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A duality of thermal regimes is the distinctive characteristic of plate tectonics since the Neoarchean

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ABSTRACT

Ultrahigh temperature granulite metamorphism (G-UHTM) is documented in the rock record predominantly from Neoarchean to Cambrian; G-UHTM granulites may be inferred at depth in Cenozoic orogenic systems. The first occurrence of G-UHTM in the record signifies a change in geodynamics that generated transient sites of very high heat flow. Many G-UHTM belts may have developed in settings analogous to modern continental backarcs; on a warmer Earth, destruction of oceans floored by thinner lithosphere may have generated hotter backarcs than those associated with the modern Pacific 'ring of fire'. Medium-temperature eclogite–high-pressure granulite metamorphism (E-HPGM) is documented in the Neoarchean rock record and at intervals throughout the Proterozoic and Paleozoic record. E-HPGM belts are complementary to G-UHTM belts in that they are generally inferred to record subduction-to-collision orogenesis. Blueschists become evident in the Neoproterozoic rock record, but lawsonite blueschist–eclogite metamorphism (HPM) and ultrahigh pressure metamorphism (UHPM) characterized by coesite or diamond are predominantly Phanerozoic phenomena. HPM-UHPM registers the low thermal gradients and deep subduction of continental crust during the early stage of subduction-to-collision orogenesis. A duality of metamorphic belts—reflecting a duality of thermal regimes—appears in the record only since the Neoarchean Era. A duality of thermal regimes is the hallmark of modern plate tectonics and the duality of metamorphic belts is the characteristic imprint of plate tectonics in the rock record. The occurrence of both G-UHTM and E-HPGM belts since the Neoarchean manifests the onset of a *'Proterozoic plate tectonics'* regime, which evolved during a Neoproterozoic transition to the *'modern plate tectonics'* regime characterized by colder subduction as chronicled by HPM-UHPM.

Keywords: backarcs, metamorphism, plate tectonics, subduction, Neoarchean, Neoproterozoic

INTRODUCTION

It is nearly forty years since the plate tectonics revolution introduced a robust paradigm for the Jurassic to present kinematics of the lithosphere. During this period there has been debate about when Earth adopted a plate tectonics mode of behavior. The appearance of blueschist facies series metamorphism in the Neoproterozoic rock record is regarded as one indicator of the beginning of the modern subduction cycle (Stern, 2005). However, due to secular cooling, we should ask whether plate tectonics on a warmer Earth will have left a different imprint in the older rock record. To answer this question, it is necessary to establish the hallmark of plate tectonics in terms of metamorphism. This hallmark may be identified by analysis of sites of modern and older Phanerozoic metamorphism within a plate tectonics framework. Once the hallmark is established, extending the analysis to the Precambrian may reveal when this imprint became evident in the rock record.

Metamorphic rocks record information that may be used to determined the pressure and temperature evolution of the crust with time (the P–T–t path) in orogenic systems, which in turn provides evidence of the thermal regimes under which the mineral assemblages equilibrated. Orogenic systems occur along convergent plate margins—at subducting margins, such as the accretionary orogens around the Pacific rim, or those that have become collision zones, such as the Himalaya–Tibet system, in which the collision is superimposed on an older accretionary complex in a *'subduction-to-collision'* orogen—and this has been the situation during at least the Cenozoic and Mesozoic Eras (Liou et al., 2004). The distinction is useful because some accretionary orogenic systems exist for hundreds of millions of years without overprinting by collision, although they may have the continuity of subduction interrupted—but not necessarily terminated—by ocean floor debris or an oceanic plateau or arc. That orogens may be composed of metamorphic belts that exhibit different sequences of metamorphic facies with increasing metamorphic grade in relation to tectonic setting is well established (Miyashiro, 1961), and these paired metamorphic belts result from juxtaposition of terranes with different metamorphic facies series (Brown, 1998, 2002).

In the past twenty-five years we have extended our understanding of how extreme may be the temperatures and pressures of metamorphism retrieved from crustal rocks. Temperatures >1,000 °C at pressures around 1 GPa have been retrieved from rocks of the granulite facies [ultrahigh temperature granulite metamorphism (G-UHTM); Harley, 2004], whereas other rocks at eclogite facies preserve evidence of pressures up to at least 5 GPa at temperatures of 600–1,000 °C [ultrahigh pressure metamorphism (UHPM); Chopin, 2003]. Also, we now recognize a transition between these two facies, referred to as medium-temperature eclogite–high-pressure granulite metamorphism (E–HPGM; O'Brien and Rötzler, 2003). These different types of extreme metamorphism are generated in different plate tectonic settings with contrasting thermal regimes.

PHANEROZOIC METAMORPHISM

Modern metamorphism

Metamorphism during the Cenozoic and Mesozoic Eras has taken place at: divergent plate boundaries, where newly generated oceanic crust is metamorphosed following hydrothermal circulation of sea water; convergent plate boundaries, where subduction or subduction followed by collision takes crustal rocks deep into the mantle during orogenesis, and where orogenic plateaus may be developed in the hinterland; and, at plate boundaries that involve mainly lateral displacement.

Rocks of the blueschist–eclogite facies series [lower temperature–higher pressure (LT–HP) metamorphism] are created in the subduction zone. We know this from samples of glaucophane schist entrained in serpentine mud volcanoes in the Mariana forearc, where incipient blueschists with lawsonite-pumpellyite-hematite yield T of 150–250 °C at P of 0.5–0.6 GPa (Maekawa et al., 1993) and dT/dP of 300–400 °C/GPa (approximately equivalent to 9–11 °C/km). These results are consistent with thermal models for active subduction zones and apparent thermal gradients retrieved from Eocene low-grade blueschists facies series rocks (Potel et al., 2006). Lawsonite blueschist–eclogite metamorphism (HPM) and UHPM rocks register deep subduction and exhumation of continental lithosphere during the early stage of collision. We know this from samples of coesite-bearing eclogite of Eocene age at Tso Morari in the Himalayas (Leech et al., 2005) and Pliocene age in Eastern Papua New Guinea (Baldwin et al., 2005), where the minimum P must exceed 2.7 GPa at moderate T for coesite to occur.

Granulites [higher temperature–lower pressure (HT–LP) metamorphism] are scavenged from the deeper parts of Mesozoic oceanic plateaus (Gregoire et al., 1994) and occur in exposed middle-to-lower crust of young continental arcs (Lucassen and Franz, 1996). Although the interpretation is contentious, metapelitic xenoliths retrieved from Neogene volcanoes in central Mexico (Hayob et al., 1989) and at El Joyazo in south-east Spain (Cesare and Gomez-Pugnaire, 2001) have been argued to record evidence of Cenozoic G-UHTM, and evidence of melt-related processes in garnet granulite xenoliths from Kilbourne Hole, Rio Grande Rift, suggests contemporary G-UHTM in the lower crust of rifts (Scherer et al., 1997). Modern continental backarcs are hot with uniformly thin and weak lithosphere over considerable widths (Hyndman et al., 2005). They represent an inevitable locus of deformation and an environment suitable for granulite metamorphism, particularly during terrane accretion and/or subduction-to-collision orogenesis. Thus, I infer that granulites are being generated today under orogenic plateaus, such as Tibet and the Altiplano, based on the inference of mica breakdown melting derived from interpretations of multiple geophysical data sets (Schilling and Partzsch, 2001). In some tectonically-active continental regions, extension has contributed to the thermal budget; this would be evidenced in rocks that experienced a similar history by a high-T decompression segment in a clockwise P-T-t path (cf. Harley, 2004).

The modern plate tectonics regime is characterized by a duality of thermal regimes in which two principal types of regional-scale metamorphic belts are being formed. This duality is the hallmark of plate tectonics. The characteristic imprint of plate tectonics in the rock record is the contemporaneous occurrence of two contrasting types of metamorphism reflecting this duality of thermal regimes. The first is characterized by low dT/dP, registered by LT–HP metamorphism, corresponding to the subduction zone. The second is characterized by high dT/dP, registered by HT–LP metamorphism, corresponding to the arc–backarc system. Complexity is imposed by phases of extension–contraction, terrane accretion and collision.

Older metamorphism

The oceanic lithosphere is <200 Ma old. A plethora of papers since the 1968 plate tectonics revolution suggests that we may reasonably extrapolate back through one or two ocean lithosphere cycles. Thus, we may expect similar tectonics since the last stages of Gondwana amalgamation at the dawn of the Phanerozoic Eon.

Metamorphism in extensional–contractional accretionary orogenic systems, such as the Paleozoic Lachlan Belt of Australia, is dominated by HT–LP metamorphism, with close-to-isobaric clockwise (CW) or counter-clockwise (CCW) hairpin P–T–t paths. G-UHTM, E-HPGM and UHPM rocks are absent at outcrop, although blueschists may occur intermittently early in the orogenic cycle. Short-lived phases of orogenesis correspond to interruptions in the continuity of subduction caused by topographic features on the ocean plate (Collins, 2002).

In terrane accretion orogenic systems, paired metamorphic belts are characteristic due to orogen-parallel terrane migration and juxtaposition by accretion of contemporary belts of contrasting type (Brown, 1998, 2002), with a LT–HP metamorphic belt outboard and a HT–LP metamorphic belt inboard, exemplified by the Paleozoic–Mesozoic metamorphic belts of the western U.S. (Patrick and Day, 1995). In some systems an important additional feature was ridge subduction, which is reflected in both the pattern of HT–LP metamorphism and the associated magmatism (Brown, 1998). Granulites may occur at the highest grade of metamorphism in the HT–LP belt, but UHPM rocks generally appear to be absent in the outboard LT–HP belt.

In subduction-to-collisional orogenic systems, subduction may generate HPM-UHPM of continental materials until the subduction zone is choked, as exemplified by the Caledonian, Variscan and Dabie-Sulu orogenic systems (Liou et al., 2004). Deformation of the continental backarc may generate CW or CCW metamorphic P–T–t paths in granulite facies series rocks, according to the mechanisms and relative rates of thickening and thinning versus heat transfer by conduction and advection.

Each of these Phanerozoic orogenic systems preserves contrasting metamorphic belts that may be inferred to record different thermal regimes, consistent with the premise that plate tectonics may be extrapolated back to the Neoproterozoic.

METAMORPHIC REGIMES THROUGH EARTH HISTORY

Figure 1 is a plot of metamorphic belts classified by type, based on the maximum P–T conditions and age associated with these conditions for each belt (data from Brown, 2006). Different apparent thermal gradients are implied by each type of metamorphism. These are: HPM-UHPM metamorphism, which has apparent thermal gradients of 150–350 °C/GPa (approximately equivalent to 4–10 °C/km); E-HPGM, which has apparent thermal gradients of 350–750 °C/GPa (10–20 °C/km); and, G-UHTM, which has apparent thermal gradients >>750 °C/GPa (>>20 °C/km). The gradients are inferred to reflect different tectonic settings.

The distribution of these types of metamorphism throughout Earth history is displayed in Fig. 2. Changes in the metamorphic record broadly coincide with the transitions from the Archean to Proterozoic and Proterozoic to Phanerozoic Eons. 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 might imply a different style of tectonics in the Archean Eon in comparison with the Proterozoic and Phanerozoic Eons.

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. The data in Fig. 2 plot in particular periods, and there is a clear distinction between the Archean, where the data are minimal, and the Proterozoic and Phanerozoic, where the data are abundant, and between the pre-Neoproterozoic, where UHPM does not occur, and Neoproterozopic and younger belts, where UHPM is common. These observations are inconsistent with a progressively degraded record with increasing age. However, it is likely that some Phanerozoic G-UHTM rocks have not yet been exposed at Earth's surface, leading to bias in the younger part of the record. Extrapolation back in time also raises questions about partial-to-complete overprinting by younger events. Our ability to recognize the effects of overprinting and to ‘see through’ them has improved significantly with better technical capabilities for rapid chemical mapping of mineral grains and high spatial resolution in situ geochronology. Overprinting has been avoided in compiling the dataset used for this analysis (Brown, 2006).

The data in Figs. 1 and 2 provide a set of compelling first-order observations, although patterns based on first occurrences may be challenged by new discoveries. Based on the age distribution of metamorphic belts that record extreme P-T conditions, the modern era of cold subduction began in the Neoproterozoic, registered by the occurrence of UHP-UHPM. However, cold subduction alone is not the hallmark of plate tectonics. In contrast, G-UHTM and E- HPGM occur back to the Neoarchaean, registering a duality of thermal regimes, which is the hallmark of plate tectonics. Evidence of plate tectonics is present in the Neoarchean rock record, and this may manifest the beginning plate tectonics on Earth.

High-pressure to ultrahigh-pressure (HPM-UHPM) metamorphism

Blueschist belts appear for the first time in the Neoproterozoic Era, where two examples, the Aksu Group, China, and inliers of the Anti-Atlas belt, Morocco, are overlain by sediments of Ediacaran age (Maruyama et al., 1996). HPM-UHPM has been chronicled during multiple periods: the Edicaran; the Cambrian; the Ordovician-Silurian; the Devonian; the Permo-Triassic; the Lower Cretaceous; through the Cenozoic Era; and, Earth's youngest UHPM rocks of Miocene-Pliocene age in eastern Papua New Guinea. P–T–t paths from UHPM terranes vary from hairpins, in which the exhumation path is close to the burial path in terms of dT/dP, and in the range 150–350 °C/GPa (4–10 °C/km), implying syn-subduction exhumation, to CW paths with decompression segments to Barrovian-type thermal regimes of 350–750 °C/GPa (10–20 °C/km), consistent with thermal relaxation after initial fast exhumation to Moho depths.

Medium-temperature eclogite–high-pressure granulite metamorphism (E-HPGM)

There are about fifty documented terranes of this type, with approximately equal numbers of Proterozoic and Phanerozoic examples, although the Phanerozoic examples are dominated by various segments of the European Variscides. About one-third of high-pressure granulite belts have evolved from medium-temperature eclogite facies assemblages, and about one-quarter of the remainder evolved into UHTM conditions, both without distinction between Proterozoic and Phanerozoic examples. Periods of E-HPGM coincide with the first formation of supercratons (Superior/Sclavia) and the Nuna, Rodinia and Gondwana supercontinent cycles, and also occur in the Lower Paleozoic Caledonides and Variscides. E-HPGM is rare in the exposed post-Carboniferous rock record, but this may reflect lack of complete exhumation of young examples.

Ultrahigh-temperature granulite metamorphism (G-UHTM)

G-UHTM is dominantly a Neoarchean to Cambrian phenomenon documented during four distinct periods in Earth history (Fig. 2): the Neoarchean; the Orosirian; the Ectasian to Stenian; and, the Ediacaran to Lower Cambrian. There is only one confirmed example of G-UHTM older than Neoarchean, which is the Voronezh Crystalline Massif of Sarmetia (ca. 3.2 Ga in age). G-UHTM is rare in the exposed post-Cambrian rock record, but may be inferred for the lower crust of large Cenozoic orogenic systems as discussed above. In the Phanerozoic Eon, parts of the European Variscides evolve from E-HPGM to G-UHTM, but there is only one confirmed example of G-UHTM younger than Paleozoic exposed at Earth's surface, which is the Gruf Unit in the central Alps (ca. 33 Ma in age). The four main periods of G-UHTM show a remarkable coincidence with the first formation of supercratons (Superior/Sclavia) and the supercontinent cycle (Nuna, Rodinia and Gondwana).

Archean metamorphism

The Eoarchean through Mesoarchean rock record, particularly the greenstone belts, records P–T conditions characteristic of low-to-moderate-P–moderate-to-high-T metamorphic facies [the ca. 3,800 Ma metamorphism recorded by the Isua Supracrustal Belt of southern West Greenland, Komiya et al. (2002); and, the ca. 3,230 Ma metamorphism recorded in the Barberton and related greenstone belts of South Africa, Diener et al. (2006)]. Apparent thermal gradients were around 750 °C/GPa (~20 °C/km)—consistent with generally thinner lithosphere during the Archean. Although granulites are common throughout the Archean Eon, extreme thermal conditions typical of G-UHTM generally are not documented before the Neoarchean. Furthermore, blueschists are not documented and there is no metamorphic imprint of subduction of continental crust into the mantle. 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 was operating to take basalt and other supracrustal materials into the mantle by the Neoarchean Era (Jacob, 2004).

INFERENCES AND IMPLICATIONS

The rock record indicates a dramatic change in the thermal regimes of crustal metamorphism through the Neoarchean, which may register the switch from an Archean mode of tectonics to a '*Proterozoic plate tectonics*' regime. The premise is consistent with aggregation of the 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. This resulted in stabilized lithosphere in which cratons form cores of continents that subsequently grew dominantly by marginal accretion. The change coincides with the first occurrence of ophiolite-like complexes in Proterozoic suture zones (Moores, 2002) and with the increase in $\delta^{18}O$ of magmas through the Paleoproterozoic (Valley et al., 2005). Although the style of Proterozoic subduction remains cryptic, the change in tectonic mode whereby interactions between discrete lithospheric plates generated settings with contrasting thermal regimes was a landmark event in Earth history.

The concentration of most exposed G-UHTM belts in the interval Neoarchean to Cambrian, and their broad correlation in time with amalgamation of continental crust into supercratons and supercontinents, suggests that G-UHTM may record closure and thickening of continental backarcs with their characteristic high heat flow (Hyndman et al., 2005). The thermal regime of E-HPGM [350–750 °C/GPa (~10–20 °C/km)] and maximum pressures of metamorphism suggest that crustal rocks have been taken to mantle depths during subduction-to-collision orogenesis. However, given the contrasting metamorphic record of the Proterozoic versus the Phanerozoic, where HPM-UHPM became common, I agree with Stern (2005) that cold subduction did not commence before the Neoproterozoic Era.

The transition to the '*modern plate tectonics'* regime through the Neoproterozoic is one in which ocean crust became thinner whereas the lithosphere became thicker (Moores, 2002), and the anastomosing pattern of Brasiliano–Pan-African orogens that created Gondwana was replaced by semi-circumferential large-scale plate-margin orogens (e.g., the Terra Australis, Caledonide and Tethyan orogens). These features may indicate a change to a smaller number of plates, perhaps reflecting a fundamental change in the pattern of mantle convection that led to a sharp decrease in the thermal gradient of subduction zone metamorphism and facilitated deeper subduction of continental crust during the Phanerozoic.

CONCLUSIONS

I propose that the hallmark of plate tectonics is the development of two contrasting thermal regimes where plates converge—on modern Earth these are the subduction zone and the arc–backarc system, respectively. The first imprint of this hallmark in the rock record is the appearance of contemporaneous contrasting types of metamorphism, viz. E-HPGM and G-

UHTM, in Neoarchean belts. I propose a common genesis for E-HPGM and G-UHTM in former subduction zones (subduction-to-collision orogens) and arcs–backarcs, particularly continental backarcs, as far back as the Neoarchean. Plate tectonics has operated on Earth since the Neoarchean. This model may be changed with new findings and acquisition of new data, and there are inevitably local details of relative age and spatial location that are obscured by generalizing at a global scale. A pre-Neoarchean tectonics regime may have involved plates, but if so these were probably thin with an ultramafic crust (Davies, 2006); if contrasting thermal regimes were generated, they do not appear to be preserved in the record of metamorphism.

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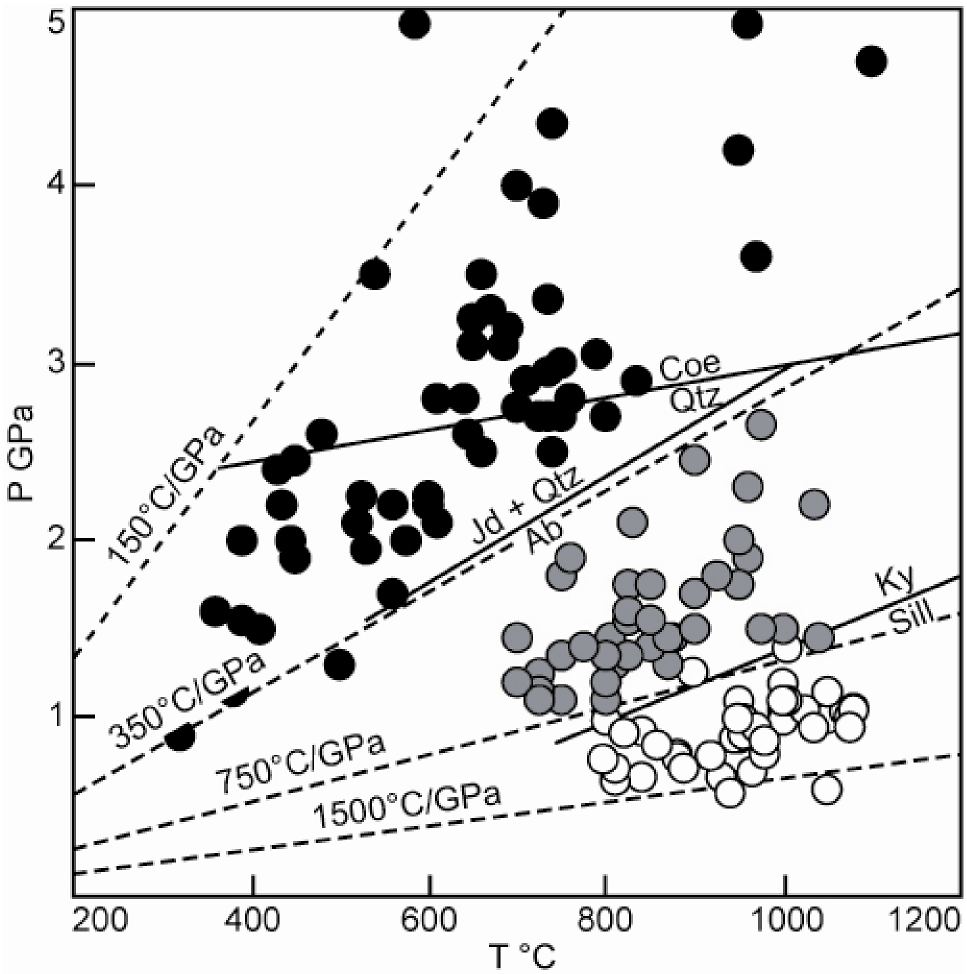

Figure 1. Metamorphic patterns based on representative P-T data by belt in relation to apparent thermal gradients; open circles – G-UHTM belts (P at maximum T), gray circles – E-HPGM belts (peak P-T), and filled circles –HPM-UHPM belts (T at maximum P).

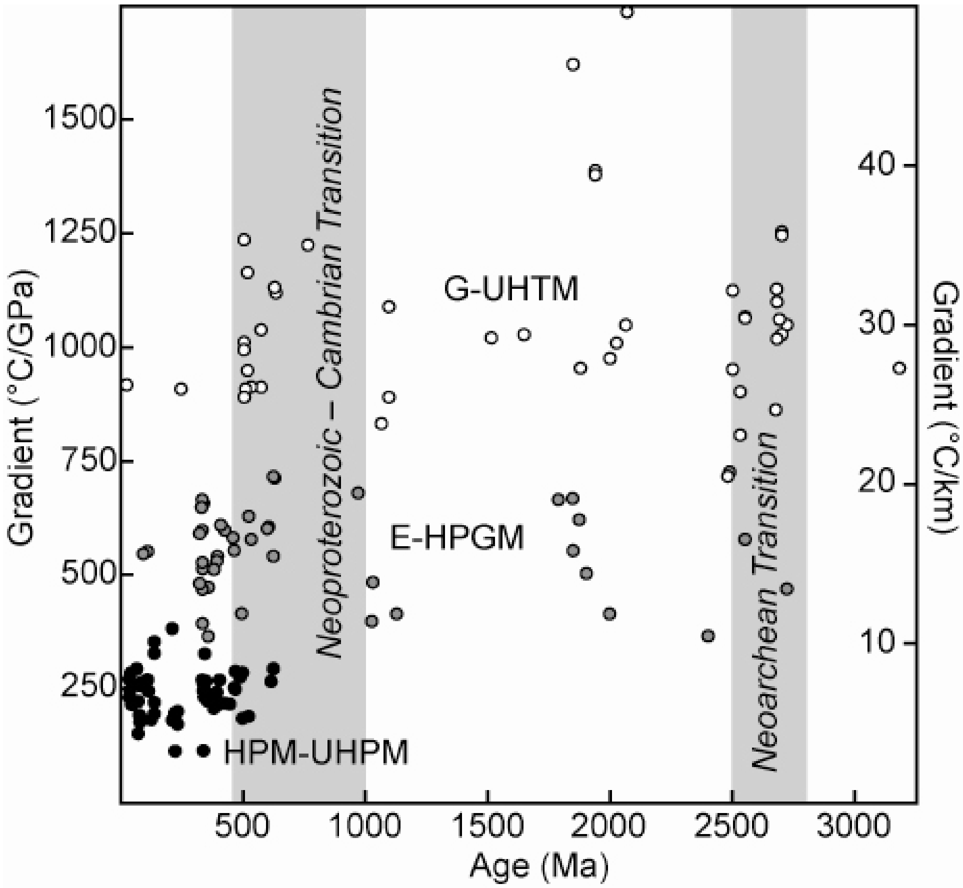

Figure 2. Plot of apparent thermal gradients by belt versus age of peak P-T, for the three main types of metamorphic belt; open circles – G-UHTM belts, gray circles – E-HPGM belts, and filled circles – HPM-UHPM belts.