterozoic, where UHPM does not occur, and Neoproterozoic and younger belts, where UHPM is common. These observations are inconsistent with a progressively degraded record with increasing age. Extrapolation back in time also raises questions about partial-to-
complete overprinting by younger events, which is a concern in any metamorphic study. However, our ability to recognize the effects of overprinting and to 'see through' them has improved significantly, and overprinting has been avoided in compiling the dataset used for this analysis (Brown, 2007a). Finally, it is likely that some Mesozoic-Cenozoic G-UHTM rocks have not yet been exposed at Earth's surface, leading to bias in the younger part of the record.

4.1.2. Paired metamorphic belts revisited

Orogenic belts may be composed of belts with contrasting types of metamorphism that record different apparent thermal gradients. Classic paired metamorphic belts are composed of an inboard HT-LP belt, commonly with penecontemporaneous granites, juxtaposed along a tectonic contact against an outboard HP-LT belt; they are found in accretionary orogens of the circum-Pacific (Miyashiro, 1961).

In accretionary orogens, HP-LT blueschists and low-temperature eclogites are generated in the subduction zone, and a majority of lawsonite eclogites are associated with the HP-LT terranes of the circum-Pacific accretionary orogens (Tsujimori et al., 2006). Complementary HT-LP metamorphism may be generated in an arc-backarc or orogenic hinterland. Events that may occur at the trench include ridge subduction, entry into the subduction channel of an ocean floor topographic high and evolution of plate kinematics leading to change from a retreating hinge to an advancing arc. These events may affect the thermal structure of the over-riding plate, may lead to a change in the displacement vector across the axis of plate divergence or across an associated transform as a ridge is subducted and may change the tectonics from extension to shortening (e.g. Brown, 1998b, 2002; Collins, 2002). HP-LT blueschists and low-temperature eclogites represent educted and accreted materials that have been translated along a convergent margin as a forearc terrane – due to changes in plate kinematics – to juxtapose metamorphic belts of contrasting type during a single orogenic cycle along a common convergent margin (e.g. Brown, 1998a, b, 2002).

In Miyashiro's original classification of types of metamorphism (Miyashiro, 1961), an intermediate P/T type of metamorphism was included for unpaired belts such as those in the Scottish Highlands and the Northern Appalachians, although in both cases the medium P/T metamorphic belt (Barrovian type) is juxtaposed against an intermediate lower P/T metamorphic belt (Buchan type), which is also the case in the eastern Himalaya in Nepal. Miyashiro (1973) subsequently suggested that "... paired and unpaired (single) metamorphic belts form by the same mechanism, and an unpaired belt represents paired belts in which the contrast between the two belts is obscure, or in which one of the two belts is undeveloped or lost."

I suggest we may extend the concept of 'paired metamorphic belts' more widely than accretionary orogens, outside the original usage by Miyashiro (1961), to subduction-to-collision orogenic systems. The modern plate tectonics regime is characterized by a duality of thermal environments in which two principal types of regional-scale metamorphic belts are being formed contemporaneously. Brown (2006, 2008) considers this duality to be the hallmark of one-sided subduction and the characteristic imprint of plate tectonics in the ancient rock record to be the broadly
contemporaneous occurrence of two contrasting types of metamorphism reflecting the duality of thermal environments. On this basis, I propose the following: Penecontemporaneous belts of contrasting type of metamorphism that record different apparent thermal gradients, one warmer and the other colder, commonly juxtaposed by plate tectonics processes, may be called 'paired metamorphic belts'.

Thus, the combination of penecontemporaneous G-UHTM with E-HPGM in adjacent terranes may be described as a paired metamorphic belts. This extends the original concept of Miyashiro (1961) beyond the simple pairing of HT-LP and HP-LT metamorphic belts in circum-Pacific accretionary orogenic systems, and makes it more useful in the context of the relationship between thermal regimes and tectonic setting. This is useful in subduction-to-collision orogenic systems, where an accretionary phase is overprinted by a collision phase that will be registered in the rock record by the imprint of penecontemporaneous higher-P/lower-T metamorphism at the suture and higher-T/lower-P metamorphism in the arc-backarc or orogenic hinterland (Brown, 2006).

4.2. The Archaean-to-Proterozoic transition

Granulite facies ultrahigh temperature metamorphism (G-UHTM) is dominantly a Neoarchean-Cambrian phenomenon documented during four periods — Neoarchean, Orosirian, Ectasian-Stenian and Ediacaran-Lower Cambrian — synchronous with formation of supercratons/supercontinents; it may also be inferred at depth in Mesozoic–Cenozoic orogenic systems (Brown, 2007a). The first occurrence of G-UHTM signifies a change in geodynamics that generated sites of very high heat flow, perhaps analogous to modern arcs and subduction zone backarcs or orogenic hinterlands. In the Neoarchean, G-UHTM occurred in the Kaapvaal Craton and the Southern Marginal Zone of the Limpopo Belt, southern Africa, and in the Lewision Complex of the Assynt terrane, Scotland (the Badcallian event), at ca. 2.72-2.69 Ga, and within the Napier Complex, East Antarctica and the Andriamena Unit, Madagascar, at ca. 2.56-2.46 Ga (references in Brown, 2007a, 2008).

Although rare in the Neoarchean-to-Paleoproterozoic transition, medium-temperature eclogite - high-pressure granulite metamorphism (E-HPGM) also is first recognized in the Neoarchean and occurs at intervals throughout the Proterozoic and Paleozoic rock record (Brown, 2007a). E-HPGM belts complement G-UHTM belts, and are generally inferred to record subduction-to-collision orogenesis. The oldest occurrence is represented by eclogite blocks within mélange in the Gridino Zone of the Eastern Domain of the Belomorian Province, where the eclogite facies metamorphism appears to have been reliably dated at ca. 2.72 Ga and the P-T data of 1.40-1.75 GPa and 740-865°C are well-characterized. This occurrence is one of the earliest records of E-HPGM within a suture zone and is critical in evaluating the start of plate tectonics; the fact that these Neoarchean ages come from blocks in a mélange cannot be avoided.

The occurrence of both G-UHTM and E-HPGM belts since the Neoarchean manifests the onset of a 'Proterozoic plate tectonics regime,' which may have begun locally during the Mesoarchean to Neoarchean and may only have become global during the Neoarchean-to-Paleoproterozoic transition (Brown, 2007b,
This premise is consistent with aggregation of continental crust into progressively larger units to form supercratons, perhaps indicating a change in the pattern of mantle convection during the transition to the Proterozoic Eon.

The emergence of one-sided subduction requires lithosphere with sufficient strength that the over-riding plate can sustain the associated bending stresses and the presence of weak hydrated rocks above the subduction interface (Gerya et al., 2008). These requirements were met as basalt became able to transform to eclogite during subduction releasing water to the overlying mantle rocks. Secular change in thermal regime to allow this transformation appears to have been gradual, occurring regionally first during the Mesoarchean to Neoarchean — leading to the successive formation of the supercratons Vaalbara, Superia and Sclavia — and worldwide during the Paleoproterozoic — evidenced in belts that suture Nuna (Columbia) — unless this distribution is an artifact of (lack of) preservation or thorough overprinting of eclogite in the exposed Archean cratons.

The transition to a Proterozoic plate tectonics regime resulted in stabilized lithosphere in which cratons form the cores of continents that grew dominantly by marginal accretion. It coincided with the first occurrence of ophiolite-like complexes in Proterozoic sutures and the increase in $\delta^{18}O$ of magmas through the Paleoproterozoic, which may reflect maturation of the crust, the beginning of recycling of supracrustal rocks and their increasing involvement in magma genesis via subduction (references in Brown, 2007b, 2008). Although the style of Proterozoic subduction remains cryptic, the change in tectonic regime whereby interactions between discrete lithospheric plates generated tectonic settings with contrasting thermal regimes was a landmark event in Earth history (Brown, 2006, 2008). The absence of HPM-UHPM terranes before the Ediacaran may relate to the subducting lithosphere. For example, the lithosphere might have been strong enough to allow shallow subduction involving transformation of basalt to eclogite and hydration of the overlying mantle but may not have been strong enough to allow deep subduction or to provide a mechanism for eduction of continental crust if, indeed, it was ever subductable before the Ediacaran.

5. Ancient Earth

5.1. Pre-Neoarchean metamorphism

The Eoarchean-Mesoarchean rock record records P-T conditions characteristic of low-to-moderate-P — moderate-to-high-T metamorphic facies. In greenstone belts metamorphic grade varies from prehnite-pumpellyite facies through greenschist facies to amphibolite facies and, rarely, into the granulite facies; ocean floor metamorphism of the protoliths is common. In high-grade terranes, ordinary granulite facies metamorphism and multiple episodes of anatexis are the norm.

In southern West Greenland, in the Isua Supracrustal Belt (ISB), the metamorphism is polyphase — Eoarchean and Neoarchean — and an age of ca. 3.7 Ga has been argued for the early metamorphism. P-T conditions of 0.5-0.7 GPa and 500-550°C (or up to 600°C) have been retrieved from the ISB (references in Brown, 2008). These data yield warm apparent thermal gradients of 800-1,000°C/GPa (~23-28°C/km), which is just within the range for a purely conductive response to
thickening, but may reflect thinner lithosphere with higher heat flow than later in Earth history. Also in southern West Greenland, in mafic rocks on the eastern side of Innerzurtukt Island in the Itsaq Gneiss Complex of the Færingehavn terrane, where the gneisses record several events in the interval 3.67-3.50 Ga, early orthopyroxene + plagioclase assemblages record poorly defined but rather ordinary granulite facies conditions whereas overprinting garnet + clinopyroxene + quartz assemblages probably record the widespread Neoarchean high-pressure granulite facies metamorphism associated with final terrane assembly in the interval 2.715-2.650 Ga (Nutman and Friend, 2007). This is consistent with plate tectonics processes operating on Earth by the Neoarchean (Brown, 2006).

It has been suggested that some Archean TTG suites and eclogite xenoliths scavenged by kimberlites from deeper levels in Archean cratons are respectively melt and complementary residue from a basaltic source, such as the low MgO eclogites from the Koidu kimberlite within the TTG crust of the Man Shield in West Africa, where imprecise Paleoarchean formation ages for the eclogites and TTG crust overlap and are permissive for crustal growth by partial melting of the protolith of the eclogite xenoliths (Barth et al., 2002). Values of $\delta^{18}O$ for the eclogites lie outside the mantle range, suggesting the protolith may represent ocean floor, which in turn permits Archean crustal growth in the Man Shield to have occurred in a convergent margin setting involving subduction of ocean lithosphere. High MgO eclogites in the Man Shield and elsewhere are inferred to correspond to metamorphosed cumulates from hydrous basalt magmas emplaced beneath thick continental arcs, supporting a role for arc magmatism in the formation of cratonic roots in the Mesoarchean to Neoarchean.

In South Africa, recent work on the ca. 3.23 Ga metamorphism of the Barberton and related greenstone belts has yielded P-T data from the Onverwacht Group greenstone remnants of 0.8-1.1 GPa and 650-700°C, from the southern Barberton greenstone belt of 0.9-1.2 GPa and 650-700°C, and from amphibolite-dominated blocks of supracrustal rocks in tectonic mélangé from the Inyoni Shear Zone of 1.2-1.5 GPa and 600-650°C (references in Brown, 2008). Apparent thermal gradients are in the range 450-700°C/GPa (~13-20°C/km), within the limit for a conductive response to thickening. Consequently, a conclusion that these HP-LT conditions represent metamorphic evidence for subduction-driven tectonic processes during the evolution of the early Earth may be premature. The lowest of these gradients is close to the highest gradient retrieved from Phanerozoic HPM-UHPM terranes inferred to have been associated with subduction (Brown, 2007a). Thus, although the Inyoni Shear Zone may represent a suture recording a site of former subduction, the apparent thermal gradients derived from the P-T conditions retrieved from the high pressure rocks do not provide unambiguous evidence of subduction.

5.2. Pre-Neoarchean tectonics
Blueschists are not documented in the Archean Eon and there is no metamorphic imprint of subduction of continental crust to mantle conditions and return to crustal depths (although this could be interpreted to mean that the subducted continental crust was not returned). However, the chemistry of Mesoarchean-to-Neoarchean eclogite xenoliths and the chemistry and paragenesis
of Neoarchean diamonds in kimberlites within cratons suggest some process associated with supercraton formation at convergent margins was operating to take basalt and other supracrustal material into the mantle by the Neoarchean Era (references in Brown, 2008). This may have been some form of subduction, but the hotter ocean lithosphere may have been weaker due to lower viscosity leading to more frequent slab breakoff and slab breakup, and preventing exhumation.

Tonalite-trondhjemite-granite suites (TTGs) dominate the Archean rock record, but their origin has been controversial. One recent view suggests that many older TTGs formed by melting of garnet amphibolite of broadly basaltic composition hydrated by interaction with sea water, whereas melting of eclogite increased in importance through the importance through the Mesoarchean to Neoarchean, as shown by an increase in Nb/Ta in TTGs (Foley et al., 2002, 2003). Melting of garnet amphibolite may be achieved in the lower part of thickened basaltic crust or by subduction on a warmer Earth. Conceptually, this is consistent with early plate-like behavior that allowed crust to float to form thick stacks above zones of boundary-layer downwelling, or, for a slightly cooler Earth, thick stacks above zones of 'sub-lithospheric' subduction, and this indeed may have been the convective mode of the Eoarchean to Paleoarchean. By the Mesoarchean to Neoarchean, and possibly as early as the Paleoarchean, subduction was operating in some regions of the Earth; this subduction was likely characterized by warmer geotherms that enabled melting of subducting garnet amphibolite and, with secular cooling, a change to melting of subducting eclogite.

Worldwide, the oldest surviving Paleoarchean crustal remnants generally are composed of juvenile TTGs formed prior to a period of polyphase granulite facies metamorphism in the interval 3.65-3.60 Ga, and extreme thermal conditions typical of G-UHTM are not generally registered before the Neoarchean. This appears to be counterintuitive, since we might expect the higher abundance of heat-producing elements might have led to higher crustal heat production and hotter orogens. However, it is possible that contemporary heat loss through oceans and continents was higher and lithosphere rheology was generally weaker on early Earth. This is permissive for a 'crème brûlée' lithosphere rheology structure; also, it is consistent with: (1) modeling suggesting dominance of unstable subduction for plate collision regimes with very hot geotherms in which convergence is accommodated by pure shear thickening and development of gravitational (Rayleigh-Taylor) instabilities; (2) modeling that rules out the commonly-proposed flat subduction model for early Earth tectonics; (3) the proposition that early plate-like behavior may have allowed crust to float to form thick stacks above zones of boundary-layer downwelling, or, for a slightly cooler Earth, thick stacks above zones of 'sub-lithospheric' subduction; and, (4) the absence of E-HPGM and HPM-UHPM in the early Earth rock record, inferred herein to by more typical of plate collisions in the Proterozoic and Phanerozoic (references in Brown, 2008).

One alternative tectonic model is that of continental overflow (Bailey, 1999), whereby continental-style crust would override oceanic-style lithosphere to facilitate partial melting of the underlying plate and formation of TTGs. Such a process may have created an environment favorable for subduction and may have been the initial step
required to initiate subduction and enable plate tectonics. Continental overflow might lead to shallow subduction, but this requires that the mantle viscosity was large enough to resist rapid sinking of the oceanic-type lithosphere plate, which may not have been the case for the Archean mantle.

Assuming a hotter early Earth, numerical modeling that takes into account early depletion of the upper mantle suggests this feature might have limited the ability of the ocean lithosphere to subduct and might have impacted the viability of early plate tectonics (Davis, 2006, 2007); this modeling also suggests spatial and temporal variability in crustal thicknesses that might have allowed some plates to subduct whereas other plates might have been blocked to form protocontinental crust. In an alternative scenario without early depletion of the upper mantle, numerical modeling suggests that the lower viscosity and higher degree of melting for a hotter fertile mantle might have led to both a thicker crust and a thicker depleted harzburgite layer forming the ocean lithosphere (van Hunen and van den Berg, 2008). Compositional buoyancy resulting from the thicker crust and harzburgite layers might be a serious limitation for subduction initiation, and a different mode of downwelling or 'sub-lithospheric' subduction might have characterized early Earth. An additional problem for deep subduction is posed by the lower viscosity, which might lead to more frequent slab breakoff and possible breakup of the crust and harzburgite layers of the subducting ocean lithosphere. In this case the lower viscosity of the slab might have been the principal limitation inhibiting plate tectonics on early Earth (van Hunen and van den Berg, 2008; Gerya et al., 2008).

For thinner Archean ocean lithosphere, modeling also suggests that plate motions in the Archean might have been faster than on modern Earth, which may explain the scarcity of accretionary prisms in the Archean rock record since high convergence rates will favor subduction erosion over accretion. Another consequence of a hotter Earth is the reduced subsidence of lithosphere in extension, which will limit the accommodation space for passive-margin sediments and contribute to the scarcity of passive-margin sequences in the Archean. Formation of diamonds in the Mesoarchean to Neoarchean requires geotherms similar modern Earth, which in turn probably reflects the presence of cool mantle roots beneath continents. Stretching continents underlain by cool mantle roots may yield passive margins similar to those on modern Earth. Thus, the development of recognizable passive margins may have occurred only after the stabilization of cratons (Bradley, 2007; Hynes, 2008).

6. Concluding Discussion

Stabilization of cratonic lithosphere and aggregation into supercratons occurred during the Paleoarchean-Neoarchean, probably by mobile-lid convection, although apart from geochemical arguments, the evidence is sparse and resulting belts are smaller-scale than modern orogenic systems. Metamorphism associated with orogenesis provides a mineral record that may be inverted to yield ambient apparent thermal gradients. On modern Earth, tectonic settings with lower thermal gradients are characteristic of subduction zones whereas those with higher thermal gradients are characteristic of backarc and orogenic hinterlands. If a duality of thermal regimes is
the hallmark of one-sided subduction and plate tectonics, then a duality of metamorphic belts is the characteristic imprint of one-sided subduction and plate tectonics in the record. Ideally, these belts should be 'paired' broadly in time and space, although the spatial arrangement may be due to late orogenic juxtaposition. Apparent thermal gradients derived from inversion of age-constrained metamorphic P-T data can be used to identify tectonic settings of ancient metamorphism and evaluate Precambrian geodynamic regimes.

The Neoarchean records the first occurrence of granulite facies ultra-high temperature metamorphism (G-UHTM) and medium-temperature eclogite-high-pressure granulite metamorphism (E-HPGM), signifying changes in global geodynamics to allow sites of higher and lower heat flow than that required by apparent thermal gradients recovered from the earlier record. The occurrence of G-UHTM and E-HPGM belts since the Neoarchean signifies change to globally 'subductable' oceanic lithosphere, possibly beginning as early as the Palearchean, and transfer of water into upper mantle. The first appearance of dual metamorphic belts also registers operation of a global 'Proterozoic plate tectonics regime', which evolved during a Neoproterozoic transition to the 'modern plate tectonics regime' characterized by subduction of continental crust deep into the mantle and its (partial) return from depths of up to 350 km. This Neoproterozoic transition has implications for transfer of water deeper into mantle. The age distribution of metamorphic belts is not uniform, occurring in periods that correspond to amalgamation of continental lithosphere into supercratons (Vaalbara/Superia/Sclavia) or supercontinents (Nuna (Columbia), Rodinia, and Gondwana as a step to Pangea).

The rock record indicates a dramatic change in the thermal environments of crustal metamorphism through the Neoarchean to the Archean-to-Proterozoic transition, which may register the switch to a 'Proterozoic plate tectonics regime'. This premise is consistent with aggregation of the crust into progressively larger units to form supercratons (Bleeker, 2003), perhaps indicating a change in the pattern of mantle convection during the transition to the Proterozoic Eon. The emergence of plate tectonics requires forces sufficient to initiate and drive subduction, and one-sided subduction requires lithosphere with sufficient strength to subduct coherently and hydration of the overlying mantle rocks (Gerya et al., 2008). These requirements likely were met as basalt became able to transform to eclogite during subduction. Secular change in thermal regime to allow this transformation appears to have been gradual, occurring regionally first during the Mesoarchean to Neoarchean – leading to the successive formation of the supercratons Vaalbara, Superia and Sclavia – and worldwide during the Paleoproterozoic – evidenced in orogenic belts that suture Nuna (Columbia) – unless this distribution is an artifact of preservation or thorough overprinting of eclogite in the exposed Archean cratons.

The transition to a 'Proterozoic plate tectonics regime' resulted in stabilized lithosphere in which the cratonic cores of continents grew by marginal accretion. Furthermore, the transition coincides with the first occurrence of ophiolite-like complexes in Proterozoic suture zones (Moores, 2002) and with the increase in d18O of magmas through the Paleoproterozoic, which Valley et al. (2005) argue may reflect maturation of the
crust, the beginning of recycling of supracrustal rocks and their increasing involvement in magma genesis via subduction. Although the style of Proterozoic subduction remains cryptic, the change in tectonic regime whereby interactions between discrete lithospheric plates generated tectonic settings with contrasting thermal regimes was a landmark event in Earth history. The transition to the 'modern plate tectonics regime' through the Neoproterozoic is one in which ocean crust became thinner whereas the lithosphere became thicker (e.g. Moores, 2002), and the pattern of Brasiliano-Pan-African orogens that sutured the disparate continental fragments of Gondwana was replaced by semicircular large-scale plate-margin orogenic systems (e.g. the Terra Australis, the Appalachian/Caledonian-Variscide-Altaid and the Cimmerian-Himalayan-Alpine orogenic systems).

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