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Metamorphism and the evolution of subduction on Earth

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ABSTRACT

Subduction is a component of plate tectonics, which is widely accepted as having operated in a manner similar to the present-day back through the Phanerozoic Eon. However, whether Earth always had plate tectonics or, if not, when and how a globally-linked network of narrow plate boundaries emerged are matters of ongoing debate. Earth's mantle may have been as much as 200–300 ºC warmer in the Mesoarchean compared to the present day, which potentially required an alternative tectonic regime during part or all of the Archean Eon. Here we use a dataset of the pressure (*P*), temperature (*T*) and age of metamorphic rocks from 564 localities that vary in age from the Mesoarchean to the Cenozoic to evaluate the petrogenesis and secular change of metamorphic rocks associated with subduction and collisional orogenesis at convergent plate boundaries. Based on thermobaric ratio (*T*/*P*), metamorphic rocks are classified into three natural groups: high T/P type (*T/P* >775°C/GPa, mean *T/P* ~1105°C/GPa), intermediate T/P type (*T/P* between 775 and 375°C/GPa, mean *T/P* ~575°C/GPa), and low T/P type (*T/P* <375°C/GPa, mean *T/P* ~255°C/GPa). With reference to published thermal models of active subduction, we show that low T/P oceanic metamorphic rocks preserving peak pressures >2.5 GPa equilibrated at *P*–*T* conditions similar to those modeled for the uppermost oceanic crust in a wide range of active subduction environments. By contrast, those that have peak pressures <2.2 GPa may require exhumation under relatively warm conditions, which may indicate subduction of young oceanic lithosphere or exhumation during the initial stages of subduction. However, low T/P oceanic metamorphic rocks with peak pressures of 2.5–2.2 GPa were exhumed from depths where, in models of active subduction, the slab and overriding plate change from being decoupled (at lower *P*) to coupled (at higher *P*), possibly suggesting a causal relationship. In relation to secular change, the widespread appearance of low T/P metamorphism in the Neoproterozoic represents a 'modern' style of cold collision and deep slab breakoff, whereas rare occurrences of low T/P metamorphism in the Paleoproterozoic may reveal atypical localized regions of cold collision. Low T/P metamorphism is not known from the Archean geological record, but the absence of blueschists in particular is unlikely to manifest secular change in the composition of the oceanic crust. In addition, the premise that the formation of lawsonite requires abnormally low thermal gradients and the postulate that oceanic subduction-related rocks register significantly lower maximum pressures than do continental subduction-related rocks, and imply different mechanisms of exhumation, are not supported. The widespread appearance of intermediate T/P and high T/P metamorphism at the beginning of the Neoarchean, and the subsequent development of a clear bimodality in tectono-thermal environments are

interpreted to be evidence of the stabilization of subduction during a transition to a globally-linked network of narrow plate boundaries and the emergence of plate tectonics.

INTRODUCTION

> "*Without hypotheses to test and prove or disprove, exploration tends to be haphazard and ill-directed. Even completely incorrect hypotheses may be very useful in directing investigation toward critical details.*" (Hess, 1954, p. 344)

As the plate tectonics revolution gathered steam during the 1960s, linking sea-floor spreading with transform faults and subduction, it evolved into a paradigm to describe the Cenozoic to Mesozoic tectonics of the lithosphere—the strong outer layer of Earth above the weaker asthenosphere. The theory of plate tectonics developed from geophysical studies of the ocean basins (Vine and Matthews, 1962; Wilson, 1965; McKenzie and Parker, 1967; Le Pichon, 1968, Morgan, 1968), which extend back in age only to the early Mesozoic, and was confirmed by seismology (Sykes, 1967; Isacks et al., 1968), which uses contemporary earthquake activity. The history of the plate tectonics revolution is covered in many books, but for a contemporary perspective the interested reader is referred to the book by Oreskes "*Plate tectonics: An insider's history of the modern theory of the Earth*" (2002), and for a very readable synthesis of the development of the theory of plate tectonics to the book by Livermore "*The tectonics plates are moving*" (2018). Plate tectonics has enabled us to understand recent recycling of the lithosphere and the geodynamics of the contemporary Earth, but has Earth always had plate tectonics?

Notwithstanding the absence of pre-Mesozoic ocean basins, plate tectonics is widely accepted as having operated in a manner similar to the present-day back through the Phanerozoic

Eon (e.g., Stern 2005, 2018). By contrast, applying this paradigm to the Precambrian has led to debate about when and how plate tectonics first emerged on Earth. This uncertainty occurs not only because plate tectonics destroys oceanic lithosphere—the critical evidence for its operation during the past 200 Ma—at convergent plate boundaries, leaving only imprints of plate boundary processes stored in the continents, but also because Earth's mantle was warmer in the past than at the present day, although by how much is controversial (Aulbach and Arndt, 2019a,b; Condie et al., 2016; Herzberg, 2019; Herzberg et al., 2010; Putirka, 2016). A warmer mantle may have required an alternative tectonic regime during part or all of the Archean Eon.

Despite a growing consensus that Earth had adopted plate tectonics by sometime in the late Archean (Brown, 2006; Sizova et al., 2010, van Hunen and Moyen, 2012; Cawood et al., 2018; Dhuime et al., 2018; Johnson et al., 2019), there are some who argue for plate tectonics as early as the Hadean (Hopkins et al., 2008; Harrison and Wielicki, 2016; Kusky et al., 2018), or at least for subduction at that time (Turner et al., 2014), consistent with the null hypothesis that plate tectonics was the principal mode of heat loss throughout Earth history (Korenaga, 2013, 2018; Foley, 2018). Conversely, there are others who argue against global modern-style subduction before the Neoproterozoic (Stern, 2005), requiring an alternative paradigm to plate tectonics for the Hadean to Mesoproterozoic interval (Stern, 2018). Although this divergence of views has existed for more than a decade, we have arguably not made much progress towards a resolution (Hawkesworth and Brown, 2018). One reason this has proven to be a difficult issue to resolve is that the evolution of mantle potential temperature (T_P) can be modelled adequately (Fig. 1) either in a plate tectonic regime with constant surface heat flow and low present-day Urey ratio or with a switch in heat-flow scaling at relatively low present-day Urey ratio from stagnant lid (lower heat flow) to plate tectonics (higher heat flow). A changeover from a stagnant lid regime to plate tectonics at 3 Ga or 2 Ga (Korenaga, 2013, 2017) is consistent with the mantle T_P data of Herzberg et al. (2010), but a changeover at 1 Ga, as argued by Stern (2018), is not (Fig. 1).

If plate tectonics has not been operative throughout Earth history, what preceded it? Rather than a plate tectonics or 'mobile lid' regime, which is governed by the relative motion of rigid plates of lithosphere, the early Earth may have been characterized by a 'stagnant lid' regime that consisted of a thick, deformable, more-or-less continuous 'squishy' lithosphere (Gerya, 2014; Johnson et al., 2014; Sizova et al., 2015; Rozel et al., 2017). This 'squishy' lithosphere may have experienced intermittent subduction, perhaps spontaneously or possibly driven by large impacts or mantle plumes, and may have undergone overturns leading to extensive resurfacing (Arndt and Davaille, 2013; O'Neill et al., 2007, 2017, 2018; Gerya et al., 2015; Sizova et al., 2015). For a warmer mantle, subducting slabs could have had a greater propensity to breakoff due to their different buoyancy structure (van Hunen and van den Berg, 2008; Sobolev and Brown, 2019).

The creation of a global network of narrow plate boundaries and its maintenance through time are critical conditions for a plate tectonic mode of geodynamics on any planet (Bercovici and Ricard, 2014; Lenardic, 2018). Conversely, localized regions of subduction that were not part of a network of narrow plate boundaries, such as exist on Venus, are not evidence for plate tectonics (Kaula and Phillips, 1981; Smrekar et al., 2018). Consequently, to argue that plate tectonics operated on the early Earth requires evidence of a (close to) global network of connected plate boundaries. Given the limited rock record available for the early Earth and the inherent preservation biases involved, it may simply not be possible to determine if early Earth had plate tectonics (Lenardic, 2018). Furthermore, Earth may have evolved into a plate tectonic regime sometime before sufficient evidence of its existence was retained in the global geological record. Thus, the geological record is only ever likely to provide a lower limit on the emergence of plate tectonics on Earth.

From a geological perspective, how to determine a minimum age for plate tectonics on Earth may be broken into several components (Cawood et al., 2018). For instance, when did the lithosphere first behave as a mosaic of plates—torsionally-rigid lithospheric fragments bounded by a network of narrow zones of plate divergence and generation, transform displacement or plate convergence and destruction? Related to this question, how far back in time can we identify independent horizontal motions between different cratons? These questions have been addressed recently by Cawood et al. (2018). Here we concentrate on the appearance of a linked network of relatively narrow plate boundaries, which is related to the secular evolution of subduction and should be evident from the record of crustal metamorphism.

The hallmarks of subduction are commonly considered to be the presence of arc magmatic rocks and low thermal gradient (low T/P) metamorphic rocks, such as blueschists and low-temperature eclogites (Brown, 2006; Pearce et al., 2008; Stern, 2005). However, the unambiguous identification of arc magmatism in the Archean rock record based mainly on trace element discrimination is potentially ambiguous and open to interpretation (e.g., Pearce et al., 2008; Pearce, 2014; Johnson et al., 2016, 2017; Smithies et al., 2018). Furthermore, with a few exceptions, low T/P metamorphic rocks are absent from the rock record before the late Tonian, and in reality it is a duality of thermobaric types of metamorphic that is the true hallmark of metamorphism related to convergent plate boundaries (Brown, 2006). We emphasize that it is the widespread imprint of these hallmarks that might identify the operation of plate tectonics, not simply isolated occurrences, no matter how certain the interpretation. In this study, our goal is to

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interrogate the rock record both to identify the oldest evidence of stable subduction of oceanic lithosphere and to assess secular change in the thermobaric ratios of metamorphism associated with convergent plate boundaries, focusing on orogenic sutures as they have the highest potential to preserve evidence of subduction in the rock record.

PLATE TECTONICS AND METAMORPHISM

In the 1970s the relationship between plate tectonics and metamorphism was addressed by Oxburgh and Turcotte (1971), Ernst (1971, 1973) and Miyashiro (1972, 1973), which placed Miyashiro's (1961) concept of paired metamorphic belts in a plate tectonics context. Earth's plate tectonics regime is characterized by asymmetric (one-sided) subduction of ocean lithosphere at convergent plate boundaries (Gerya et al., 2008). In this regime, the downgoing slab depresses isotherms creating a 'cool' metamorphic environment, whereas the breakdown of hydrous minerals generates fluids and melts that promote magma generation in the overlying mantle wedge leading to 'warm' conditions in the overriding plate. Plate motions lead to collisions between arcs, ribbon terranes and continents, sometimes involving ocean plateaus, preserving evidence of low T/P metamorphism in the suture, and creating thickened lithosphere to generate intermediate T/P metamorphism in the mountain belt and high T/P metamorphism in the hinterland or back-arc (Brown and Johnson, 2018; Hyndman, 2018).

The first evidence of blueschist facies metamorphism occurs in the Neoproterozoic (late Tonian; Xia et al., 2019; Yong et al., 2013), and this is commonly taken as one indicator of the beginning of the modern style of subduction and plate tectonics (Stern, 2005). However, on a warmer Earth prior to the Neoproterozoic, subduction and plate tectonics might have left a different imprint in the ancient rock record (e.g., Brown, 2006, 2007, 2014). Based on numerical models, it has been suggested that higher mantle temperatures in the past led to a different style of collision between continents, protocontinents and arcs, particularly in the late Archean–early Proterozoic (Chowdhury et al., 2017; Perchuk et al., 2018). Furthermore, weaker slabs could have led to more frequent breakoff, such that subduction might have been intermittent (van Hunen and van den Berg, 2008; Sizova et al., 2015), preventing subduction of continental crust to mantle depths (van Hunen and van den Berg, 2008; Sizova et al., 2014).

In reading the rock record, in addition to the effects of higher mantle T_P and crustal heat production, the role of preservation, the influence of sampling bias and the reliability of data gaps are other issues to consider. Because the geological record degrades back through time, we must also weigh regional (commonly older) versus global (commonly younger) datasets, and distinguish evidence for the localized initiation of subduction (e.g., Turner et al., 2014; Pearce, 2014) from intermittent or transient subduction (e.g., van Hunen and van den Berg, 2008; Moyen and van Hunen, 2012; Sizova et al., 2015) from present-day globally continuous subduction (Livermore, 2018).

In this article, we test an alternative to the null hypothesis that plate tectonics has always been the geodynamic mode on Earth, specifically that the stabilization of subduction and the emergence of plate tectonics across the globe had occurred by the Proterozoic but probably not much earlier. The transition is shown by the widespread occurrence of two contrasting types of metamorphism in the Neoarchean rock record, which may be evidence of a global distribution of dual thermobaric environments that are characteristic of subduction and plate tectonics at the present day (Brown and Johnson, 2018). This may have been a gradual process as a network of narrow plate boundaries spread across the globe, but appears to have been completed by the

Proterozoic when a distinct bimodality in thermobaric ratios began to appear in the crustal record of metamorphism.

CONTEXT

This article is based on content from the 2018 Mineralogical Society of America Presidential Address by the first author. However, it is important to note that it is the last in a series of three invited articles with a common backbone—a dataset of age and *P–T* conditions for several hundred localities that we consider to be representative of crustal metamorphism from the Neoarchean to the present day. The dataset also contains information from 11 localities prior to the Neoarchean, but there are too few of these from the limited relicts of pre-Neoarchean crust to be considered representative. In an Invited Centennial Article (Johnson and Brown, 2018), we used a dataset of 456 localities to investigate "*Secular change in metamorphism and the onset of global plate tectonics*". This was followed by the 51st Hallimond Lecture of the Mineralogical Society of Great Britain and Ireland (Brown and Johnson, 2019), where we used an enlarged dataset of 564 localities to assess "*Time's arrow, time's cycle: Granulite metamorphism and geodynamics*." In this final article of the series, we use the same dataset to evaluate key changes in the intensive variables of crustal metamorphism, particularly in relation to the appearance of dual tectono-thermal environments, and secular change in the evolution of subduction and collisional orogenesis since the Archean. We argue that is is the widespread appearance of dual tectono-thermal environments that is the critical evidence of a linked network of relatively narrow plate boundaries, which signifies the emergence of plate tectonics on Earth. Inevitably, there is some overlap between these articles, but each has a different orientation and goal, with the hope that the reader will find something novel and of interest in each.

METHODS AND DATA ANALYSIS

The thermal history of the crust is stored in the metamorphic rock record (Brown and Johnson, 2018, 2019). At the present day, different tectonic settings along convergent plate boundaries exhibit contrasts in heat flow that are registered as differing metamorphic facies series in distinct crustal terranes (Miyashiro, 1961; Brown, 1998, 2006, 2010). Based on an extensive review of the literature on crustal metamorphism up to the end of February 2018, we have created a dataset of T, P, thermobaric ratio (T/P), and age (t) of metamorphism for 564 localities from the Cenozoic to the Eoarchean, although before the Neoarchean Era data are sparse (Brown and Johnson, 2018; dataset update of 28 February 2018 (Supplementary Data Table 1)).

We have restricted the dataset to crustal protoliths, so we do not include data from orogenic peridotites or data based on ultrahigh-pressure minerals in chromitites associated with ophiolitic complexes and in mantle xenoliths. The principal outputs that we use are quantitative estimates of the pressure (P), temperature (T), and age of metamorphism—all three must be available for a particular sample or locality to be included in the dataset. Our analysis relies on an assumption that the close-to-peak mineral assemblages are robust recorders of P and T. For this reason, the initial studies were limited to rocks equilibrated under conditions of relatively high temperature, such as granulites and eclogites (Brown, 2007, 2014), which are difficult to retrogress or overprint without fluid influx. In these early studies, for high-temperature metamorphism at $P < 1$ GPa, a minimum temperature for inclusion was set at 700 ºC, whereas for high-pressure metamorphism at $T < 700$ ºC a minimum pressure of 1 GPa was applied to ensure a reasonable minimum temperature and the likelihood of an equilibrated peak mineral assemblage. In the data for the low T/P type metamorphism, a majority of the pressures are minima based on, for example, the presence of coesite relicts. Overall, about 30% of the low T/P metamorphic rocks in the dataset were interpreted to retain evidence of peak pressure whereas about 70% of the data represent the *P*–*T* conditions at the maximum pressure retrieved, and therefore are minima (Supplementary Data Table 1).

We are cognizant that as methods improve progressively lower grade metamorphic rocks may be incorporated in the dataset, providing a reliable age for the peak metamorphism is also available. Thus, in the current dataset we include seven localities with T <700 ºC in the high T/P type, eleven localities with P of 0.8–1.0 GPa in the intermediate T/P type, and one locality with P <1.0 GPa in the low T/P type. Of the 223 high T/P type data, two localities are from well-known regional-scale UHT contact metamorphic aureoles (Rogaland in southern Norway and Makhavinekh Lake in eastern Canada). In addition, in low T/P type metamorphic rocks overprinted during exhumation, mineral indicators of close-to-peak pressures, such as coesite or diamond, are commonly preserved as inclusions in rock-forming or accessory minerals, which has proven to be important for retrieving minimum *P*–*T* conditions from these rocks.

Thermobaric ratio is a more useful parameter than T or P because, on the contemporary Earth, each thermobaric type of metamorphism is associated with a particular plate tectonic setting. Insofar as metamorphic P can be translated to depth, the thermobaric ratio ($T/P \sim T/z$) can be viewed as a proxy for the transient geothermal gradient at the metamorphic peak. To highlight this relationship, discussions of earlier versions of this dataset (Brown, 2006, 2007, 2014; Brown and Johnson, 2018) used the term "apparent thermal gradient." However, as discussed more fully in Brown and Johnson (2019), we now prefer the term thermobaric ratio to avoid any possible confusion with the true geothermal gradient or the geotherm or the metamorphic field gradient. Using thermobaric ratio (*T/P*), metamorphic rocks are classified into three groups, which are based on the natural groups from Brown (2007) based on rock type (Fig. 2): high T/P type (>775 ºC/GPa, arithmetic mean ~1100 ºC/GPa; $n = 223$), including common and ultrahigh temperature (UHT) granulites; intermediate T/P type (775–375 ºC/GPa, arithmetic mean ~580 ºC/GPa; $n = 152$), including high pressure (HP) granulites and medium or high temperature (medium-T/high-T) eclogites; and, low T/P type (<375 ºC/GPa, arithmetic mean ~250 ºC/GPa; $n = 189$), including blueschists and low-temperature (low-T) eclogites, and ultrahigh pressure (UHP) metamorphic rocks.

Plots of *T* and *P* versus age are provided in Supplementary Figures 1 and 2[1], respectively; secular change in the *T* and *P* of metamorphism was discussed recently by Brown and Johnson (2019), and is not reiterated here. A histogram and probability density function (PDF) curve for the age of metamorphism for the 564 localities used in this study are provided in Supplementary Figure 3[1]. Such analysis demonstrates the close association between crustal metamorphism and the supercontinent cycle, which has been recognized for more than a decade (Brown, 2007).

In this study, we concentrate on the petrogenesis of low and intermediate T/P metamorphic rocks and their relationship to subduction at convergent plate boundaries and in collisional orogenesis. We begin by discussing whether the metamorphic conditions preserved by low T/P oceanic rocks correspond to subduction zone thermal gradients. We then critically assess two topical issues relating to subduction-related metamorphism: whether the formation of lawsonite requires abnormally low thermal gradients; and, whether oceanic subduction-related rocks register significantly lower maximum pressures than continental subduction-related rocks, and by implication had different mechanisms of exhumation. Finally, we discuss several key changes in crustal metamorphism through time that are revealed by a plot of *T/P* from metamorphic rocks grouped by type plotted against age (Fig. 3); these data are also shown on a series of four maps to demonstrate the spatial relationships between the different types of metamorphism (Supplementary Figure 4[1]). These are: (1) the widespread appearance of low *T*/*P* metamorphism during the Neoproterozoic, which is interpreted as evidence of cold collision and deep continental subduction; (2) the rare occurrence of low *T*/*P* metamorphism in the Paleoproterozoic, which may be evidence of atypical localized regions of cold collision; and, (3) the widespread appearance of dual high and intermediate T/P type metamorphism at the beginning of the Neoarchean, which may manifest the stabilization of subduction and the emergence of plate tectonics by the late Archean–early Proterozoic.

LOW T/P METAMORPHISM AND SUBDUCTION

If we are to use the *P*–*T* conditions retrieved from low T/P metamorphic rocks to understand tectonics, it is clearly important to know how these data relate to the *P*–*T* conditions associated with active subduction of oceanic lithosphere. However, it turns out that this is a controversial issue. In a recent study it was argued that "*(thermal) models (of subduction) predict temperatures that are on average colder than those recorded by exhumed rocks*", and further "*that exhumed high*-P *rocks provide a more accurate constraint on* P–T *conditions within subduction zones, and that those conditions may closely represent the subduction geotherm*" (Penniston-Dorland et al., 2015; note that these authors define the subduction geotherm as "*the* P–T *distribution along the subducting slab top*"). In addition, Penniston-Dorland et al. (2015) argued that the next generation of thermal models should more comprehensively incorporate all sources of heat, with a particular emphasis on shear heating as the most likely missing contribution to the heat budget. However, van Keken et al. (2018) have recently addressed this issue and have argued that the discrepancy between models and rocks is beyond what can be explained by inclusion in the models of additional sources of heat, such as shear heating. They find that the addition of reasonable amounts of shear heating leads to a temperature rise of <50ºC in the oceanic crust compared to models that exclude this heat source (cf. Abers et al., 2017; Maunder et al., 2018). Therefore, to explain the discrepancy these authors argued that "*typical blueschists and eclogites were exhumed preferentially under relatively warm conditions that occurred due to the subduction of young oceanic lithosphere or during the warmer initial stages of subduction*" (cf. Abers et al., 2017).

In their study, Penniston Dorland et al. (2015) did not distinguish between continental and oceanic low T/P metamorphic rocks. Nearly half of the low T/P metamorphic rocks for which we have *P–T* and age information are continental in origin (Supplementary Data Table[1]), and represent subduction of arc or continental ribbon terranes, or subduction of the leading edge of a continent during collisional orogenesis. Given the potential for slab breakoff as the buoyant continental crust it is subducted to mantle depths and its intrinsic higher heat production, it may not be reasonable to expect a relationship between the peak *P–T* conditions of continental rocks subsequently exhumed from mantle depths and the thermal gradients associated with active subduction of oceanic lithosphere.

To assess whether the peak *P–T* conditions retrieved from low T/P continental metamorphic rocks are consistent with those from low T/P oceanic metamorphic rocks, in Figure 4 we show a comparison between the thermal models of van Keken et al. (2018) for 56 present-day active subduction zones and peak *P–T* conditions of low T/P metamorphic rocks from this study (Supplementary Data Table[1]) separated into continental (n = 84) and oceanic (n = 105). There is reasonable correspondence between the metamorphic data and the range of modeled slab *P–T* paths for the uppermost oceanic crust, but the correspondence is not as good for those for the lowermost oceanic crust (Fig. 4a). Also, the correspondence is poor for the *P–T* conditions averaged over the oceanic crust for each model and the overlap is biased towards the warmer active subduction zones (Fig. 4b).

In Figure 4c and d we show a third degree (cubic) polynomial regression through each of the oceanic and continental data to facilitate a more appropriate comparison with the thermal models. There is a relatively poor correspondence between the regression through the *P–T* conditions retrieved from low T/P metamorphic rocks of continental affinity and the average *P–T* conditions of the 56 models for the uppermost oceanic crust (Fig. 4c). Unsurprisingly, consistent with the comparison between the data and the individual models, the correspondence is worse for the average of the 56 models of *P–T* conditions averaged over the oceanic crust (Fig. 4d). However, for low T/P metamorphic rocks of oceanic affinity, an *a priori* premise that they may closely represent the model subduction *P–T* paths might be plausible. Indeed, there is a striking similarity in shape between the regression through the *P–T* conditions retrieved from low T/P metamorphic rocks of oceanic affinity and the average *P–T* conditions of the 56 models for the uppermost oceanic crust, although the rock-based regression is offset to higher *T* (by ~100–150 ºC) and/or lower *P* (by ~0.5–1.0 GPa; Fig. 4c). This is significantly larger than the offset expected from the effects of shear heating (Van Keken et al., 2018; Abers et al., 2017; Maunder et al., 2018). As we might expect, the rock-based regression has larger offsets to higher *T* and/or lower *P* when compared with the average of the 56 models of *P–T* conditions averaged over the whole oceanic crust (Fig. 4d).

For low T/P metamorphic rocks of oceanic affinity, one simple interpretation of these relationships is that they were preferentially exhumed under warmer than average conditions and

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from the uppermost several kilometers of oceanic crust. However, the rare occurrence of eclogites with gabbro protoliths in some low T/P metamorphic terranes, such as the Ligurian meta-ophiolites, Italy (Piccardo et al., 2002), and the Zermatt-Saas ophiolite, Switzerland (Angiboust et al., 2009), may suggest that this interpretation does not apply to all low T/P metamorphic rocks of oceanic affinity.

We note that there are various factors that affect the slab temperature in the models, including the age and speed of the incoming plate, and the dip of the slab (Maunder et al., 2018). In the slab above the decoupling depth, slab temperature is dependent on the age, whereas below this depth slab temperature is dependent on the speed, with slower slabs being hotter; varying the decoupling depth from 40 to 100 km also has an effect of the temperatures in the slab crust (Maunder et al., 2018). Furthermore, within the topmost kilometer or two of the slab, faster slabs may have hotter tops due to more vigorous convection in the mantle wedge (Magni et al., 2014). Thus, the relationship between P–T data retrieved from exhumed low T/P metamorphic rocks and P–T paths determined from slabs in thermal models of subduction is not going to be straightforward.

The implication of the van Keken et al. (2018) study is that the discrepancy between the P–T conditions retrieved from rocks and those in the thermal models is that the former are anomalous and do not relate to steady-state subduction. However, do the retrieved P–T conditions represent the peak P–T conditions? Uncertainties associated with thermobarometry have been discussed in detail by Powell and Holland (2008). In general, we concur with Penniston-Dorland et al. (2015) that systematic errors in the P–T determinations are unlikely. However, we posit that the discrepancy may be related in part to underestimation of the peak pressure attained by low T/P metamorphic rocks. As discussed above, for the low T/P type metamorphism about 70% of the pressures are based on minima, for example, the presence of coesite relicts. Furthermore, in eclogites in particular, the mineral assemblages are commonly high-variance. Phase equilibrium modeling of such assemblages generally predicts large stability fields in which the abundance and composition of minerals show little change, features that do not permit tight constraints on either *P* or *T*. For similar reasons, the application of conventional thermobarometry to such rocks is also problematic. These problems have been discussed recently with respect to the intragranular coesite eclogites at Yangkou Bay in the Sulu belt, where it has been shown that *P*–*T* conditions were significantly underestimated in previous studies (Xia et al., 2018)—this may be true for other localities.

Leaving aside the discussion about possible underestimation of pressure, and taking the data at face value, oceanic low T/P metamorphic rocks with P_{max} < 2.2 GPa lie at pressures below a majority of the *P*–*T* paths for both uppermost oceanic crust and those averaged over the oceanic crust (Fig. 4), which means their *P*–*T* conditions are too 'warm' to have been formed and exhumed in most of the relatively 'cool' subduction environments active on Earth at the present day. However, rocks with P_{max} >2.5 GPa overlap the full range of *P*–*T* paths for the uppermost oceanic crust in Figure 4a, and could be evidence of exhumation related to a wide range of subduction zone tectono-thermal environments.

To address this possibility more fully, in Figure 5 we show a comparison between three exemplar thermal models for the top of the ocean crust that are representative of warm, intermediate and cold subduction, respectively, from initiation to 30 Ma (van Keken et al., 2018), together with peak *P*–*T* conditions of oceanic low T/P metamorphic rocks. Although all of the oceanic low T/P metamorphic rocks could be explained by preferential exhumation under relatively warm conditions (Fig. 5a), because all lie at *P*–*T* conditions within the slab (i.e. on *P*–*T* paths cooler than those shown for the top of the ocean crust in Fig. 5a), this is only a requirement for a minority of the data. This is demonstrated by Figures 5b and c, where only 30% of the data plot at $P < 2.2$ GPa and, therefore, lie at *P*–*T* conditions outside the slab for colder subduction (i.e. on *P*–*T* paths that are warmer than those shown for the top of the ocean crust). Another ~30% of the data, those at $P > 2.5$ GPa, could have been exhumed from the oceanic crust under any thermal conditions, because these data all lie at *P*–*T* conditions within the slab for all three exemplar thermal models, as shown in Figure 5 (i.e. on *P*–*T* paths that are cooler than those shown for the top of the ocean crust in all three examples).

The remaining ~40% of the data lie within a pressure range that corresponds to the assumed depth at which the behavior between the slab and the overriding plate and/or mantle wedge changes from decoupled (at lower *P*) to coupled (at higher *P*) in the thermal models of van Keken et al. (2018). At depths of 75 to 80 km, as the slab begins to couple with the overriding mantle of the wedge, corner flow draws hotter mantle from beneath the arc–backarc system into the wedge, warming the down going oceanic lithosphere. This correspondence suggests a possible relationship between the change from decoupling to coupling along the subduction interface and the exhumation of these intermediate pressure low T/P metamorphic rocks. Although the depth at which a subducting slab becomes coupled to the mantle wedge may depend on a variety of parameters, a depth of 70–80 km appears to be a robust result (Wada and Wang, 2009) and the correspondence is probably not simply a coincidence.

Lastly, we address the issue of secular cooling of the mantle. In Figure 6 we show a comparison between model slab *P*–*T* paths for the uppermost and lowermost oceanic crust from the thermal models of van Keken et al. (2018) for 56 present-day active subduction zones calculated for mantle T_P of 1350 ºC, 1420 ºC, 1500 ºC and 1570 ºC (P. Van Keken, January

2019, unpublished), and peak *P–T* conditions of low T/P metamorphic rocks. The temperature rise from the lowest to the highest mantle T_P varies with depth, being 10–50 ºC at 30 km, 20–70 ºC at 60 km, 90–130 ºC at 90 km and 80–120 ºC at 120 km for the uppermost oceanic crust (the rise is similar for the lowermost oceanic crust). Overall, there is no apparent relationship between the age of low T/P metamorphism of oceanic rocks and the range of subduction zone tectono-thermal environments that might reflect secular cooling. This may not be surprising since the decrease in average mantle T_P since the beginning of the Neoproterozoic—likely <100 ºC—approximates the probable range of mantle T_P (assumed to have been similar to the estimate of ~120 ºC for MORB; Herzberg et al., 2007). Furthermore, even at mantle T_P much higher than expected for the Neoproterozoic (1500 and 1570 ºC; Fig. 6 c,d), it remains difficult to explain oceanic low T/P metamorphic rocks with P_{max} < 2.2 GPa other than by preferential exhumation under relatively warm conditions that occurred due to the subduction of young oceanic lithosphere or during the warmer initial stages of subduction.

In addition to factors that affect the model results, any interpretation of large datasets leads to generalized conclusions, whereas a balance among different processes will be important in the evolution of specific examples. As Agard et al. (2009) have shown in relation to the exhumation of oceanic low T/P metamorphic rocks, while the exhumation of some may be related to warm subduction, the exhumation of others was more likely related to processes such as continental subduction or a modification of the convergence vector (e.g., the velocity and/or angle of subduction) across the subduction zone. Overall, how *P–T* data derived from exhumed metamorphic rocks might relate to the *P–T* conditions associated with active subduction of oceanic lithosphere is a complex issue that is likely to be debated for a while before any acceptable resolution is achieved.

WHY DO LOW T/P ROCKS ONLY APPEAR WIDELY IN THE GEOLOGICAL RECORD SINCE THE NEOPROTEROZOIC?

Figure 7 shows the global distribution of low T/P metamorphic rocks. With a few exceptions, these localities are younger than Tonian (<0.72 Ga) in age (Fig. 3; Supplementary Data Table[1]). Three main hypotheses have been proffered to explain why blueschists in particular are largely absent from the rock record prior to the late Neoproterozoic, but arguments for the absence of blueschists also apply to low T/P rocks in general.

In a landmark paper concerned with the production and preservation of blueschist and low-T eclogite facies metamorphic rocks, England and Richardson (1977) proposed that blueschist mineral assemblages were overprinted during exhumation and/or blueschists were removed from the rock record by erosion. These authors envisaged a thick wedge of cold sediments overlying oceanic lithosphere or a continental margin that was loaded during subduction and terminal collision. They argued that as pressure decreased due to erosion so thermal relaxation would lead to an increase in temperature for a time determined by the initial depth. For this type of P–T evolution of low T/P terrains, the increase in temperature will lead to the production of rocks with mineral assemblages characteristic of higher T/P greenschist, amphibolite or granulite facies. For a reasonable erosional time constant of 200 Ma, England and Richardson (1977) were able to show that blueschists would be expected at the surface at 50–100 Ma after the termination of subduction, and, furthermore, that continued erosion of such belts for several hundred million years would significantly reduce the probability of blueschist preservation.

Although the timescales of overprinting and complete loss by erosion are functions of assumptions made in the modeling, the predictions of the model are broadly supported by the observation that most Precambrian low T/P localities are represented by HP metamorphic rocks, commonly eclogites, within terranes that have been severely overprinted during exhumation (Carlson et al., 2007; Weller and St-Onge, 2017; Xu et al., 2018). This may imply that any blueschists that may have been produced were removed by erosion leaving behind only the strongly retrogressed medium-T/high-T eclogites.

As an alternative to removal by erosion, Brown (2006) postulated that secular cooling of the upper mantle led to increasingly stronger lithosphere that, by the late Tonian, enabled deep subduction of continents, deeper slab breakoff and formation and preservation of blueschists and low-T eclogites during collisional orogenesis. This hypothesis has been tested for a range of conditions using a 2-D petrological–thermomechanical numerical model (Sizova et al., 2012, 2014). Based on a series of experiments, Sizova et al. (2012, 2014) proposed that an increase of the ambient upper-mantle temperature to >80–100 ºC higher than the present-day value, corresponding to the early Neoproterozoic, leads to modes of collision that differ from the modern tectonic regime. In particular, dehydration of the subducting slab and high fluid pressure weaken the overriding plate, which undergoes extension associated with decompression partial melting of the mantle wedge. Early during the collision, conductive heating of the subducting slab by the hot asthenosphere of the wedge weakens the slab, causing shallow breakoff, which localizes at the ocean–continent transition at a depth of ~100 km. In these circumstances the formation and preservation of low T/P metamorphic rocks during collisional orogenesis does not occur, consistent with the geological record.

Recently it was proposed that sodic amphibole (and blueschists) became more prevalent, in particular since the late Precambrian, due to secular change in the composition of oceanic crust, which became less magnesian due to a decrease in mantle melting as a consequence of secular cooling (Palin and White, 2016). This hypothesis is based on the calculated *P–T* stability of sodic amphibole, which is stable in MgO-poor (≤11.2 wt%) compositions, but is not predicted to form in higher-MgO rocks under low thermal gradients (Palin and White, 2016). However, there is a wide range of basalt compositions in ancient greenstone belts, including more than half with MgO-poor (≤11.2 wt%) compositions (dataset of Condie et al., 2016; n = 3414 samples). If tectonic settings that could have generated low thermal gradients were widespread during the Precambrian, blueschists would be expected to have formed, although it remains an open question whether they would have been preserved and exhumed. Thus, if they formed, the absence of blueschists prior to the late Tonian is less likely due to an absence of suitable rock compositions and more likely due to a preservation/exhumation bias related to the change from warm to cold collisional orogenesis during the late Precambrian (Sizova et al., 2012, 2014).

We can further examine the possibility that rock compositions limit the appearance of low T/P mineral assemblages by using the metamorphic facies concept. This fundamental concept in petrology is based on the observation that, within a limited range of *P–T* conditions, there is an inevitable relation between the mineral assemblage and chemical composition of a rock—if we know the chemical composition of the protolith, we can predict the corresponding mineral assemblage at any *P–T* condition (Fyfe and Turner, 1966; Turner, 1968). This relationship between the range of possible chemical compositions and the set of predicted mineral assemblages is immutable.

Clearly, the the metamorphic facies concept cannot be affected by secular change in the composition of rocks. Thus, recent suggestions that secular change in the composition of shales, greywackes and basalts may limit the application of the metamorphic facies concept to rocks of Archean age (Nicoli and Dyck, 2018; Palin and Dyck, 2018) are misleading. Given knowledge of the range of protolith compositions, and applying quantitative metamorphic petrology, the facies concept allows us to predict what mineral assemblages will be stabilized under low T/P metamorphic conditions from the earlier rock record, particularly Archean greenstone belts. Such an approach would help us as a community to meet the challenge posed by Ganne et al. (2012) that the apparent scarcity of old blueschist facies series metamorphism is most likely due to a methodological problem in deciphering the *P–T* evolution within greenstone belts rather than a result of poor preservation or absence.

ARE RARE OCCURRENCES OF LOW T/P METAMORPHISM IN THE PALEOPROTEROZOIC EVIDENCE OF ATYPICAL LOCALIZED REGIONS OF COLD COLLISION OR SOMETHING MORE?

One notable feature of the Paleoproterozoic Era is the occurrence of several localities that record low *T/P* thermobaric ratios comparable to rocks preserved and exhumed in Phanerozoic collisional orogens (Fig. 3; Supplementary Data Table[1]). These data have been used to suggest that subduction-related processes similar to those active on the contemporary Earth may have been operative during the Paleoproterozoic Era (Ganne et al., 2012; Weller and St-Onge, 2017; Glassley et al., 2014; Xu et al., 2018). For example, the preferred geodynamic model for the early Palaeoproterozoic tectonic evolution of greenstone belts in the West African craton involves supracrustal rocks metamorphosed under low *T/P* conditions in an accretionary prism followed by extrusion by buoyancy flow during ongoing subduction (Ganne et al., 2012). Similarly, *P–T* conditions retrieved from an eclogite xenolith in Paleoproterozoic carbonatite at the western edge of the Trans North China orogen were used to argue for cold subduction as early as 1.8 Ga (Xu et al., 2018).

However, the similarity is particularly compelling in the case of the Trans-Hudson orogen, which has been considered as an ancient example of a Himalayan-type continental collision (St-Onge et al., 2006). In this interpretation, the upper plate comprises the Rae and North Atlantic cratons, which are sutured by various Paleoproterozoic belts (St-Onge et al., 2009), including the Nagsugtoqidian orogen in southern West Greenland, where low T/P metamorphic rocks have been retrieved from the suture of a continent–continent collision zone (Glassley et al., 2014). The lower plate is represented by the Superior craton on the southern side of the Trans-Hudson orogen in Canada. Therefore, the inferred Paleoproterozoic upper plate is considered to occupy the same position as south-east Asia in the Cenozoic prior to the collision of India with the Lhasa block along its southern margin. In this context, the low T/P eclogite in the Kovik tectonic window in the Trans-Hudson orogen is considered analogous to the non-coesite-bearing portions of the Tso Morari eclogite massif in the Himalayas (Weller and St-Onge, 2017).

There is a range of contemporary mantle T_P of ~120 ºC (Herzberg et al., 2007), which suggests that the mantle is not in an end-member thermally well-mixed regime, but may be closer to a thermal isolation regime, which is characteristic when a subduction zone girdle surrounds a supercontinent (Lenardic et al., 2011). Assuming a similar range of mantle T_P in the past, as suggested by the data shown in Fig. 1 (Supplementary Data Table[1]), then different styles of Proterozoic orogenic belt might be anticipated according to the variation in mantle T_P. For example, orogens related to closing of an internal ocean within the supercontinent subduction girdle would have been associated with higher mantle T_P, whereas those associated with elimination of a segment of an external ocean outside the supercontinent subduction girdle would have been associated with lower mantle T_P.

In this wider context, we consider the Paleoproterozoic localities that record low *T/P* thermobaric ratios could represent atypical localized regions on Earth where the style of subduction and collision was similar to modern tectonic environments, rather than being representative of the dominant subduction and collisional style prevalent during the Paleoproterozoic Era. For example, if the incoming oceanic lithosphere that was being subducted in these cases represented segments of an external ocean related to a supercraton, the subducting slabs could have been relatively old and cold, which would have skewed their thermal structure to low temperatures. Interestingly, in the interpretation of Pehrsson et al. (2013), for the Trans-Hudson orogen the upper plate cratons were derived from the supercraton Nunavutia whereas the lower plate Superior craton was derived from the supercraton Superia, suggesting the possibility of an old and cold superocean separating them that could have been subducted during the convergence and collision.This prediction will be tested over time. In addition, if more data of low T/P type are discovered from a wider range of localities from different Precambrian orogenic belts, these conclusions may need to be revisited.

OTHER ISSUES RELATED TO LOW T/P METAMORPHISM

Does the formation of lawsonite require abnormally low thermal gradients?

It has been argued that lawsonite-bearing low T/P type metamorphic rocks preserve evidence of very low temperature conditions in subduction zones, that is that their formation requires abnormally low thermal gradients of less than approximately 250 ºC/GPa (Tsujimori et al., 2006). Our analysis of *P–T* data from 189 localities with low T/P metamorphic rocks demonstrates that lawsonite-bearing metamorphic rocks (n = 45; 1 outlier excluded) have a mean *T/P* of 236 ± 64 (1σ) ºC/GPa, with a range of 155–357 ºC/GPa, whereas lawsonite-absent low T/P metamorphic rocks (n = 143) have a mean *T/P* of 260 ± 59 (1σ) ºC/GPa, with a range of *T/P* = 133–393 ºC/GPa (Fig. 8a). Thus, there is no significant difference in thermal gradients between Lws-bearing and Lws-absent metamorphic rocks. This outcome may not be surprising since lawsonite occurs in low T/P type metamorphic rocks of both continental and oceanic affinity (Supplementary Data Table[1]).

Based on phase equilibrium modeling, and assuming fluid-saturated conditions, lawsonite eclogite and blueschist are expected to be the dominant rock types that form during subduction of oceanic crust, and therefore it might be expected that they would be abundant in exhumed subduction complexes (Wei and Clarke, 2011). What then is the explanation for the relative scarcity of lawsonite in the rock record? There are multiple reasons. Since the quantity of H_2O required to saturated the phase assemblage increases into the lawsonite stability field (Weller et al., 2015, Fig. 6d), a low initial H_2O content in the protolith would have limited the amount of lawsonite in the mode, making it vulnerable to retrograde loss during exhumation, perhaps without leaving sufficient microstructural evidence of its former presence. The sparse abundance could also have been related to dehydration during subduction prior to reaching the lawsonite stability field, such that the rock became H_2O undersaturated, precluding the formation of lawsonite (Clarke et al., 2006). In addition, as shown in Figure 8a, the stability limit of lawsonite-bearing rocks has a steep slope in *P–T* space and any of these rocks that were exhumed along decompression *P–T* paths will likely be strongly retrogressed. Thus, in some cases, the scarcity of lawsonite may simply be due to extensive retrogression during exhumation (e.g. Zack et al., 2004). This is a common problem that affects many eclogites for which the exhumation *P*–*T* paths are not as cold as the prograde *P*–*T* paths and, in the case of rocks with lawsonite, breakdown will be accompanied by the release of a large amount of structurally-bound fluid to promote retrogression (Wei and Clarke, 2011).

Is there a difference in P_{max} between oceanic and continental low T/P metamorphic rocks?

Next we examine the postulate that oceanic subduction-related rocks record lower P_{max} (<2.3 GPa, Agard et al., 2009; <2.7 GPa, Erdman and Lee, 2014) than continental subduction-related rocks (>2.7 GPa) that may also have slightly higher prograde thermal gradients (Erdman and Lee, 2014), suggesting that the mechanism and pathways of their exhumation likely differ. Oceanic and continental low T/P metamorphic rocks yield a similar range of thermobaric ratios (Fig. 8b). A histogram of P_{max} values for oceanic low T/P metamorphic rocks (n = 104; 1 outlier excluded) and continental low T/P metamorphic rocks (n = 84) is shown in Figure 8c. This figure shows that there is very little difference in P_{max} values between oceanic and continental low T/P metamorphic rocks, which is confirmed by the mean P of 2.38 ± 0.88 (1σ) GPa with a range of P from 1.0 to 7.0 GPa for oceanic rocks compared to the mean P of 2.99 ± 1.04 (1σ) GPa with a range of P from 1.1 to 7.0 GPa for continental rocks. It is unclear whether these data inform us about general differences in exhumation processes in circumstances where the range of possible exhumation mechanisms is large (Agard et al., 2009; Kylander-Clark et al., 2012; Sizova et al., 2012; Hacker et al., 2013; Warren, 2013; Malusà et al., 2015).

WHEN AND HOW DID PLATE TECTONICS EMERGE ON EARTH?

"*. . . the existence of a local zone of tectonic divergence, lateral shear and/or convergence is not the same as the existence of plate tectonics . . . subduction is a component of plate tectonics but subduction does not constitute a plate tectonic planet.*" (Lenardic, 2018, p. 4).

There are two significant changes in the metamorphic record, discussed in reverse order. First, during the Neoproterozoic, low T/P metamorphism became widespread in the rock record, mostly preserved in sutures associated with late Neoproterozoic and Phanerozoic collisional orogens, particularly in Eurasia (Figs 3, 7). This change has been interpreted as evidence of an evolution to stronger slabs, deeper slab breakoff and colder collisional orogenesis related to secular cooling of the mantle (van Hunen and van den Berg, 2008; van Hunen and Allen, 2011; Sizova et al., 2014). More important to the discussion here is an earlier change, in the Neoarchean, when there was an appreciable increase in the number of localities where evidence of high or intermediate T/P metamorphism was preserved (Fig. 3; Supplementary Figure 4[1]). This change has been interpreted as evidence of the stabilization of subduction and widespread collisional orogenesis to create the supercratons (Brown and Johnson, 2019). Thus, the Neoarchean likely records the completion of a globally-linked network of narrow plate boundaries and the emergence of plate tectonics.

In addition to these two singular changes, there is a gradual secular evolution in the pressure of intermediate T/P metamorphism, which on average has increased by ~0.25 GPa from the Neoarchean to the Neoproterozoic (Supplementary Figure 2). This increase of pressure through time is consistent with the prediction by Rey and Coltice (2008) that elevation of collisional orogens is expected to have increased through the Proterozoic. In Figure 9a we show all *T/P* data for the period from 4.0 Ga to the present day, contoured for density. As the low T/P data swamp the Precambrian data in Figure 9a, we also show in Figure 9b the *T/P* data for the period from 4.0 Ga to 0.85 Ga, contoured for density. These plots emphasize the gradual evolution of bimodality in type of metamorphism during the Proterozoic, consistent with secular change in mantle T_P in a plate tectonics regime that emerged on Earth in the Neoarchean.

In Figure 10 we plot histograms of ages, probability density functions and cumulative smooth kernel density estimates for low T/P and intermediate T/P type metamorphism. These data clearly define three principal periods of activity increasing in magnitude from the first at >2.3 Ga, to the formation of Columbia at c. 2.2 to 1.8 Ga, to the breakup of Rodinia and the period of intense terrane tectonic activity since 0.8 Ga. These three periods of enhanced tectonic activity are separated first by the Palaeoproterozoic tectono-magmatic lull at 2.3–2.2 Ga (Spencer et al., 2018) and second by the boring billion from c. 1.8–1.7 to c. 0.8–0.7 Ga (Holland, 2006; Cawood and Hawkesworth, 2014).

Interestingly, the first (>2.3 Ga) period of enhanced tectonic activity follows a regional glaciation in the late Mesoarchean, evidence of which is preserved in South Africa (Young et al., 1998), and the rise of continents above sea level (Flament et al., 2008; Korenaga et al., 2017; Bindeman et al., 2018). In addition, the second (c. 2.2–1.8 Ga) and third (<0.8 Ga) periods of enhanced tectonic activity follow ‘snowball’ Earth glaciations at 2.45–2.22 Ga and 0.75–0.63 Ga, respectively (Gumsley et al., 2017; Hoffman, 2013; Hoffman and Schrag, 2002). Noting these correlations, Sobolev and Brown (2019) have proposed that major surface erosion events following snowball Earth glaciations increased the availability of sediment at continental edges to lubricate subduction, as indicated by the zircon oxygen isotope record (Spencer et al., 2014), which facilitated the Paleoproterozoic and Phanerozoic cycles of amplified plate tectonic activity leading to the formation of Columbia and, after the boring billion, the 'modern' regime of terrane tectonics (Fig. 10). Furthermore, these authors argued that the rise of continents above sea level and the availability of sediments at the newly exposed continental edges allowed plate tectonics to emerge in the Neoarchean.

The change to a plate tectonic regime was likely gradual (Condie, 2018) and was broadly related to secular cooling since the Mesoarchean (Sizova et al., 2010). How this transition occurred depends on the geodynamic regime that existed before the Neoarchean. Prior to 2.8 Ga the crust registers moderate thermobaric ratios in both 'high-grade' gneiss terranes and 'low-grade' greenstone belts, with only rare occurrences of high T/P metamorphism and sporadic examples of intermediate T/P metamorphism, although reliable quantitative data are limited. This pattern may be evidence of transient subduction without plate tectonics, for example in a squishy lithosphere tectono-magmatic regime in which occurrences of intermediate T/P metamorphism may represent a record of episodes of local subduction and plate collision (Sizova et al., 2015, 2018; Rozel et al., 2017). Another plausible tectonic activity in the Archean is a type of episodic lid overturn and resurfacing (O'Neill et al., 2007), where the oceanic lithosphere overturns are due to the special case of retreating large-scale subduction triggered by large impacts (O'Neill et al., 2017) or mantle plumes (Gerya et al., 2015). This type of retreating subduction could have formed regional cells with plate-like behavior complete with internal spreading and transform boundaries (Gerya et al., 2015). It is likely that the retreating slabs transported water into the upwelling asthenospheric mantle via the hydrated crust of the slabs, enabling a large volume of magma to be generated, which would have been an efficient way to have produced the early, more mafic continental crust. Multiple collisions between such cells could have formed protocontinents (Sobolev and Brown, 2019).

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Such a system of embryonic tectonic cells could have evolved naturally into a globally-linked network of narrow plate boundaries. Most likely this would have occurred after the rise of the early protocontinents and the development of significant topography (Rey et al., 2008) led to the accumulation of sediments at continental edges. The sediments provided lubrication for nascent subduction channels that would have formed as the protocontinents collapsed driven by their gravitational potential energy (Rey et al., 2014), assuming the underlying mantle lithosphere was sufficiently weak. Contemporary examples of this process are represented by the initiation of young subduction zones near Sulawesi in eastern Indonesia (Hall, 2019). In this manner, a global plate tectonics regime could have evolved from a retreating subduction regime. As plate tectonics emerged, the protocontinents amalgamated to produce the Neoarchean supercratons (Bleeker, 2003; Pehrsson et al., 2013), the breakup of which ultimately led to the formation of the supercontinent Columbia (Meert and Santosh, 2017).

What are the implications for recycling of continental crust in the past?

For the past several hundreds of millions of years, the rates of creation and destruction of continental crust have arguably been in balance at ~3.2 km^3/year, although it is also possible that more crust is being destroyed than created (Stern and Scholl, 2010). The volumetric estimate comprises ~56 vol.% subduction erosion, ~34 vol.% sediment subduction and ~10 vol.% subduction of continental crust beyond the point of no return in the mantle (and some crustal foundering). However, there is considerable uncertainty over the amount of continental crust lost during deep subduction and due to foundering.

The crustal record of metamorphism suggests a gradual evolution of bimodality in the tectono-thermal environments related to subduction and collision on Earth since the Neoarchean (Fig. 9). This evolution involved a secular increase in the pressure of intermediate T/P metamorphism since the Neoarchean, the limited occurrence of low T/P metamorphism in the rock record in the mid-Paleoproterozoic and the widespread appearance of low T/P metamorphism in the rock record since the late Tonian. In these circumstances it seems unlikely that the rate of destruction of continental crust would have remained approximately constant since the beginning of the Proterozoic, as argued by Scholl and von Huene (2010), since higher mantle T_P in the past would have led to shallower slab breakoff, and probably lower rates of subduction erosion and higher rates of crustal foundering (Sizova et al., 2014, 2015; Chowdhury et al., 2017; Perchuk et al., 2018).

It is more difficult still to determine the processes responsible for crustal destruction in the Archean, because the geodynamic regime is uncertain. Before the emergence of plate tectonics, crustal downwellings were probably random small-scale features (Gerya, 2014) and although crust was destroyed by a variety of processes (Johnson et al., 2014; Sizova et al., 2015) the rate of destruction appears to have been low. Based on geochemical modeling, Dhuime et al. (2012) identify a marked decrease in the rate of net crustal growth at c. 3 Ga that may be linked to the emergence of plate tectonics and the introduction of higher rates of crustal destruction. Even though plate tectonics had emerged by the late Neoarchean–early Proterozoic, collisional orogenesis was likely different than today and crustal recycling at these locations may have been achieved principally by peeling-off of dense lower continental crust and its return to the mantle (Chowdhury et al., 2017; Perchuk et al., 2018).

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Cawood and Hawkesworth (2019) have argued that the area of continental crust reached a dynamic equilibrium of ~40% of the Earth's surface by the Mesoarchean, although they argue for a crust that was more mafic in composition and thinner than the present day prior to the Neoarchean. Furthermore, these authors have proposed that integration of thickness and area data suggests continental volume increased from the Hadean to the mid-Paleoproterozoic, but remained relatively constant in area and thickness through the boring billion (c. 1.8–1.7 Ga to 0.8–0.7 Ga; Holland, 2006; Cawood and Hawkesworth, 2014). Then, in the mid-Neoproterozoic the rate of destruction began to exceed the rate of creation, perhaps due to increased rates of sediment subduction and subduction erosion related to the widespread appearance of low T/P metamorphism in the geological record.

CONCLUDING REMARKS

We finish by pointing out the principal shortcoming of our approach using the crustal record of metamorphism, which is clearly demonstrated by Figures 3 and 10. In common with other studies based on the continental rock record, the number of data available to us from before the Neoarchean are limited (Fig. 3) and, therefore, our summary of Earth's tectonic evolution only extends back to 3 Ga (Fig. 10). At present, the balance of geological evidence and the results of experiments run using numerical models of geodynamics indicate that subduction did not become stabilized until the late Mesoarchean, which, in turn allowed the emergence of plate tectonics by the late Archean–early Proterozoic. What is clear from the series of three articles we have written in the past year (Brown and Johnson, 2018, 2019, and this article) is that the overall pattern of the tectonic behavior of the Earth's lithosphere since the early Proterozoic is relatively well understood. What then are the priorities for future studies?

To better constrain the geodynamic regime in the early Earth, precedence should be given to recovery of *P*–*T*–age data from a much larger number of localities in the Archean continental nuclei, particularly from the crust that predates the Neoarchean. This is imperative if we are to understand the transition from whatever tectonic mode operated on Earth prior to plate tectonics. The continued development of internally-consistent thermodynamic datasets and advances in the activity–composition models for phases of interest (Holland et al., 2011; White et al., 2014; Green et al., 2016; Holland et al., 2018), combined with advances in petrochronology (Engi et al., 2017), has provided us with the tools to apply quantitative petrology to a wide range of rock compositions and metamorphic grades in both greenstone belts and TTG gneiss terrains. Thus, this goal can be realized within the next few years by targeted studies based on new fieldwork combined with the use of legacy samples scattered in rock collections worldwide.

A second important consideration is to test the hypothesis implicit in this article that the rare occurrence of low T/P metamorphism in the Paleoproterozoic is evidence of atypical localized regions of cold collision. The four localities described to date (Ganne et al., 2012; Weller and St-Onge, 2017; Glassley et al., 2014; Xu et al., 2018) are intriguing, but do they imply that the global metamorphic rock record is skewed by overprinting and erosion (England and Richardson, 1977), and that the 'modern' regime (Fig. 10) featuring deep continental subduction began in the Paleoproterozoic? Time will tell.

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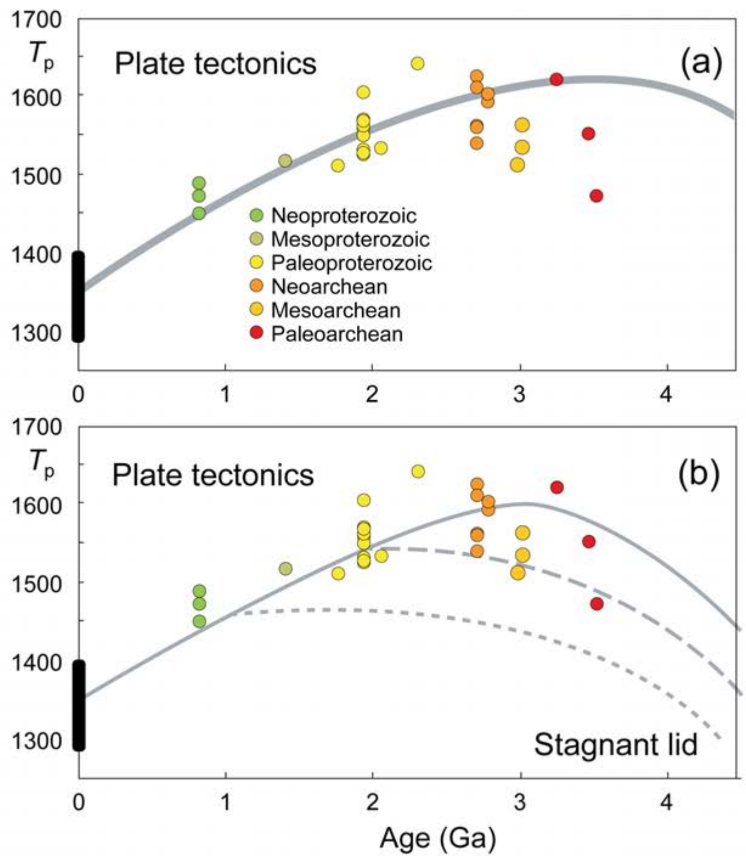
Endnote:

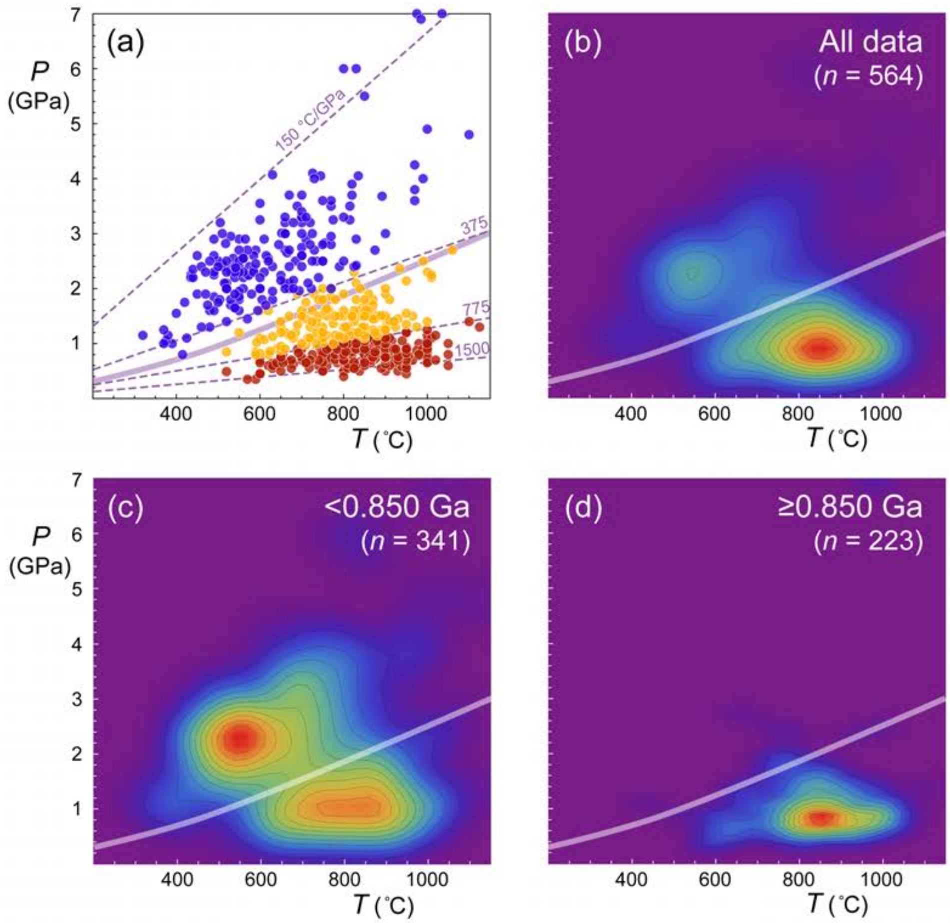
[1]Deposit item AM-19-?????, Supplemental Material. Deposit items are free to all readers and found on the MSA web site, via the specific issue's Table of Contents (go to http://www.minsocam.org/MSA/AmMin/TOC/2019/. . . . . data.html).



Brown & Johnson – Figure 1

1111

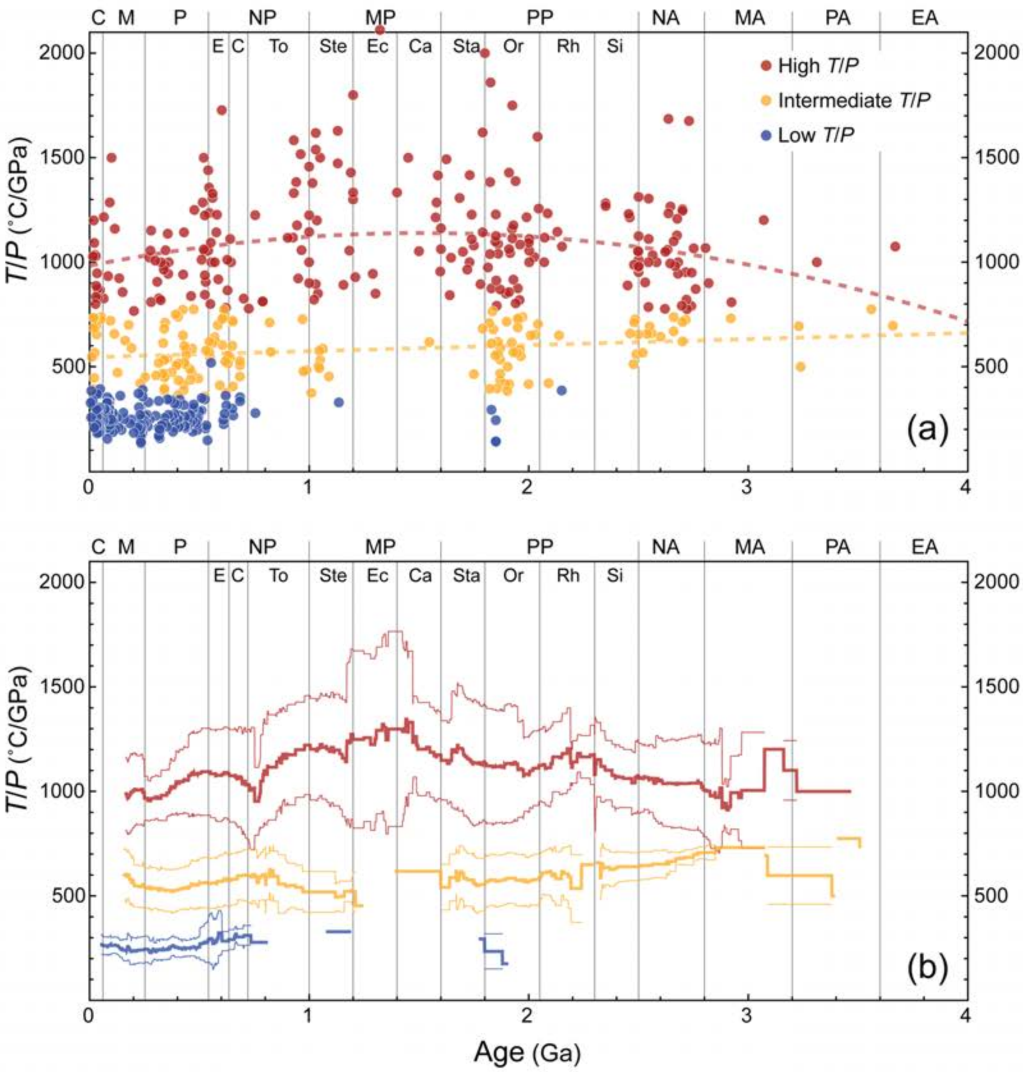
FIGURE 1. The evolution of mantle potential temperature (T_P) modelled with (a) constant surface heat flow and low present-day Urey ratio of 0.22 (after Korenaga, 2017) and (b) with a switch in heat-flow scaling and relatively low present-day Urey ratio of 0.35 from stagnant lid (lower heat flow) to plate tectonics (higher heat flow) at 3 Ga, 2 Ga or 1 Ga (after Korenaga, 2013). The TP data are taken from Herzberg et al. (2010), using the modified ages of Johnson et al. (2014).



Brown & Johnson – Figure 2

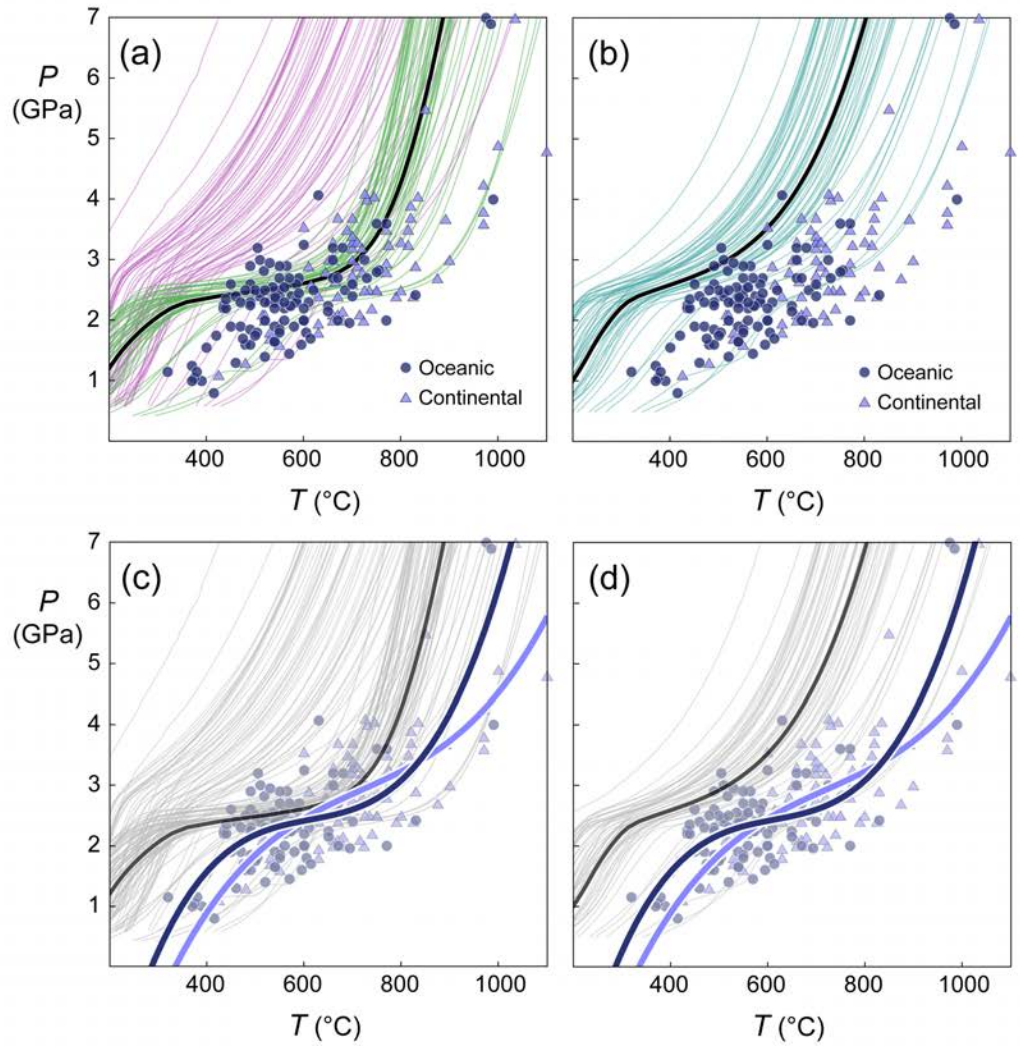
1118

FIGURE 2. Conditions of 'peak' metamorphism for 564 localities with robust pressure (*P*), temperature (*T*) and age (*t*) grouped by type (a), with the 'normal' geotherm from Stüwe (2007; thick dashed line) and representative thermal gradients (thin dashed lines). (a) Three types of metamorphism are distinguished based on thermobaric ratios (*T/P*), as follows: low T/P metamorphism in blue (n = 189), intermediate T/P metamorphism in orange (n = 152), and high T/P metamorphism in red (n = 223). (b) Shows a plot of all data contoured for density, (c) shows a plot of data <850 Ma in age contoured for density, and (d) shows a plot of data ≥850 Ma in age contoured for density. Note, the 'normal' geotherm only applies to the tectonic regime since 850 Ma; before that time the average crustal geotherm must have been hotter since all the data plot below the 'normal' geotherm. In this and subsequent figures, data were contoured for density using DensityPlot in Wolfram Mathematica.



Brown & Johnson – Figure 3

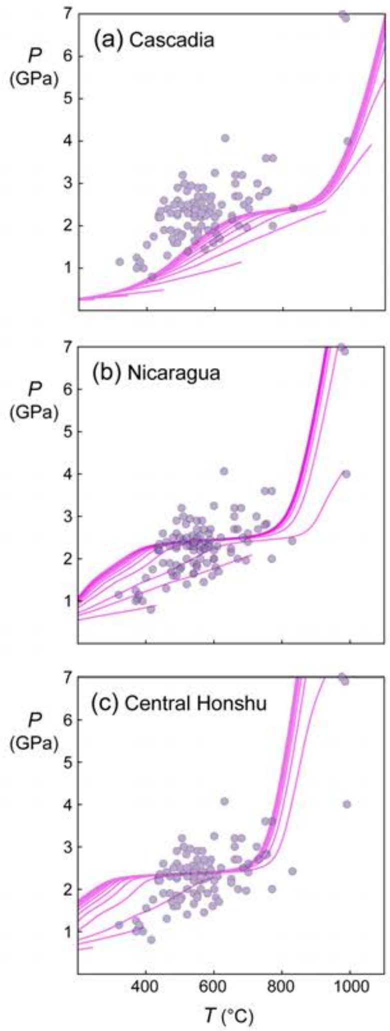
FIGURE 3. (a) Metamorphic thermobaric ratios (*T/P*) for 564 localities grouped by type plotted against age. The three types of metamorphism are high T/P in red, intermediate T/P in orange and low T/P in blue. The dashed lines show a second-order polynomial regression of the data for the high T/P (red) and a linear regression of the data for the intermediate T/P (orange) types, respectively. (b) Moving means (with one sigma uncertainty) of the thermobaric ratios (*T/P*) for high and intermediate T/P metamorphism calculated every 1 Myr within a moving 300 Myr window, and for low T/P metamorphism calculated every 1 Myr within a moving 100 Myr window.



Brown & Johnson – Figure 4

1141

FIGURE 4. Comparison between thermal models of Van Keken et al. (2011, as discussed in Van Keken et al., 2018; models without shear heating, n = 56) and peak P–T conditions of oceanic low T/P metamorphic rocks (n = 105). (a) Green lines are slab P–T paths for the uppermost oceanic crust (OC; 0.5 km below top of slab (black line is average of 56 models)) and magenta lines are lowermost OC (6.5 km into the OC). (b) P–T conditions averaged over the OC in each model (teal lines; black line is average of 56 models), i.e. this assumes the possibility of exhumation from any level in the oceanic crust. In (c) and (d), we show the same information as (a) and (b), but in greyscale, together with the third degree polynomial regression through each of the oceanic and continental data. Interpretation of this figure is discussed in more detail in the text.



Brown & Johnson – Figure 5

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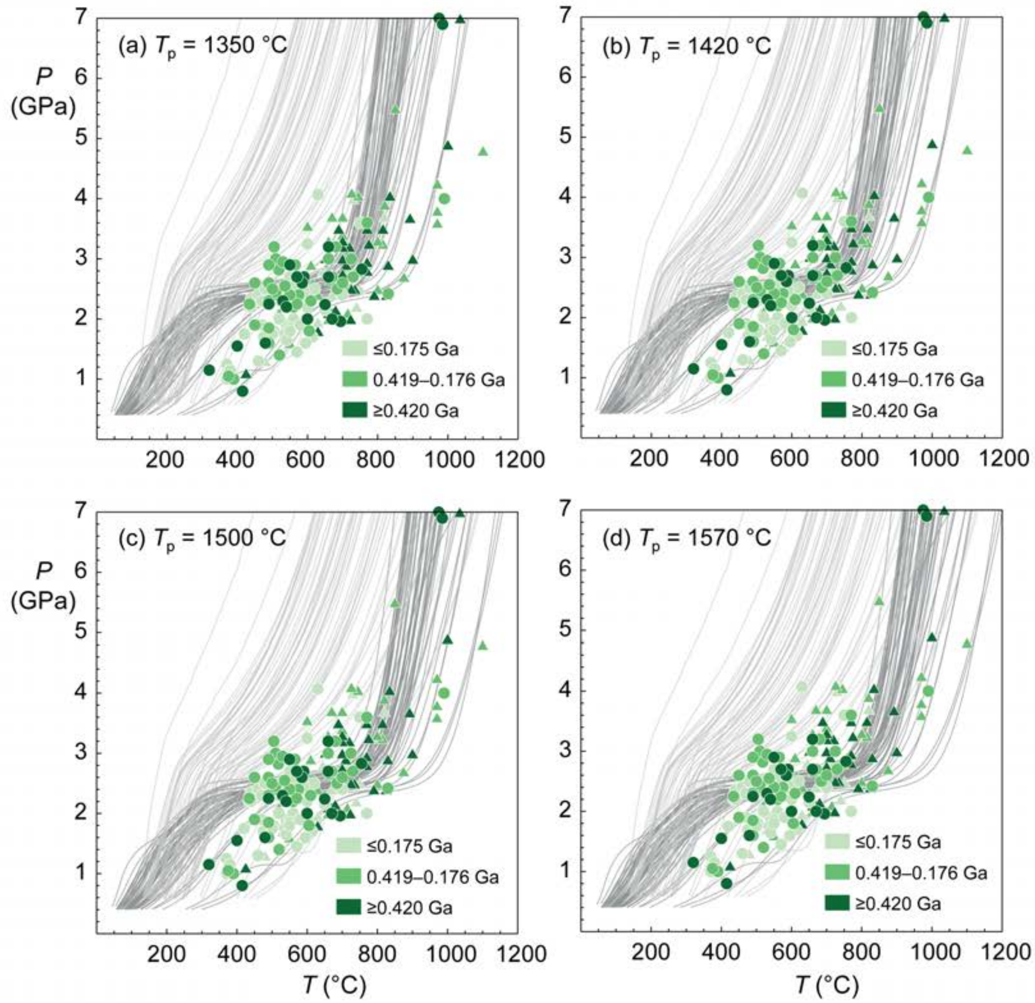
FIGURE 5. Peak metamorphic conditions of oceanic low T/P metamorphic rocks vs the thermal evolution of the top of the ocean crust for: a. the warm Cascadia, b. the intermediate Nicaragua, and c. the cold Central Honshu models of Van Keken et al. (2018; models without shear heating). From low *P*, the first two lines are for 1 and 2 Ma after subduction initiation, and thereafter the lines are for 3 to 30 Ma at 3 Ma intervals; each *P*–*T* path is limited to the *P* at the tip of the slab at each time instant.



Brown & Johnson – Figure 6

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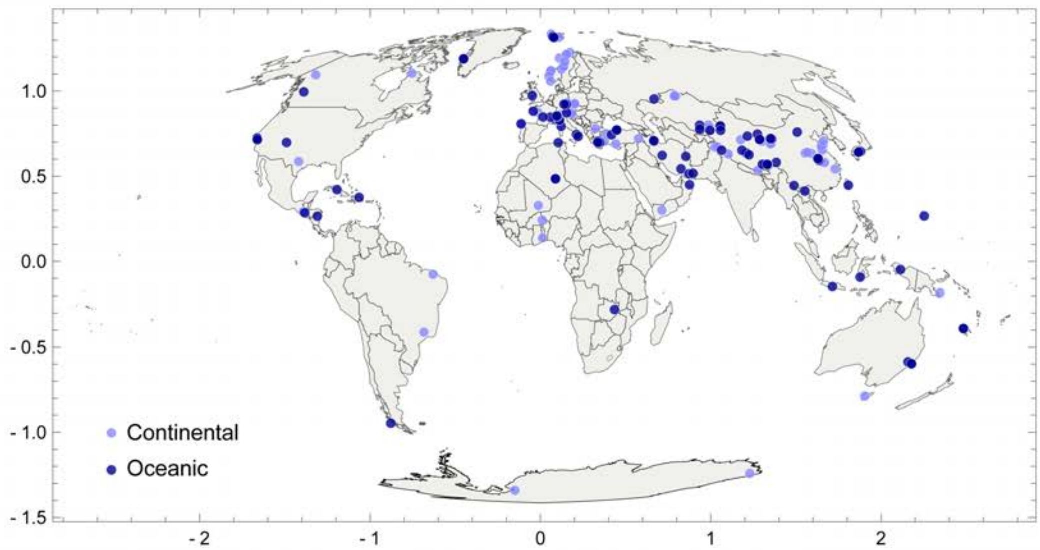
FIGURE 6. Comparison between thermal models of van Keken et al. (2011, as discussed in van Keken et al., 2018; models without shear heating, n = 56) for different mantle T_P of 1350 ºC (a), 1420 ºC (b), 1500 ºC (c) and 1570 ºC (d), and peak *P–T* conditions of low T/P metamorphic rocks (these thermal models at elevated T_P are unpublished and were provided by P. Van Keken as a personal communication, January 2019). Darker grey lines are slab *P–T* paths for the uppermost oceanic crust (OC; 0.5 km below top of slab) and light grey lines are lowermost OC (6.5 km into the OC). The data are separated into oceanic (filled circles; n = 105) and continental (filled triangles n = 84), and by age as follows: dark green = 420 Ma and older; mid green = 419–176 Ma; and, light green = 175 Ma and younger. Interpretation of this figure is discussed in more detail in the text.



Brown & Johnson – Figure 7

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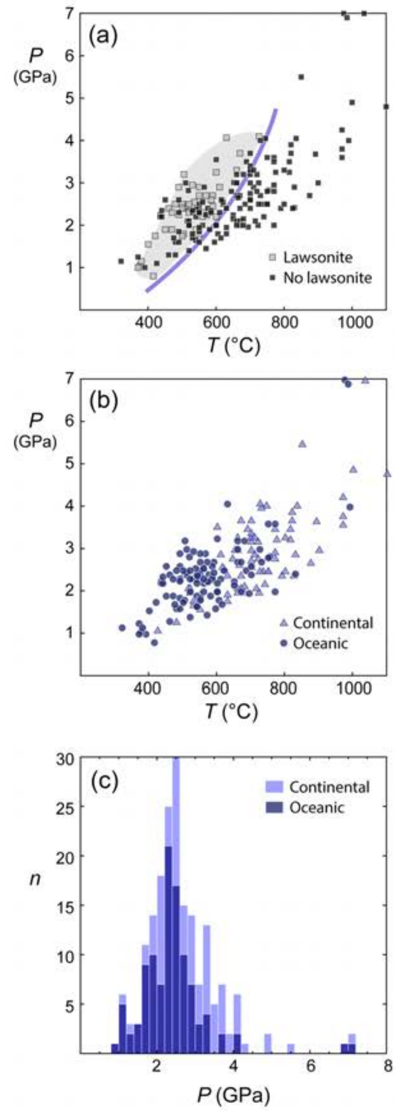
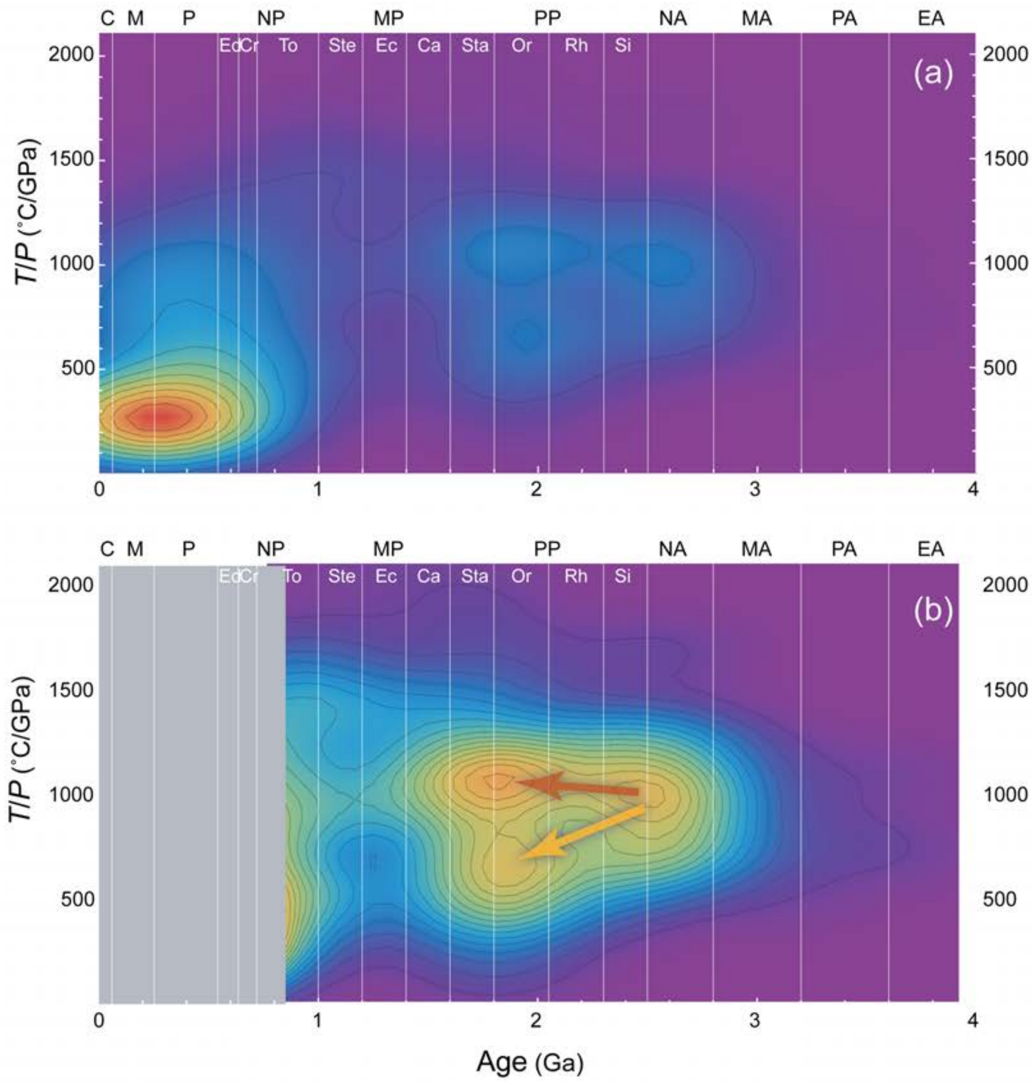
FIGURE 7. Map to show the present-day geographic distribution of low T/P metamorphic rocks.



Brown & Johnson – Figure 8

1176

FIGURE 8. a. *P–T* for rocks with Lws (or pseudomorphs) vs without Lws (line represents the approximate position of the Lws-out recation). b. *P–T* conditions for low T/P type metamorphism separated into oceanic (dark blue symbols) and continental (light blue symbols) varieties. c. Histogram of peak metamorphic pressures for low T/P type metamorphism separated into oceanic (dark blue symbols) and continental (light blue symbols) varieties.



Brown & Johnson – Figure 9

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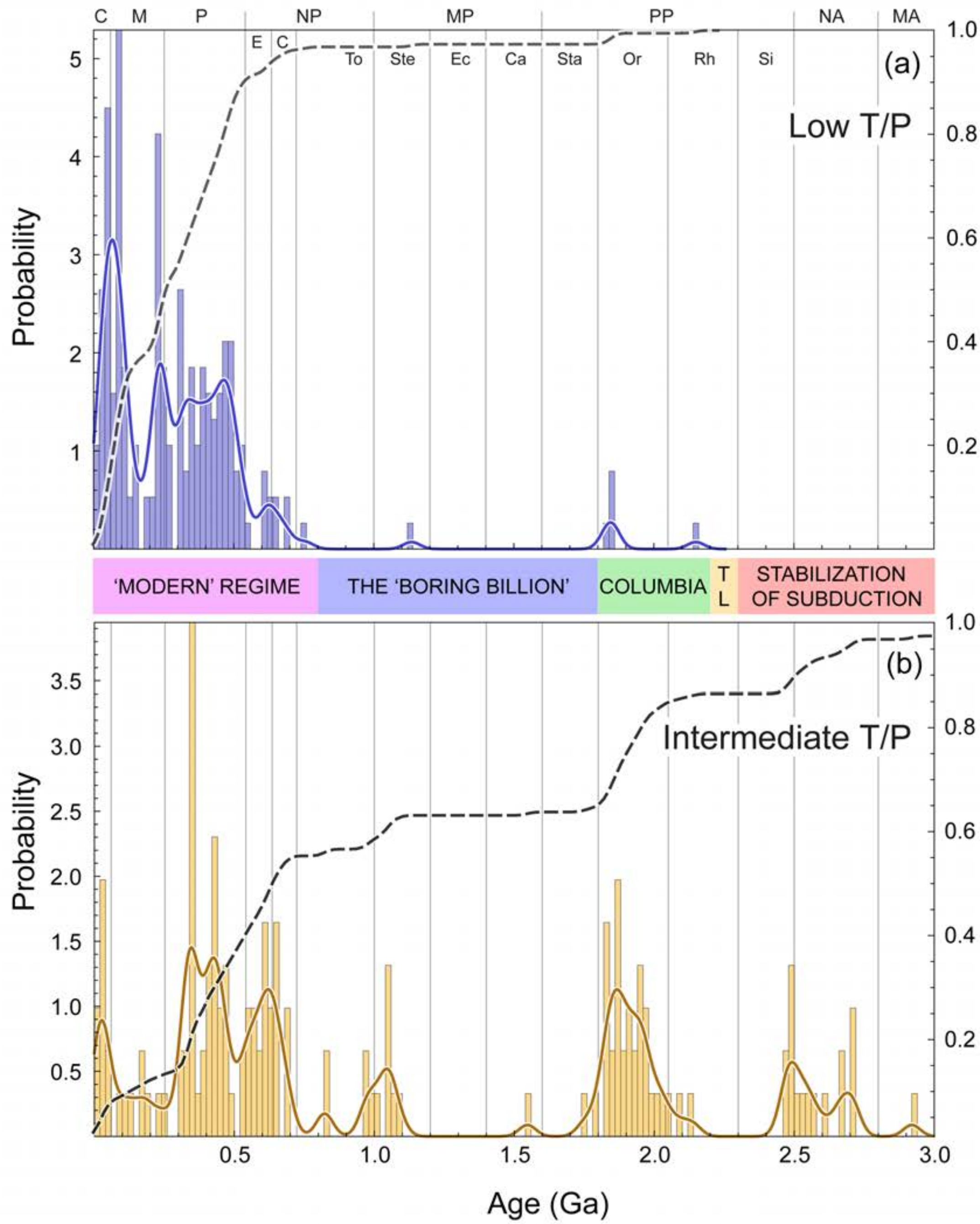
FIGURE 9. a. Metamorphic T/P data from Figure 3 contoured for density. b. Metamorphic T/P data for localities >850 Ma in age contoured for density to emphasise the development of bimodality from the Archean through the Proterozoic (in (a), this pattern is swamped by the low T/P data that are <850 Ma in age).



Brown & Johnson – Figure 10

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FIGURE 10. (a) Histogram of ages, probability density function and cumulative smooth kernel density estimate for low T/P type metamorphism. (b) Histogram of ages, probability density function and cumulative smooth kernel density estimate for intermediate T/P type metamorphism. In the tectonic summary bar, TL is tectonomagmatic lull.