An evaluation of continental growth and early Earth tectonics: Observations and models

Jun Korenaga[a] **and Christopher J Spencer**[b], [a]Department of Earth and Planetary Sciences, Yale University, New Haven, CT, United States; [b]Department of Geological Sciences and Geological Engineering, Queen's University, Kingston, ON, Canada

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Abstract

The generation of sialic continental crust on a planetary scale requires specific conditions for global tectonics because, unlike the oceanic crust, it requires more than a single stage melting of the mantle. The close relationship between continental growth and global tectonics has prompted extensive research in recent decades. However, this research has led to disparate estimates with different implications for global tectonics in the early Earth. The study of continental growth, however, has also been unnecessarily confusing because existing estimates are typically assumed to be similarly valid. It is crucial to recognize that various types of purported continental growth models have their own strengths and weaknesses. After categorizing classic growth models and identifying major difficulties in understanding continental growth, recent developments of crustal evolution and crust–mantle differentiation research are reviewed for tectonic background, crustal growth models, and the secular evolution of continental crust composition. While there exists increasing support for substantial continental growth during the Hadean Era, identifying more direct proxies on the mode of early tectonics continues to be challenging. We posit that the global databases of detrital zircons, at least in the ways that they have been studied, do not yield an estimate on net continental growth. To advance our understanding, we propose that improving our understanding of how the geological manifestation of plate tectonics would evolve with the secular cooling of the mantle.

Keywords

Continental crust; Plate tectonics; Mantle convection; Mantle-crust differentiation; Isotope geochemistry; Petrology; Zircon; Archean; Hadean; Numerical modeling

Key points

- Existing models for continental growth can be categorized into mantle-based estimates, crust-based estimates, indirect estimates, speculations, and numerical artifacts.
- Mantle-based and indirect estimates can potentially constrain net crustal growth whereas crust-based estimates, such as those based on the global databases of detrital zircons, provide only the present-day distribution of crustal ages.
- Recent models for net crustal growth persistently suggest the onset of substantial continental growth in the Hadean, accompanied with crustal recycling more intense than present.
- The chemical composition of continental crust appears to have been relatively stable through Earth history, with early continental crust not necessarily being more mafic.

Introduction

Planetary differentiation refers to a first-order process that results in discrete shells of similar composition. The initial phase of planetary differentiation occurs as Fe, Ni, and other siderophile metals are partitioned into the core (e.g., Jones and Drake, 1986; Huang and Badro, 2018). Following core formation, the silicate residue that remains becomes the reservoir from which the mantle and crust are subsequently formed. The process and timescale of mantle-crust differentiation have remained a perennial topic of inquiry with vastly different interpretations. Note that mantle-crust differentiation in the geochemistry literature almost always refers to the extraction of continental crust (or felsic crust) from the mantle. The extraction of oceanic crust (or basaltic crust) results from single-stage mantle melting, and as such, it can take place regardless of tectonic regime (i.e., plate tectonics vs. stagnant lid convection). In the stagnant lid regime, the basaltic crustal layer is formed mostly in the early phase of planetary evolution (e.g., O'Rourke and Korenaga, 2012), and it is a one-way mass transport from the interior to the surface. In the plate tectonics regime, however, the surface layer can be recycled back to the mantle, thus activating two-way mass transport, or geochemical cycles. For the chemical evolution of Earth-like planets, this difference in the mode of mass transport is the most important difference between plate tectonics and stagnant lid convection.

Single-stage melting of the ultramafic mantle produces mafic magmas, but as discussed in the subsequent sections, further processing of mafic crust to produce felsic magmas, and thus continental crust with a chemically evolved composition, likely started within the first 500 million years of Earth history. Coupled to the differentiation of an evolved crustal reservoir is the concomitant juvenile crustal reservoir with the former relating to continental crust and the latter to oceanic crust. On the modern Earth, crustal growth can be broadly categorized subductible and not. Generally, the modern oceanic crust that is generated at mid-ocean ridges is subductible with minor ophiolitic exceptions (Dewey, 1976) and therefore results in minimal net crustal growth. This is also the case for oceanic islands (both arc and hotspot related) and oceanic plateaus that are dominated by mafic lithologies and therefore are more likely to be subducted (Condie and Kröner, 2013; Arrial and Billen, 2013). In contrast, more felsic continental arcs (and minor magmas produced in continental hotspots and rift zones) produce far thicker crust that is more likely to be preserved (although exceptions exist due to subduction erosion and continental collision; Spencer et al., 2017). In this article, therefore, the term "continental crust" refers to the assemblage of magmatic rocks that are, on average, more evolved than basaltic rocks produced by single-stage mantle melting and have a relatively long residence time at surface, compared to the crustal recycling time scales of plate tectonics and delamination. Similarly, the term "crustal growth" refers specifically to net growth of magmatic rocks with the potential of long-term preservation in the geologic record and specifically excludes magmatic rocks generated at mid-ocean ridges. Importantly, the generation of magma in a continental setting is not equivalent with crustal growth as crustal melting can occur without any input from the mantle. This is referred to as "crustal reworking." A prime example of this is the magmatism that occurs in continental collisional settings where the exhumation and decompression of the orogenic core results in crustal melting. Other examples of crustal reworking may also include relamination of subducted material to the base of the continental crust (Hacker et al., 2011; Kelemen and Behn, 2016). In contrast, "crustal recycling" refers to the loss of continental crust to the mantle via subduction and/or delamination. As "crust" in mantle-crust differentiation usually refers to the continental crust, the subduction of oceanic crust is not counted as part of crustal recycling. This is contrasting to the convention in the studies of ocean island basalts, in which recycled oceanic crust is among important source materials (e.g., Hofmann, 2003; Stracke, 2012).

Intimately linked with mantle-crust differentiation is, therefore, the onset and evolution of subduction and plate tectonics. It has been argued that whereas subduction is a key component of plate tectonics, the presence of subduction zones is not necessarily a direct indicator of plate tectonics (Johnson et al., 2014; Smithies et al., 2019; Palin et al., 2020). While the estimates for when plate tectonics began range from the Hadean to the Neoproterozoic (Harrison, 2009; Stern, 2005), it is important to first define the terms involved. The term subduction is meant to represent the buoyancy-driven underthrusting of denser lithosphere (e.g., oceanic crust with oceanic lithospheric mantle) beneath lighter lithosphere (e.g., continental crust with continental lithospheric mantle), which could potentially induce crustal melting. As discussed in Section "Review of recent developments," there are numerous proxies rooted in uniformitarian that are used to identify the presence of subduction in the geologic record. Nevertheless, there is a growing body of literature suggesting that care should be taken when applying modern-day proxies for subduction throughout the geologic record (Condie, 2015; Bédard, 2018; Palin et al., 2020).

Linked to subduction is the process of seafloor spreading, for in order to accommodate subduction of an ocean basin, sea-floor spreading must occur. The processes of seafloor spreading and subduction work together to form a global network of plate boundaries. In the modern world, there are a small number of large plates (Eurasia, Africa, India, Australia, Antarctica, Pacific, North America, South America) with a few smaller plates or plate fragments isolated from the larger plates by discrete plate boundaries. To define plate tectonics, it is important to decide what geologic proxies are requisite for an inclusive definition. Given the changing thermal conditions of the planet (Herzberg et al., 2010), it is feasible that the nature of plate tectonics has evolved over time and therefore the proxies used to define the process may unnecessarily restrict plate tectonics to a narrower timespan. With secular changes in Earth's thermal structure in mind, we define plate tectonics to represent a global process where rigid lithospheric blocks are connected by a planet-wide network of plate boundaries. We further stipulate that the magmatism associated with a plate tectonic scenario should primarily occur in two distinct modes associated with divergent and convergent plate margins. It is important to note this definition does not stipulate specific proxies regarding plate velocity, metamorphic field gradients, or igneous composition, but simply requires the presence of convergent plate margin magmatism. We prefer this broad definition as it recognizes the potential for the evolution of Earth's plate tectonic system.

Given the nature of the geologic record, the amount of empirical data available to interpret both diminishes with time at Earth's surface and the resolution of geophysical data decreases with depth at the present (Gerya, 2019). Therefore, to disentangle the complex processes leading to the present day requires the use of thermomechanical and compositional proxies to project geological processes that have shaped Earth's surface and interior through geologic time. In the case of mantle-crust differentiation, we are limited to the continental crustal archive and therefore primarily rely on radioactive decay and isotopic proxies to constrain the onset of subduction and the evolution of plate tectonics, along with crustal growth, recycling, and reworking. This chapter will review the previous efforts in constraining mantle-crust differentiation as well as the current state of the relevant literature and will explore future directions for better understanding the evolution of the mantle-crust system.

Different kinds of continental growth models

When reviewing previous efforts to estimate the history of continental formation, we need to recognize that there are several different kinds of growth models in the literature. As described below, it is straightforward to tell which category a given model belongs to, based on the nature of observational constraints used for the model. Traditionally, however, different kinds of models have been referred to as "growth models" collectively, which could lead to the false impression that continental growth is severely underconstrained. There is no point in comparing apples and oranges, and even when comparing models in the same category, it is important to understand assumptions involved in those models and their limitations. In what follows, we describe five major categories of growth models, using models published mostly before 2014 (i.e., prior to the previous edition of Treatise on Geochemistry). Growth models published in the late 2010s and after will be discussed in Section "Review of recent developments."

Mantle-based models

Mantle-based models rely on the idea that the formation of continental crust leaves the mantle correspondingly depleted in the incompatible elements that are enriched in the continental crust (e.g., rare earth elements). For example, if the mantle at 3 Ga was already as depleted as the present-day mantle, the mass of the continental crust at that time would be close to the present-day mass, assuming that the continental crust has been similarly enriched in the element(s) under consideration through geologic time. This assumption can potentially be tested by tracking the secular evolution of continental crust composition, although doing so would be challenging because what matters here is the composition of the whole crust, not just the upper crust (see Section "Secular evolution of continental crust composition"). Mantle-based models rest directly on the complementary nature of the continental crust and the depleted mantle, and as such, they are about the net growth of the continental crust, that is, how much of continental crust existed in the past. As explained in this section, the mantle-based approach has various practical limitations, but it is still the most direct approach available to estimate net crustal growth. This is distinct from the crust-based approach (Section "Crust-based models"), which is unable to estimate net crustal growth unless crustal recycling can be accurately constrained by mantle composition.

The mantle-based approach has yielded a variety of growth models (Fig. 1a). The model of Armstrong (1981b), which could as well be classified as speculation (Section "Speculations"), is based on the Pb, Sr, and Nd isotope data of the depleted mantle. That of Jacobsen (1988) is based on the inverse modeling of the Nd isotope data of the depleted mantle as well as the continental crust. McCulloch and Bennett (1994) employed by far the most extensive array of observational constraints, including the Sr, Nd, Hf, Os, and Pb isotope data of the depleted mantle as well as the crust (both oceanic and continental). They also considered trace element abundances and trace element ratios. McCulloch and Bennett (1993) and Jacobsen and Harper (1996) considered both the ^{146}Sm-^{142}Nd system and the traditional ^{147}Sm-^{143}Nd system. Kramers and Tolstikhin (1997) considered only the U-Th-Pb isotope system but with an elaborate treatment of the continental crust, which is divided into four different reservoirs in their model. The models of Collerson and Kamber (1999) and Campbell (2003) are based on the Nb/Th and Nb/U ratios, respectively, of the depleted mantle.

These models vary rather substantially, particularly for deep time; the estimated continental mass spans from nearly 0% to 100% for the early Archean, carrying widely different implications for the tectonic regime in the early Earth. An important question is why they are so different. There are four major factors to be considered. First, any mantle-based model has to assume how the mantle has been chemically differentiated, and different assumptions lead to different model parameterizations, which could produce different histories of continental growth even with the same input data. If the convecting mantle were chemically and isotopically homogeneous, the implementation of the mantle-based approach would be simple, but the studies of mid-ocean-ridge basalts (MORB) and ocean island basalts (OIB) indicate that it is not the case (Zindler and Hart, 1986; Hofmann, 2003). The present-day depleted mantle is usually considered to consist of several distinct mantle reservoirs such as the depleted MORB source and enriched OIB sources such as EM1, EM2, and high-μ. The preservation of the undegassed primitive mantle is also often invoked to explain the noble gas signatures of OIBs. Different authors have attempted to capture such realistic complications in different manners, and generally, more elaborate parameterizations require more assumptions, as geochemical observations alone are insufficient to constrain all of model behaviors.

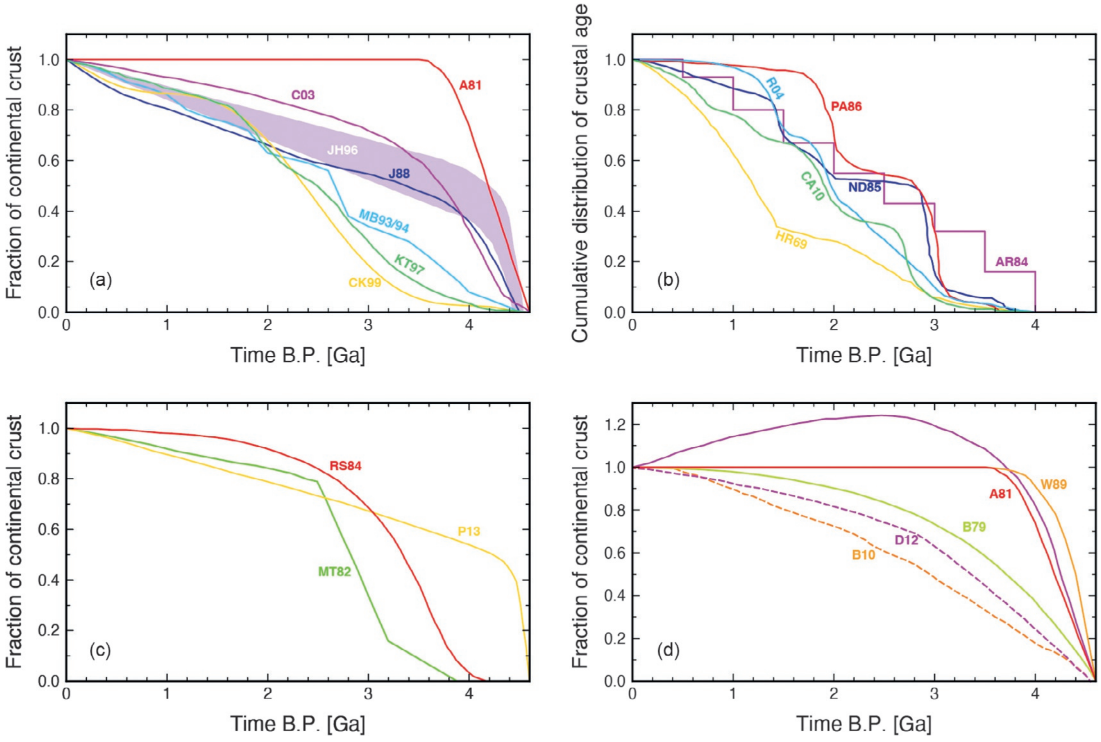

Fig. 1 Classical crustal "growth" models. (a) Mantle-based models: A81 (Armstrong, 1981b), J88 (Jacobsen, 1988), MB93/94 (McCulloch and Bennett, 1993, 1994), JH96 (Jacobsen and Harper, 1996), KT97 (Kramers and Tolstikhin, 1997), CK99 (Collerson and Kamber, 1999), and C03 (Campbell, 2003). (b) Crust-based models: HR69 (Hurley and Rand, 1969), AR84 (Allègre and Rousseau, 1984), ND85 (Nelson and DePaolo, 1985), PA86 (Patchett and Arndt, 1986), R04 (Rino et al., 2004), and CA10 (Condie and Aster, 2010). (c) Indirect models: MS82 (McLennan and Taylor, 1982), RS84 (Reymer and Schubert, 1984), and P13 (Pujol et al., 2013). (d) Speculation-based models (solid lines): F78 (Fyfe, 1978), B79 (Brown, 1979), A81 (Armstrong, 1981b), and W89 (Warren, 1989), as well as models based on the "ratio" method (dashed lines): B10 (Belousova et al., 2010) and D12 (Dhuime et al., 2012).

Second, as explained in Section "Introduction," the net growth of the continental growth reflects a dynamic balance between crustal generation and crustal recycling, and this means that different combinations of crustal generation and recycling can result in the same net growth. For example, by assuming no crustal recycling, a net growth would simply be regarded as a gradual accumulation of newly generated crust, but the same net growth may also result from the competition between intense crustal generation and recycling. Different combinations of crustal generation and recycling result in different isotopic evolutions, and by the same token, different growth histories can explain the same evolution of a certain isotope system (DePaolo, 1980; Armstrong, 1981a). Thus, the true strength of chosen observational constraints can be assessed only by exploring extensively the relevant model parameter space. This is difficult to achieve in forward modeling, which is the common strategy in most of previous studies. A notable exception is Jacobsen (1988), but his inverse approach is based on the linearized version of the general nonlinear theory, thereby limiting the extent of model space exploration.

Third, the quality of relevant geochemical data is of utmost importance. While the above two factors may be addressed by refining the modeling strategy, interpretations would be in vain or severely limited if input data were respectively, erroneous or imprecise. This has long been a challenging issue because older rocks and minerals, which are essential for constraining the early continental growth, tend to suffer more from weathering and metamorphic alteration (e.g., Collerson et al., 1991; Bennett et al., 1993; Bowring and Housh, 1995; Vervoort et al., 1996; Moorbath et al., 1997; Harrison et al., 2005). At the same time, this is also the issue that geochemists are seriously concerned with, and analytical progress has been steadily achieved (e.g., Kemp et al., 2010; Rizo et al., 2013; Morino et al., 2017; Fisher and Vervoort, 2018; Fisher et al., 2020; Bauer et al., 2020).

Lastly, the spatial coverage of igneous rocks, some of which reflect the isotopic signatures of the depleted mantle, shrinks dramatically in deep time. This is of course the inevitable consequence of plate tectonic recycling, and it is probably the most severe problem with no clear solution in sight. The situation is even more compounded by the heterogeneous nature of the mantle composition as mentioned above. Future field investigation may slowly alleviate this difficulty, and it will remain important to delineate how available geochemical data actually constrain continental growth.

With this understanding of the mantle-based approach, the diversity of the mantle-based models in Fig. 1a can now be explained. First of all, the isotope systems that are useful for estimating continental growth are limited to the following three: ^{147}Sm-^{143}Nd, ^{146}Sm-^{142}Nd, and ^{176}Lu-^{176}Hf. Rb and Sr are much more mobile than those elements (Taylor and McLennan, 1985), making the Rb-Sr system unreliable for the analysis of ancient rocks. The first lead paradox (Allègre, 1969) makes it impossible to use the U-Th-Pb system to constrain continental growth. To make use of Pb isotope data, additional assumptions are required to close the global lead isotope budget. The Re-Os system is not very useful for the mantle-based approach as the osmium isotopic composition of the depleted mantle is relatively insensitive to crustal formation because osmium is strongly compatible during the partial melting of the mantle and rhenium is only moderately incompatible (Meibom et al., 2002). The combined use of the ^{147}Sm-^{143}Nd and ^{146}Sm-^{142}Nd systems is useful because of very different half-lives (147 Gyr and 103 Myr, respectively) that allow for constrain of long-term continental growth with the former and very early crustal growth with the latter. However, ^{142}Nd data can also be affected by early Earth processes not related to continental growth, and this possibility complicates the interpretation of Nd isotope data. The ^{176}Lu-^{176}Hf system behaves very similarly to the ^{147}Sm-^{143}Nd system for most of Earth history (Vervoort et al., 1999).

Thus, even though Armstrong (1981b) and McCulloch and Bennett (1994) used multiple isotope systems, their models are constrained essentially by the ^{143}Nd isotope evolution of the depleted mantle. As pointed out by Armstrong (1981a), the ^{143}Nd isotope evolution can be explained either by a rapid growth with intense recycling or by a gradual growth with little recycling. The model of Armstrong (1981b) is biased to the former, whereas those of Jacobsen (1988) and McCulloch and Bennett (1994) to the latter. The difference between the models of McCulloch and Bennett (1993) and Jacobsen and Harper (1996), both of which are based on the combined interpretation of ^{143}Nd and ^{142}Nd data, arises partly from the difference in chosen ^{142}Nd data and partly from different assumptions on crustal recycling. The model of Kramers and Tolstikhin (1997), which is based solely on the U-Th-Pb system, is best viewed as a sample growth model used in their analysis of the lead paradox, rather than a growth model constrained by the Pb isotope data.

The growth models based on trace element ratios such as Nb/Th and Nb/U (Collerson and Kamber, 1999; Campbell, 2003) may seem simpler than the isotope-based models, because the former is not affected by the effect of crustal recycling. However, estimating the average trace element ratio of the depleted mantle, from the ratios observed in igneous rocks, is not so straightforward, owing to elemental partitioning during magma genesis. Indeed, Collerson and Kamber (1999) tried both Nb/Th and Nb/U, but the latter did not yield a sensible growth model. Their confidence in the Nb/Th-based model stems from its similarity to the models of Kramers and Tolstikhin (1997) and Reymer and Schubert (1984), but as noted above, the model of Kramers and Tolstikhin (1997) has no real observational basis, and the model of Reymer and Schubert (1984) is problematic for a different reason (see Section "Indirect models"). If one looks at the original Nb/U data used to construct the model of Campbell (2003), there is no statistically significant difference between the modern Nb/U value and the Archean one, which is actually consistent with the model of Armstrong (1981b). The Hadean part of the model of Campbell (2003) is based on the rarity of Hadean zircons, but this logic ignores the possibility of intense crustal recycling in the early Earth.

It is probably fair to summarize that the diversity of the mantle-based models owes much to different presumptions on the intensity of crustal recycling in the past. It was once reasonable to assume the limited influence of crustal recycling, because the modern rate of sediment subduction were always estimated to be much lower than that of new crustal addition (e.g., Dewey and Windley, 1981; Reymer and Schubert, 1984; Taylor and McLennan, 1985). Thus, maintaining zero net growth as in the model of Armstrong (1981b) was deemed unrealistic even for the Phanerozoic, leading to the proliferation of gradual growth models. More recent estimates on sediment subduction and crustal addition suggest, however, that crustal generation may be approximately balanced by crustal recycling, at least for modern time (e.g., Scholl and von Huene, 2007; Harrison, 2009). This underscores the importance of exploring a range of growth scenarios without unnecessarily restricting the role of crustal recycling.

Crust-based models

Crust-based models are based on the age distribution of the present-day continental crust. They do not contain information about the continental crust lost to the mantle by subduction or delamination, so they serve as the lower bound to net crustal growth. Only by assuming no crustal recycling throughout Earth history, crust-based models can be equated to net crustal growth. An ideal crust-based model is based on the formation age distribution of the entire continental crust, and such a model can be used to quantify, in conjunction with an independent estimate of net crustal growth, the extent of crustal recycling, and in conjunction with an estimate of surface age distribution, the extent of crustal reworking (Fig. 2). Here the formation age refers to the age that a given rock was produced as a result of mantle melting. The formation age of an oceanic rock is simply the corresponding seafloor age, but that of a continental rock is more difficult to estimate because it could have experienced multiple tectonic events, each of which could disturb or reset its geochronological information. Direct geochronological dating provides the so-called surface age, and the formation age can be considerably older than the surface age.

The history of crust-based models paints a somewhat tortuous path toward the global formation age distribution of the continental crust (Fig. 1b). Hurley and Rand (1969) is the first global attempt to map crustal ages, excluding only the former Soviet Union and China owing to the lack of accessible data. Their age data are based on K-Ar and Rb-Sr dating, so their model is more about the surface age distribution. In the early 1980s, the notion of the depleted mantle model age was developed (DePaolo, 1981), and Nelson and DePaolo (1985) proposed a crust-based model using Nd-depleted mantle model ages for North American igneous samples. However, the depleted mantle model age can be equated with the formation age only when interaction with preexisting crust can be ruled out, and it is usually better to be regarded as the weighted average of multiple formation ages (Farmer and DePaolo, 1983; Patchett and Arndt, 1986). Patchett and Arndt (1986) revised the model of Nelson and DePaolo (1985) by adding more data from Europe and Greenland and also by correcting for likely interactions with preexisting crust. The models of

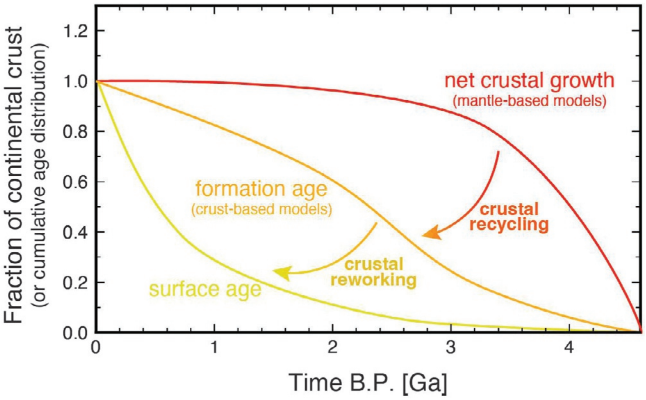

Fig. 2 Schematic diagram to illustrate the genetic relation among net crustal growth, formation age distribution, and surface age distribution. Mantle-based models aim at estimating net crustal growth, whereas crust-based models provide the distribution of formation ages of extant crustal rocks. The age distributions shown here are cumulative distributions so that they become unity at the present day. The difference between net crustal growth and formation age distribution reflects the effect of crustal recycling, and that between formation and surface age distributions reflects the effect of crustal reworking.

Hurley and Rand (1969), Nelson and DePaolo (1985), and Patchett and Arndt (1986) are all based on the age of igneous rocks. Allègre and Rousseau (1984) devised a scheme to construct a crust-based model by using Nd-depleted mantle model ages of sedimentary rocks. As terrigenous sediments sample broad regions of continental upper crust, this is an efficient approach to derive a global age distribution, although one has to assume some erosion law to undo the averaging effect of sediment formation. Since the late 1990s, the use of global databases of detrital zircons has become increasingly popular. Because each zircon grain provides its own age information, there is no need to undo averaging associated with sedimentation. Rino et al. (2004) and Condie and Aster (2010) are the early examples of such zircon-based models, but they both use the U-Pb crystallization ages, which are best regarded as the surface ages, not the formation ages.

These crust-based models were all presented in their original publications as if they were about net crustal growth, despite that they are merely the cumulative distribution of formation or surface ages. This is understandable because, as noted in Section "Mantle-based models," crustal recycling had long been regarded as a minor factor in crustal evolution. Even though the occurrence of crustal recycling by sediment subduction was well recognized, many geologists assumed that crust-based models would still provide a good approximation to net crustal growth.

Variations among the crust-based models reflect differences in adopted crustal ages and data coverages. The models of Hurley and Rand (1969), Rino et al. (2004), and Condie and Aster (2010) are all about surface ages. The models of Nelson and DePaolo (1985) and Allègre and Rousseau (1984) are both based on the direct use of Nd-depleted mantle model ages, but with very different data coverages. Among the models shown in Fig. 1b, the model of Patchett and Arndt (1986) may be seen as the best effort to estimate the formation ages. However, this model is very similar to the model of Armstrong (1981b) for the last two billion years, and this is rather odd. Because the difference between net crustal growth and the formation age distribution reflects the effect of crustal recycling (Fig. 2), the similarity between the model of Patchett and Arndt (1986), which is a crust-based model, and that of Armstrong (1981b), which is about net crustal growth, indicates almost no crustal recycling, and thus negligible generation of new continental crust, both of which are inconsistent with observations (e.g., Taylor and McLennan, 1985; Scholl and von Huene, 2007). This contradiction attests to the difficulty of estimating the formation ages of continental rocks.

Indirect models

This third category covers the growth models that are neither mantle-based nor crust-based but are still derived by some quantitative means (Fig. 1c). The model of McLennan and Taylor (1982) was designed such that the continental crust grows significantly around the Archean-Proterozoic boundary. They argued that such crustal growth was required to explain the observed differences in Archean and post-Archean sediment chemistry, although there is a substantial logical gap between sediment chemistry and crustal growth (Armstrong, 1991; Harrison, 2009). The other parts of their model are adjusted so that little crust was present before 3.8 Ga, which belongs to the realm of speculation, and crustal growth was slow and steady after 2.5 Ga, which was consistent with the then-available constraints on crustal generation and recycling.

The model of Reymer and Schubert (1984) is based on the combination of geological estimates and geophysical inferences. By comparing the magmatic arc generation rate with the sediment subduction rate, they estimated the Phanerozoic net crustal growth of about 1 km^3 $year^{-1}$. They also built a continental freeboard model to relate the thermal evolution of Earth's mantle with continental growth, and their model of thermal evolution also predicted a net crustal growth of about 1 km^3 $year^{-1}$. As thermal evolution modeling can be extended to the early Earth, they used the freeboard model to derive their growth model. The coincidence of these two different estimates on net crustal growth turns out to be fortuitous. As already noted (Section "Mantle-based models"), the rate of sediment subduction is now estimated to be comparable with the rate of new crust generation, that is, net growth is close to zero for modern time. Furthermore, the relation between the thermal evolution of the mantle and continental growth is not as simple as implied by the freeboard modeling of Reymer and Schubert (1984). Modeling the continental freeboard involves quite a few moving parts such as oceanic crust, oceanic lithospheric mantle, continental crust, continental lithospheric mantle, asthenosphere, and ocean volume, all of which can exhibit secular variations (Korenaga et al., 2017). In particular, the history of ocean volume remains the least understood factor, and this uncertainty prevents the use of continental freeboard to constrain crustal growth.

The model of Pujol et al. (2013) is based on the evolution of atmospheric argon isotopes. The continental crust is enriched in potassium, and one of its isotopes, ^{40}K, decays to ^{40}Ar with a half-life of 1.25 Gyr. Whenever the continental crust is created, ^{40}Ar in the crust would be released to the atmosphere, and being a heavy noble gas, it would remain in the atmosphere. Thus, the atmospheric abundance of ^{40}Ar as well as the atmospheric ratio of ^{40}Ar/^{36}Ar are sensitive to the history of crustal evolution, and compared to the rock record, the atmospheric ^{40}Ar/^{36}Ar is less prone to preservation bias because the atmosphere is homogeneous. To constrain crustal growth, however, one has to deconvolve all processes that contribute ^{40}Ar to the atmosphere, including crustal recycling, crustal reworking, mid-ocean-ridge magmatism, and hotspot magmatism. Pujol et al. (2013) used the argon degassing model of Hamano and Ozima (1978), which does not allow such deconvolution. The effort of Pujol et al. (2013) is important because of their new Archean atmospheric ^{40}Ar/^{36}Ar data, but their modeling approach prevented them from fully utilizing it.

Even with these deficiencies, however, these indirect models still underscore the importance of exploring nontraditional approaches. Good indirect models should be able to complement mantle-based and crust-based models.

Speculations

Occasionally, growth models have been proposed based on sheer conjecture (Fig. 1d). When a review paper is written for continental growth, the model of Fyfe (1978) is almost always included probably because it is the only model with greater continental mass in the past. The model has no supporting data; it was proposed just as a contrasting example to other models with positive net growth. The model of Brown (1979) is another hand-drawn curve, to visualize his qualitative arguments for gradual growth. The model of Armstrong (1981b) is already discussed as a mantle-based model in Section "Mantle-based models," but his model was proposed in the style of hypothesis testing. He hypothesized that the basic layering of the present-day earth structure, that is, the crust, the mantle, and the core, was rapidly created by early planetary-scale differentiation, and he set out to test this idea with the then-available observations. So it is more than a speculation, but his observational efforts were biased by his speculation. The model of Warren (1989) was proposed in a similar manner to that of Armstrong (1981b). Warren (1989) employed a unique planetary science perspective, but his geophysical and geodynamical arguments, most of which are now outdated, are too qualitative to single out a specific growth curve.

Artifacts

As mentioned in Section "Crust-based models," the prime difficulty with crust-based models is the estimate of formation ages. Global databases of detrital zircons, as they continue to grow, allow us to steadily approach to the global age distribution of continental rocks, but the use of U-Pb crystallization ages, as done by Rino et al. (2004) and Condie and Aster (2010), yields only the surface age distribution. The depleted mantle model age would be closer to the formation age, but it has to be corrected for possible interactions with preexisting crust (Patchett and Arndt, 1986). To address this issue, Belousova et al. (2010) proposed a new approach to use two age distributions from a detrital zircon database, one for U-Pb crystallization ages, and the other for Hf-depleted mantle model ages. They took the ratio of the depleted mantle model age distribution over the sum of these two distributions, and this ratio was assumed to be the new crust generation rate. That is, at a given age, if the number of zircon data with their U-Pb crystallization ages equal to the age is $N_{\text{U-Pb}}$, and the number of zircon data with their Hf-depleted mantle model ages equal to the age is N_{DM}, then, the new crust generation rate is calculated as $N_{\text{DM}}/(N_{\text{DM}} + N_{\text{U-Pb}})$. Their "crustal growth" curve was then generated by taking the cumulative sum of this crust generation rate (Fig. 1d).

The procedure described above, here called the "ratio" method, cannot yield an estimate on crustal growth nor the formation age distribution, because this is just a ratio of two numbers. And this is a dimensionless quantity. This itself cannot be a crust generation "rate." One sensible way to make use of this ratio is to multiply this ratio with some kind of "total crust generation rate." If we assume, as done by Belousova et al. (2010), that N_{DM} and $N_{\text{U-Pb}}$ represent newly generated crust and reworked crust, respectively, then, the ratio $N_{\text{DM}}/(N_{\text{DM}} + N_{\text{U-Pb}})$ can be interpreted as the ratio of newly generated crust over the total crust. But with this interpretation, the total crust generation rate would be $N_{\text{DM}} + N_{\text{U-Pb}}$, and the rate of new crust generation rate is $N_{\text{DM}}/(N_{\text{DM}} + N_{\text{U-Pb}})$ x $N_{\text{DM}} + N_{\text{U-Pb}} = N_{\text{DM}}$. That is, we return to the distribution of depleted mantle model ages.

As discussed in Section "Crust-based models," using a depleted mantle model age as a formation age has its own problems given the fact that depleted mantle model ages do not strictly represent formation ages, but it is at least dimensionally correct. As demonstrated later by Korenaga (2018, 2021), the ratio method of Belousova et al. (2010) does not yield any meaningful constraint on crustal growth or the formation age distribution. That is, synthetic crustal age frequencies that increase through time yield the nearly same cumulative age frequency curve as the opposite synthetic age frequency pattern (age frequency decreases through time) (Fig. 3). The tests of the ratio method produced by Korenaga (2018) demonstrate an inconsistency in the results generated by the ratio method. This inconsistency can be traced back to the fact that the Hf-depleted mantle model age of a given

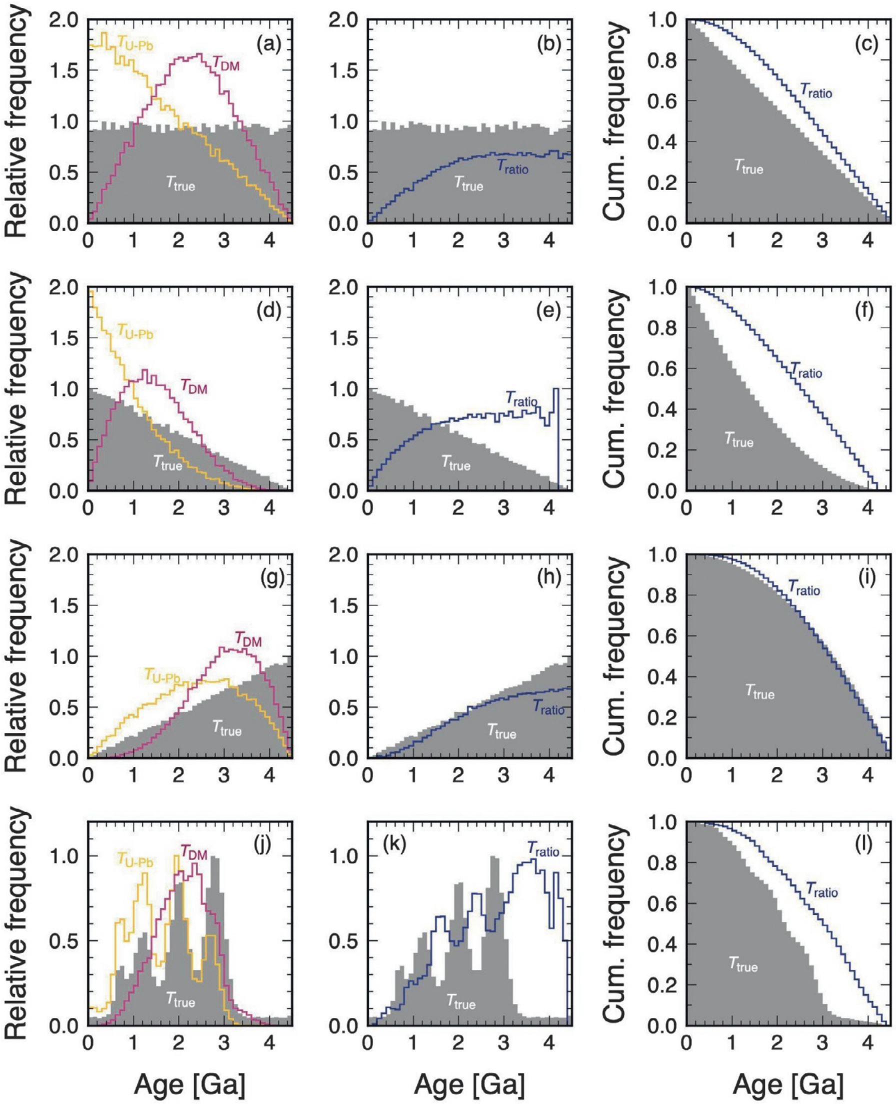

Fig. 3 Demonstration of how the "ratio" method works, with four different sets of synthetic data: (first row) constant crust production through time (second row) more production in recent times (third row) less production in recent times, and (fourth row) multiple peaks in crustal production. The first column shows the true distribution (gray) and the corresponding distributions of U-Pb crystallization age ($T_{U\text{-}Pb}$; yellow) and the depleted mantle model age (T_{DM}; magenta). The second column compares the ratio of the depleted mantle age distribution over the sum of two age distributions (blue), which, according to Belousova et al. (2010), would represent new crust generation rate, with the true distribution of crust production (gray). The third column is a cumulative version of the second column. After Korenaga J (2021) Hadean geodynamics and the nature of early continental crust. *Precambrian Research* **359**: 106178.

zircon is always greater than its U-Pb crystallization age. There is no logical connection between their method and continental growth; see section 2.2 of Korenaga (2021) for the most detailed account on this matter.

The ratio method of Belousova et al. (2010) was further adopted by Dhuime et al. (2012), with additional data screening based on oxygen isotope data. Given that the ratio method produces a numerical artifact regardless of the age distribution, it is noted by Korenaga (2018) that the model of Dhuime et al. (2012) is also not useful when discussing continental growth. At the same time, it is proposed that the ratio method be replaced with the unmixing method (discussed below; Korenaga, 2018). Importantly, consensus has not yet been attained with regards to the ratio vs. unmixing methods, as both methods continue to be discussed in recent studies (e.g., Cawood et al., 2022; Zhu et al., 2023); however, it is important to note that a rebuttal of the unmixing method in support of the ratio method has not yet been made.

It is important to distinguish between different kinds of growth models. A mantle-based model is an estimate on net crustal growth, and a crust-based model is an estimate on formation age distribution. More indirect approaches, such as an approach based on atmospheric argon isotopes, are also possible. A scientific discussion of continental growth would be most fruitful if we focus on growth models built quantitatively from data. Models built qualitatively from speculations are of limited value, though some of them could still be thought-provoking (e.g., Fyfe, 1978; Armstrong, 1981b). In contrast, it is difficult to find any value in artifacts.

Review of recent developments

Tectonic background

Tectonic proxies and superlatives

Tracing tectonic processes through time is accomplished primarily through compositional and mineralogical proxies that are either directly compared with modern tectonic settings or integrated into tectonophysics modeling. Macro-scale geologic features such as thrust faults, pillow basalts, and eolianites are also used to infer tectonic processes.

Magmatism associated with modern-day subduction zones carries a series of specific compositional characteristics including elevated Th/Nb of mafic lithologies (Elliott et al., 1997; Pearce et al., 2005), and Ta-Nb depletion with respect to the primitive mantle (Briqueu et al., 1984; Baier et al., 2008). These compositional proxies for subduction magmatism have been used in the past to infer the presence of subduction in the Archean, with the oldest mafic rocks with elevated Th/Nb (without significant crustal contamination) being ~3.8 Ga (Jenner et al., 2009; Hawkesworth et al., 2019). While geochemical proxies may infer the presence of subduction zones generating basaltic magmas during the Eoarchean Era, numerical modeling suggests that mechanisms other than subduction such as "sagduction" (dripping of the lower crust) or crustal overturns can be called upon to explain the transfer of basaltic material into the mantle where melting can produce signatures commonly associated with subduction (Johnson et al., 2014; Sizova et al., 2015; Roman and Arndt, 2020). In contrast, other workers argue that although shifts in global basaltic composition are present (the largest being in the latest Archean–early Proterozoic), these are best explained by discontinuous changes in the mineralogy of partial melting in the mantle that is caused by secular cooling of the mantle and does not require any change in tectonic processes responsible for petrogenesis (Keller and Schoene, 2018).

Tonalite, trondhjemite, and granodiorite (TTG) suites of the Archean Eon also carry many of the compositional proxies associated with subduction in more intermediate and felsic lithologies (Martin et al., 2014; Hoffmann et al., 2019). This "arc-signature" is interpreted to represent partial melting of hydrated mafic rocks (amphibolite) within the garnet stability field (as low as 0.7 GPa; Johnson et al., 2017). Although the petrogenesis of TTGs have commonly been categorized to either record high-, medium-, or low-pressure compositional indicators (Martin et al., 2005; Moyen, 2009; Moyen and Martin, 2012; Hoffmann et al., 2019), recent work has established that the compositional diversity seen in Archean TTGs can be explained purely through magmatic differentiation (Smithies et al., 2019) within the middle crust (Kendrick et al., 2022).

While compositional proxies rarely provide a clear distinction between specific tectonic processes, it has been argued that mineralogical proxies provide a clearer indication of tectonic processes through geologic time. Mineralogical proxies primarily take the form of metamorphic mineral phases associated with thermobaric regimes akin to modern plate tectonic processes, and the earliest occurrence of specific mineral phases or phase associations can indicate plate tectonic processes. A simple example of this is the presence of high-pressure, low-temperature metamorphism epitomized by the occurrence of blueschist and/or the incidence of paired-metamorphism (Matsuda and Uyeda, 1971; Ernst, 1972; Brown, 2010), which at present are exclusively associated with convergent margin processes associated with subduction (Fryer et al., 1999; Pabst et al., 2012; Tamblyn et al., 2022).

The earliest occurrence of blueschist sensu stricto (i.e., a glaucophane-bearing schist) in the geologic record with a precise age constraint is the Aksu blueschist from northern China (769 ± 19 Ma; Xia et al., 2019). Additional Neoproterozoic blueschist occurrences include is from the Gourma belt in eastern Mali with an age of ~800–730 Ma (Caby et al., 2008) and the ~750–600 Ma blueschist-bearing melange of Anti-Atlas Mountains in Morocco (Hefferan et al., 2002). While the oldest occurrence of blueschist provides a temporal backstop to which modern-style plate tectonics was likely in operation, the compositional requirements of the protolith to facilitate blueschist-facies phase equilibria may play a role in the oldest occurrence of blueschists in geologic time (Palin and White, 2016). Also, the exhumation of rocks that experienced ultra-high pressure metamorphism requires a fortuitous sequence of subduction zone dynamics (Agard et al., 2009); whereas plate tectonics may occasionally produce it, its absence does not mean the lack of plate tectonics. While blueschists are not present in the geologic record prior to the Neoproterozoic Era, additional low-temperature, high-pressure rocks (thermobaric ratio $(T/P) < 375\ ^\circ\mathrm{C/GPa}$; see Brown and Johnson, 2019) occur as old as ~2.1–2.2 Ga (François et al., 2018; Loose and Schenk, 2018; Weller and St-Onge, 2017).

Paired metamorphism has been directly observed going back as far as the latest Archean Eon (2.54–2.5 Ga) as intact map-scale belts with two distinct metamorphic facies akin to those observed in the Phanerozoic Eon (Huang et al., 2020). Before the Archean-Proterozoic transition, metamorphism was primarily dominated by high thermobaric ratios. It is then within the early Proterozoic (2.2–2.0 Ga) when the thermobaric ratios diverge to include both *high T/P* that dominates the Archean and low T/P indicative of low-temperature, high-pressure metamorphism (Brown and Johnson, 2019; Holder et al., 2019). Both the presence of paired metamorphic belts in the latest Archean and the divergence of thermobaric ratios during the Proterozoic have been interpreted by the previously cited studies as evidence for the onset of global plate tectonics during the Archean–Proterozoic transition.

The nature of mineral inclusions in diamonds also provides insight into the reworking of crustal-derived material to mantle depths. Prior to 3.2 Ga, inclusions in diamonds were strictly peridotitic with $^{187}\mathrm{Os}/^{188}\mathrm{Os}$ akin to the depleted mantle, whereas after 3.0 Ga eclogitic diamond inclusions with elevated $^{187}\mathrm{Os}/^{188}\mathrm{Os}$ were common (Shirey and Richardson, 2011). It has been proposed that this indicates the recycling of crustal Os in subduction systems and the beginning of the Wilson Cycle. Smit et al. (2019) further investigated this possibility by analyzing the sulfur isotope signature of sulfide inclusion in diamonds and found that mass-independently fractionated sulfur, which is the signature of the anoxic atmosphere before ~2.5 Ga, is observed for inclusions younger than 2.9 Ga but not for those with an age of 3.5 Ga. These diamonds are, however, all sampled from continental lithosphere. Thus, they may simply reflect how the preservation potential of continental lithosphere, with regard to subducted oceanic crust, has changed through time (Luo and Korenaga, 2021), and the observations made by Shirey and Richardson (2011) and Smit et al. (2019) do not necessarily conflict with the operation of plate tectonics earlier than 3 Ga.

Structural features of Eoarchean supracrustal belts have also been used to posit the presence of convergent plate margins and plate tectonic processes as early as 3.8 Ga (Polat et al., 2015; Kusky et al., 2021; Nutman et al., 2021). It is noted that antiformal, imbricate thrust stacks in the Isua Belt of Greenland share broad similarities with Cenozoic orogenic systems (Windley et al., 2021). It is further noted that the classic dome and keel structures observed in the Paleoarchean Pilbara craton are similar to those found in the Cenozoic Sierra Nevada plutons (Kusky et al., 2021). These uniformitarian interpretations are contested by others who argue the structural features discussed are non-unique to plate tectonic process and can also form within intraplate and non-convergent settings through vertical tectonics and delamination (Webb et al., 2020; Harris and Bédard, 2014; Moore and Webb, 2013; Johnson et al., 2016). This interpretational ambiguity inevitably brings us to theoretical consideration of likely tectonic regimes in the early Earth, which is discussed in the next section.

Modeling constraints and physical feasibilities

The extreme scarcity of geological data relevant to the early Earth necessitates theoretical approaches to infer global processes from fragmentary data. For example, the East Pilbara Terrane in Western Australia has often been used to discuss Archean tectonics (e.g., Van Kranendonk et al., 2007), but its spatial extent is ~40,000 km^2, corresponding to only 0.02% of the present-day continental area. The Acasta Gneiss Complex in northwestern Canada, which contains the oldest rocks on Earth (Bowring and Williams, 1999), is even smaller, by more than two orders of magnitude (Iizuka et al., 2007). We probably need to abandon the hope of reconstructing the style of global tectonics by assembling such minute remnants. We cannot, of course, disregard field constraints simply because of their limited spatial extents. Perhaps the most reasonable approach in this situation is to assess whether available observations are consistent with any of the competing hypotheses on the style of global tectonics.

The ongoing debate on the style of early global tectonics centers on whether plate tectonics was operating, and if not, what kind of tectonics was taking place instead (e.g., Cawood et al., 2018; Stern, 2018; Korenaga, 2021). Using ancient geological data to discount the possibility of plate tectonics is not easy. If plate tectonics was operating in the early Earth, the details of its geological and geochemical consequences are likely to be different from what we observe for the modern Earth, because the relevant physical conditions, such as the potential temperature of the mantle and its chemical state, are expected to have been different in the past (e.g., Herzberg et al., 2010; Palin and White, 2016). A variety of processes can take place with plate tectonics. Even limiting ourselves to mantle-crust differentiation, there are three major types of magmatism, including mid-ocean-ridge magmatism, hotspot magmatism, and arc magmatism, and there exist two different kinds of crust, oceanic and continental. Each type of magmatism can be quantitatively different in the past. The oceanic crust is expected to have been thicker because of a hotter mantle (McKenzie and Bickle, 1988; Langmuir et al., 1992). The continental crust may have possessed different dynamical characteristics because radiogenic heat production was intrinsically greater in the past (e.g., Morgan, 1985; Rey and Coltice, 2008). To demonstrate that a given observation is inconsistent with the operation of plate tectonics, we need to provide reasonably accurate theoretical predictions for such various aspects of geological processes, but in many cases, our modeling capability is not sufficiently mature. For one thing, both mantle and crustal dynamics hinge critically on rock rheology, the quantitative understanding of which is still subject to considerable uncertainties (e.g., Jain and Korenaga, 2020, Mai and Korenaga, 2022). If some early Earth observations do not readily conform to the expectations from the modern plate tectonics, it would be worth asking first whether they can be explained by some plate tectonics processes under different conditions, before jumping to the conclusion that plate tectonics was absent, especially because such observations usually correspond to a highly localized part of global tectonics. Whereas such an approach appears to be certainly possible (Kusky et al., 2021; Windley et al., 2021), there has been a strong tendency in the literature to favor non-plate-tectonics interpretations. This tendency owes partly to some widely-cited geodynamical studies that suggest a likely transition from a non-plate-tectonics regime to plate tectonics in the middle of Earth history (e.g., O'Neill et al., 2007; Moore and Webb, 2013). As recently reviewed (Korenaga, 2017b, 2021), however, such theoretical studies suffer from a number of modeling issues, and a few representative cases are briefly summarized in the following.

The work of O'Neill et al. (2007) is one of the early studies that promote the notion of plate tectonics being more unlikely in the past. Their reasoning goes as follows. Radiogenic heat production was greater in the past, so the mantle was hotter. A hotter mantle is less viscous, generating lower convective stress. At some point in Earth history, therefore, convective stress may become too low to break the strong lithosphere, preventing the initiation of subduction, which is equivalent to the shutdown of plate tectonics. They generated a series of convection simulations, which appear to support this idea. The main problem with this argument is that, whereas convective stress is certainly reduced for a lower-viscosity mantle (Solomatov, 2004), the amplitude of stress change is trivial for the range of temperature changes over Earth history (only a few hundred degrees Kelvin; Herzberg et al., 2010). Why the numerical simulations of O'Neill et al. (2007) exhibit a transition from plate tectonics to stagnant lid convection is that, by increasing the amount of radiogenic heating within the mantle, their model also suppresses the core heat flux, that is, mantle plumes, and the reduced strength of mantle plumes helps to lower convective stress substantially. The likely thermal evolution of Earth, however, indicates a higher core heat flux in the past (e.g., Nimmo, 2007; O'Rourke et al., 2017), so an argument based on the secular evolution of convective stress should actually lead to the greater likelihood of plate tectonics in the past. When simulating mantle convection to discuss its possible secular evolution, we have to be careful about the thermal budget, which describes how the surface heat flux is supported by the radiogenic heating of the mantle and its secular cooling, as well as the core heat flux (Korenaga, 2017b). The thermal budget of mantle convection simulated in the study of O'Neill et al. (2007) and its variations (e.g., O'Neill et al., 2016) is too different from that of the actual Earth to interpret their modeling results in terms of Earth evolution.

Similarly, the heat-pipe model of Moore and Webb (2013) is compromised by their adopted evolution of radiogenic heating (see section 2.6 of Korenaga, 2021). In their model, the early mantle has about 18 times greater radiogenic heating than the present-day mantle, as opposed to the actual four- to five-hold difference. This treatment can only be justified if the half-lives of relevant radioactive isotopes were shorter than their actual values, or if Earth was much older than 4.5 Ga. Their modeling results are presented in a nondimensional form (a common practice in fluid mechanics), so this fact is not obvious, but if we dimensionalize their numerical results, it would become evident that, in their model, subduction initiation takes place only after ~33 Gyr from the beginning of Earth history. Such model behavior is clearly inconsistent with the present-day operation of plate tectonics.

Various tectonic regimes other than plate tectonics and stagnant lid convection have been proposed in the literature. The possibility of intermittent plate tectonics, in which the surface is occasionally (typically at an interval of a few hundred million years) renewed by global subduction events, was first noted by Moresi and Solomatov (1998), while they were systematically exploring the effect of plastic yielding on mantle convection. Later studies have repeatedly shown the presence of such an intermediate episodic regime (e.g., Stein et al., 2004, 2013; O'Neill et al., 2007; Weller et al., 2015; Lourenço et al., 2016, 2020). However, the viability of this episodic regime depends critically on the subtle detail of how the yield strength of rocks is modeled in numerical simulations. The yield strength of rocks at lithospheric depths is characterized by a weak cohesive strength ($\ll$1 MPa), which is constant with depth, and a strongly pressure-dependent term (Byerlee, 1978; Kohlstedt et al., 1995). Despite this, it is common to vary the former depth-independent term, while using low pressure dependence for the latter, in convection simulations, and having low pressure dependence is essential for intermittent plate tectonics to happen in simulations (Stein et al., 2004; Korenaga, 2010). When a yield strength is said to be varied from, for example, 20–200 MPa in some study, authors are usually varying only the magnitude of the pressure-independent term, with zero pressure dependency. However, there is no rock mechanics basis for such parameterization of rock rheology.

Suggesting a tectonic regime other than plate tectonics for the early Earth implicitly requires us to explain why plate tectonics takes place on the modern Earth, but this is still an unsettled issue. In other words, any discussion on the style of ancient tectonics depends on the assumed conditions for the operation of plate tectonics. If, for example, the presence of surface water is the key to plate tectonics (e.g., Mian and Tozer 1990; Regenauer-Lieb et al., 2001; Korenaga, 2007), the likely existence of the Hadean ocean (Wilde et al., 2001; Mojzsis et al., 2001) could have facilitated plate tectonics. The theoretical study of Korenaga (2010) has derived a scaling law that allows us to quantify the effect of water, whether on surface or in the mantle, on the likelihood of plate tectonics. According to this scaling, the thermal cracking of oceanic lithosphere, owing to its strongly temperature-dependent viscosity, can effectively nullify the yield strength of the strongest part of the lithosphere in the presence of surface water, and plate tectonics is possible throughout Earth history (Korenaga, 2011). The thermal cracking of the oceanic lithosphere has observational support (Korenaga and Korenaga, 2008; Korenaga, 2017a; Chesley et al., 2019), but its efficacy in reducing the yield strength is an open question. If it weakens the oceanic lithosphere as suggested by Korenaga (2007), however, the yield strength of the oceanic lithosphere remains low in the early Earth. This possibility should be contrasted with the suggestions of non-plate-tectonic regimes, such as the "plutonic-squishy lid" regime of Lourenço et al. (2020), which requires a moderate yield strength of the lithosphere (>40 MPa).

The possibility of plate tectonics in the early Earth certainly helps the formation of early continental crust (Campbell and Taylor, 1983). It is possible to generate felsic magma without plate tectonics, through the melting of hydrated crust by reheating (Petford and Gallagher, 2001; Annen et al., 2006) or by delamination (Sizova et al., 2015; Rozel et al., 2017; Piccolo et al., 2019), but these mechanisms do not lead to the continuous production of continental crust on a global scale (Korenaga, 2021). Future developments in early Earth geodynamics are thus important for a better understanding of continental growth, and by the same token, establishing the history of continental growth from observations can provide strong constraints on the form of early tectonics.

Another important perspective is that the Hadean Earth has to bridge the magma ocean stage to the Archean Earth. Because carbon dioxide is not very soluble in magma (e.g., Papale, 1997), the post-magma-ocean Earth is usually considered to have been covered with a dense, CO_2-rich atmosphere (Abe, 1993; Sleep et al., 2001; Zahnle et al., 2007; Sossi et al., 2020; Gaillard et al., 2022). The only plausible mechanism to remove such a massive amount of atmospheric carbon (~100 bars), down to below 1 bar at the beginning of the Archean (Catling and Zahnle, 2020), is the subduction of carbonated seafloor (Sleep et al., 2001, 2014). A recent theoretical study suggests that, whereas the timescale of such carbon sequestration is more than one billion years with conventional plate tectonics, it can be sped up to less than 200 million years with rapid plate tectonics enabled by a peculiar mantle state resulting from the solidification of a magma ocean (Miyazaki and Korenaga, 2022). Having plate tectonics alone is not sufficient to bring the surface temperature of Earth to a moderate one by the beginning of the Archean; Hadean plate tectonics has to be exceptionally fast with respect to the modern standard. Thus, if we are to propose, either theoretically or observationally, a tectonic regime that does not recycle the surface as efficiently as plate tectonics does, we will also need to explain how to transform a dense CO_2-rich atmosphere to a habitable one, or to somehow dispute the notion of an initially dense CO_2-rich atmosphere.

Crustal growth models

Mantle-based models

After the model of Campbell (2003), interests in mantle-based models waned for a while, in contrast to growing efforts to utilize the global databases of detrital zircons. As reviewed in Section "Different kinds of continental growth models," however, such efforts have yielded just the distribution of surface ages (Rino et al., 2004; Condie and Aster, 2010), or in some cases, artifacts (Belousova et al., 2010; Dhuime et al., 2012). The work of Kumari et al. (2016, 2019) represents a renewed interest in the mantle-based approach. Their modeling approach is similar to that of McCulloch and Bennett (1994), with the major difference being the number of mantle reservoirs employed. They tested eight different net growth patterns (Hurley and Rand, 1969; Brown, 1979; Armstrong, 1981b; Dewey and Windley, 1981; McLennan and Taylor, 1982; Allègre and Rousseau, 1984; Patchett and Arndt, 1986; Goodwin, 1996) using the Rb-Sr, Sm-Nd, and U-Th-Pb systems, with their most preferred model being the (speculation-based) model of Brown (1979). As explained in Section "Mantle-based models," the only Sm-Nd isotope systems would be meaningful as observational constraints. More importantly, Kumari et al. (2016, 2019) used only one pair of crustal generation and recycling rates, for each of the net growth patterns they tested. For any given net growth curve, however, there exist infinite pairs of crustal generation and recycling rates. Why they were able to pick one is because they assumed (1) that both rates have the same decay constant, and (2) that the decay constant is equivalent to the average decay constant for heat-producing elements. Both assumptions are difficult to justify. There is no a priori reason to believe that the secular evolution of crustal recycling follows that of crustal generation. Also, there is no geophysical basis for the assumption that the rate of crustal generation or recycling is proportional to the amount of radiogenic heating in the mantle. Their second assumption stems from a common misconception about the thermal evolution of Earth, so a further explanation is provided in the following.

The amount of radiogenic heating was definitely greater in the past, because of the very nature of radioactive decay, but this does not mean that surface heat flow, or the vigor of mantle convection, was higher in the past. In the classical thermal evolution models for Earth's mantle (e.g., Schubert et al., 1980; Davies, 1980), the evolution of surface heat flow follows that of internal heat production, but such evolution models have long been known to violate geochemical constraints on the amount of radioactive isotopes in the mantle (Christensen, 1985; McDonough and Sun, 1995), and at present, radiogenic heat production within Earth accounts for less than half of surface heat flow. Christensen (1985) suggested that, if the vigor of mantle convection does not depend on mantle temperature, it is possible to construct a thermal evolution model that is consistent with the abundance of heat-producing elements in Earth's mantle. Although his scaling for the relation between surface heat flux and mantle temperature was later shown to be incorrect (Solomatov, 1995), Korenaga (2003) showed that a similar scaling could be obtained by incorporating the effect of mantle melting on the vigor of mantle convection. This means that the vigor of mantle convection (and thus surface heat flow) would not change much with time (in fact, it is estimated to have been slightly lower in the past), being decoupled from the evolution of mantle temperature as well as that of radiogenic heating. When radiogenic heating was higher than surface heat flow, the mantle would warm up, and when the former became lower than the latter, the mantle could start cooling down. This is shown to be consistent with the thermal history of Earth's mantle inferred from the petrology of Precambrian igneous rocks (Herzberg et al., 2010), and the reduced vigor of mantle convection, or equivalently, the slower tempo of plate tectonics, in the past is supported by the lifetime of passive margins (Bradley, 2008) as well as the evolution of continental plate motion (Condie et al., 2015; Pehrsson et al., 2016). As these observational constraints are valid only back to the mid-Archean, the tempo of plate tectonics can be different in the Hadean and the early Archean, as discussed in Section "Modeling constraints and physical feasibilities."

Thus, it would be imprudent to assume that crustal evolution would follow the temporal evolution of radiogenic heating. As discussed in Section "Mantle-based models," we need to explore extensively different scenarios of crustal evolution if we wish to understand the true strength of chosen observational constraints. Rosas and Korenaga (2018) used Monte Carlo sampling to delineate the permissible range of crustal generation and recycling for published ^{142}Nd/^{144}Nd and ^{143}Nd/^{144}Nd data (Fig. 4), and their results indicate that early crustal growth may have been even more rapid than the model of Armstrong (1981b) suggests. In addition to Monte Carlo sampling, their model is notable for the following two points. First, the present-day rate of crustal recycling predicted by their model is consistent with the present-day rate of sediment subduction (Scholl and von Huene, 2007; Stern and Scholl, 2010). Second, the present-day formation age distribution predicted by their model is consistent with the one estimated from a global database of detrital zircons (Korenaga, 2018; see also Section "Crust-based models"). Neither the rate of sediment subduction nor the formation age distribution was used as a constraint during their Monte Carlo sampling, so it is interesting that fitting to the Nd isotope data alone results in such consistencies.

The model of Rosas and Korenaga (2018) suggests that crustal recycling was more intense in deep time (Fig. 4b), in a manner similar to what Armstrong (1981a) speculated. As noted in Section "Mantle-based models," there is a long tradition of downplaying the role of crustal recycling, and a common argument against intense crustal recycling in the past is the observed difference between the continental crust and the oceanic crust (including both MORB and OIB), in terms of isotope signatures and trace element ratios (e.g., McCulloch and Bennett, 1993; Rollinson, 2017). For example, Rollinson (2017) questions the presence of a massive felsic continental crust in the past and its subsequent destruction by recycling, because the isotope systematics of OIB requires that the contribution of recycled upper continental crust to OIB has to be subordinate to that of recycled oceanic crust (e.g., White, 1989; Stracke, 2012). As discussed by Korenaga (2021), however, this is a misleading argument. Because the continental crust is isotopically quite distinct and is also enriched in those isotopes, one only has to add a small amount of it to change the isotope composition of source mantles for MORB and OIB. This does not preclude the long-term recycling of a substantial amount of continental crust. As seen in Fig. 4c, the model of Rosas and Korenaga (2018), which is characterized by intense crustal recycling in the early Earth, can reproduce the ^{143}Nd/^{144}Nd evolution of the depleted MORB-source mantle. The chemical and isotopic compositions of the present-day convecting mantle (i.e., MORB and OIB source mantles) already include the time-integrated effect of the extraction of continental crust and its recycling, so one cannot simply deduce the history of crustal recycling based on the present-day differences between continental and oceanic rocks.

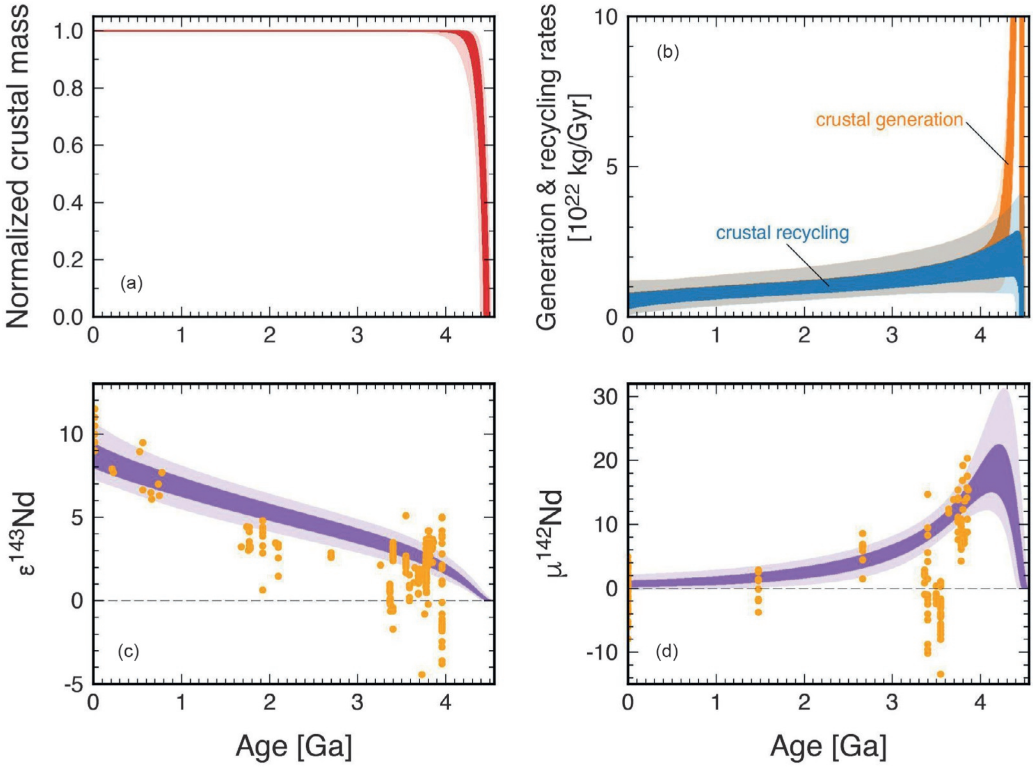

Fig. 4 Mantle-based model of Rosas and Korenaga (2018). In each panel, dark and light shades encompass mid-50% and mid-90% of Monte Carlo solutions, respectively. (a) Net crustal growth. (b) Rates of crustal generation (orange) and crustal recycling (blue). (c) 143Nd and (d) 142Nd evolution of the depleted mantle. Published data are shown by orange circles (Baadsgaard et al., 1986; Moorbath et al., 1997; Vervoort and Blichert-Toft, 1999; Caro et al., 2006, 2017; Bennett et al., 2007; Murphy et al., 2010; Rizo et al., 2012; Jackson and Carlson, 2012; Debaille et al., 2013; Roth et al., 2014; Puchtel et al., 2016; Morino et al., 2017). ε^{143}Nd(t) is defined as $[(^{143}\mathrm{Nd}/^{144}\mathrm{Nd})_t/(^{143}\mathrm{Nd}/^{144}\mathrm{Nd})_t^{\mathrm{CHUR}} - 1] \times 10^4$, and μ^{142}Nd(t) as $[(^{142}\mathrm{Nd}/^{144}\mathrm{Nd})_t/(^{142}\mathrm{Nd}/^{144}\mathrm{Nd})_t^{\mathrm{std}} - 1] \times 10^6$, where "CHUR" and "std" stand for the chondritic uniform reservoir and the terrestrial standard reference, respectively.

There are, however, at least two major limitations to the work of Rosas and Korenaga (2018). First, their parameterization of crustal growth is limited to the monotonic variation of crustal generation and recycling rates. After the onset of crustal growth, the crustal generation rate can be either steadily decreasing or increasing with time, and the same is true for the recycling rate. Whereas this parameterization can cover most of the so far proposed patterns for net growth, it cannot handle non-monotonic growth patterns such as the model of Fyfe (1978). Deviating from monotonic variations requires more model parameters, which would be more poorly constrained given the currently available Nd isotope data. This problem may be alleviated by combining with other isotope systems (Section "Indirect models"). Second, whereas the ^{143}Nd/^{144}Nd evolution of the depleted mantle can be attributed solely to the growth of the continental crust, the same does not apply to the ^{142}Nd/^{144}Nd evolution. There have been two contrasting interpretations of ^{142}Nd/^{144}Nd heterogeneities observed in Archean rocks: (1) continental growth (e.g., Caro et al., 2006; Rizo et al., 2012; Roth et al., 2014) and (2) initial Sm/Nd heterogeneities originating in planetary formation (Boyet and Carlson, 2005; Debaille et al., 2013; Jacobsen and Yu, 2015; Hyung and Jacobsen, 2020). In the second interpretation, the ^{142}Nd/^{144}Nd evolution of the depleted mantle becomes irrelevant to continental growth.

In the model of Rosas and Korenaga (2018), the onset of continental growth takes place very early (>4.35 Ga), and this owes to the continental growth interpretation of ^{142}Nd/^{144}Nd data as well as the suprachondritic nature of early Archean ^{143}Nd/^{144}Nd data (Fig. 4). The reliability of such positive ε^{143}Nd data from such Archean samples has long been debated (e.g., Vervoort et al., 1996), and it is of particular concern because ^{176}Hf/^{177}Hf data, which usually correlate well with ^{143}Nd/^{144}Nd data (Vervoort et al., 1999), become suprachondritic only after 3.8 Ga (Fisher and Vervoort, 2018; Kemp et al., 2019; Salerno et al., 2021). Besides the possibility that ^{143}Nd/^{144}Nd data are simply compromised by fractionation of Sm and Nd during metamorphic alteration (e.g., Fisher et al., 2020), it has been proposed that the Sm-Nd system and Lu-Hf system could have behaved differently in the early Earth, owing to the consequence of magma ocean solidification (Caro et al., 2005) and subduction zone processes (Hoffmann et al., 2011). One of lower mantle minerals, Ca-perovskite, has a unique partitioning behavior (Corgne et al., 2005), and its crystallization during magma ocean solidification can lead to the formation of a primitive lower mantle with a suprachondritic Sm/Nd but with the chondritic Lu/Hf. The solidification of a magma ocean is the process that sets the initial condition for subsolidus mantle convection, and recent modeling studies suggest that the formation of a chemically heterogeneous primitive mantle is a likely consequence (Maurice et al., 2017; Ballmer et al., 2017; Boukaré et al., 2018; Miyazaki and Korenaga, 2019). Given the partitioning behavior of

Ca-perovskite, such chemical heterogeneities are likely to be associated with isotopic heterogeneities. The decoupling of Nd-Hf isotope signatures owing to magma ocean solidification is thus a possibility that is difficult to dismiss.

Guo and Korenaga (2023) have explored the influence of such initial isotopic heterogeneities in their analysis of the Nd-Hf isotope evolution of the depleted mantle. Their geochemical box modeling incorporates the effect of finite-time mantle mixing on mantle melting, which allows them to investigate how quickly the signature of mantle depletion, created by the extraction of continental crust, can appear in observable crustal rocks. When the mantle differentiates into the crust and the depleted mantle residue, the latter carries the signature of mantle depletion. Because such a mantle residue is chemically depleted, however, its solidus is now elevated so that it does not melt again unless it is somehow heated up even further, is added with some volatiles such as water, or is remixed with more fertile rocks. Whereas the first two possibilities require some special tectonic conditions, the third possibility is what happens everywhere in the convecting mantle. Convective mixing takes some finite time, so some time lag is expected between the onset of continental growth and the first appearance of depleted mantle signatures in igneous rocks. According to Guo and Korenaga (2023), the observed ^{142}Nd/^{144}Nd evolution suggests that such a time lag is around 650–750 million years in the early Earth, regardless of its origin, that is, whether it is caused by continental growth, initial heterogeneities, or the combination of both. In turn, this time lag indicates that the appearance of suprachondritic ^{176}Hf/^{177}Hf signatures at ~3.8 Ga (e.g., Fisher and Vervoort, 2018) requires the onset of substantial continental growth by ~4.4 Ga. At the same time, this also suggests that processes other than continental growth are necessary to explain the full magnitude of the suprachondritic ^{143}Nd/^{144}Nd data in the early Archean, including metamorphic alteration (Fisher et al., 2020), magma ocean solidification (Caro et al., 2005), and subduction zone processes (Hoffmann et al., 2011). Despite this remaining ambiguity in early ^{143}Nd/^{144}Nd data, the combination of ^{142}Nd/^{144}Nd and ^{176}Hf/^{177}Hf evolution suggests that continental growth on a planetary scale started within the first 100 million years of Earth history (Guo and Korenaga, 2023).

Crust-based models

As explained in Section "Different kinds of continental growth models," it is important to distinguish between different types of crustal growth models, and studies based on (mostly detrital) zircons are inherently about crust-based models. That is, the age information contained in zircons can be used to estimate the formation age distribution of the extant continental crust, which serves as the lower bound for net crustal growth. Each zircon grain can provide at least two different ages: a U-Pb crystallization age and a Hf-depleted mantle model age. Roberts and Spencer (2015) presented the then most comprehensive database of detrital zircons, which contains ~42,000 pairs of these types of ages. However, they used this database following the methods of Belousova et al. (2010) and Dhuime et al. (2012), so their suggested "growth curves" belong to the category of artifacts.

Based on the earlier suggestion that the depleted mantle model age reflects the weighted average of multiple formation ages (Farmer and DePaolo, 1983; Patchett and Arndt, 1986), Korenaga (2018) suggested a simple scheme to make use of both U-Pb crystallization ages and Hf depleted mantle model ages and estimate the formation age distribution (Fig. 5a). In the framework of a single-step binary mixing scenario between a primary crust and a newly formed crust, a depleted mantle model age can be interpreted as the average of the U-Pb crystallization age and the formation age of the primary crust (Fig. 6a). Under this assumption, the formation age of a given zircon grain can be determined by simple external division, that is, by adding twice the difference between the crystallization age and the model age to the crystallization age (Fig. 6b). In the unmixing method of Korenaga (2018), each pair of a U-Pb crystallization ages and a Hf depleted mantle model age produces two pseudodata, T_1 and T_2, the former being equivalent to the crystallization age and the latter being the extrapolated age as described above, and both times represent independent episodes of crustal formation. A formation age distribution is then estimated by using both kinds of pseudodata; for example, if a given zircon database contains 10,000 pairs of U-Pb crystallization ages and Hf-depleted mantle model ages, the unmixing method yields 20,000 formation age estimates made of 10,000 T_1 and 10,000 T_2. By conducting a series of tests with various synthetic data, Korenaga (2018) showed that this simple scheme could yield a reliable estimate on the formation age distribution (Fig. 7; compare with Fig. 3), even when some of the simplifying assumptions are violated, such as single-step mixing and binary mixing.

Garçon (2021) attempted to constrain the history of new crust generation following the approach proposed by Allègre and Rousseau (1984), with a more extensive compilation of sedimentary Nd isotope data. However, the decomposition of the observed Nd isotopic evolution into the amounts of newly added crust and reworked crust is inherently nonunique, and the adopted scheme should be seen as one end-member maximizing the degree of episodicity of continental growth. Unlike the earlier work of Allègre and Rousseau (1984), Garçon (2021) correctly acknowledges the difference between net crustal growth and the distribution of formation ages, and whereas the suggested degree of episodicity in new crust generation may have been overestimated, a certain degree of episodicity is likely to be required by the data. Garçon (2021) argues that such episodicity probably reflects enhanced crustal growth during supercontinental assemblies, though the timings of the peaks suggested from the sedimentary Nd isotope record and those from detrital zircons, the latter of which correlates well the supercontinental cycles (e.g., Condie, 1998), do not match well. This may not be surprising because sedimentary Nd records, unlike zircon databases, do not provide crystallization ages. The deposition age of a given sedimentary rock and the crystallization ages of the grains that constitute the sedimentary rock can be separated by varying duration.

Additional models calling for episodic growth of the continental crust are predominantly crust-based models (Fig. 1b; Allègre and Rousseau, 1984; Nelson and DePaolo, 1985; Patchett and Arndt, 1986; Rino et al., 2004; Condie and Aster, 2010). Nevertheless, it has been argued by Albarède (1998) that these episodic crust-based growth models are likely tied to mantle-driven processes. It is broadly assumed that continental crust formation centers on major mantle instabilities or superplumes, and their crustal

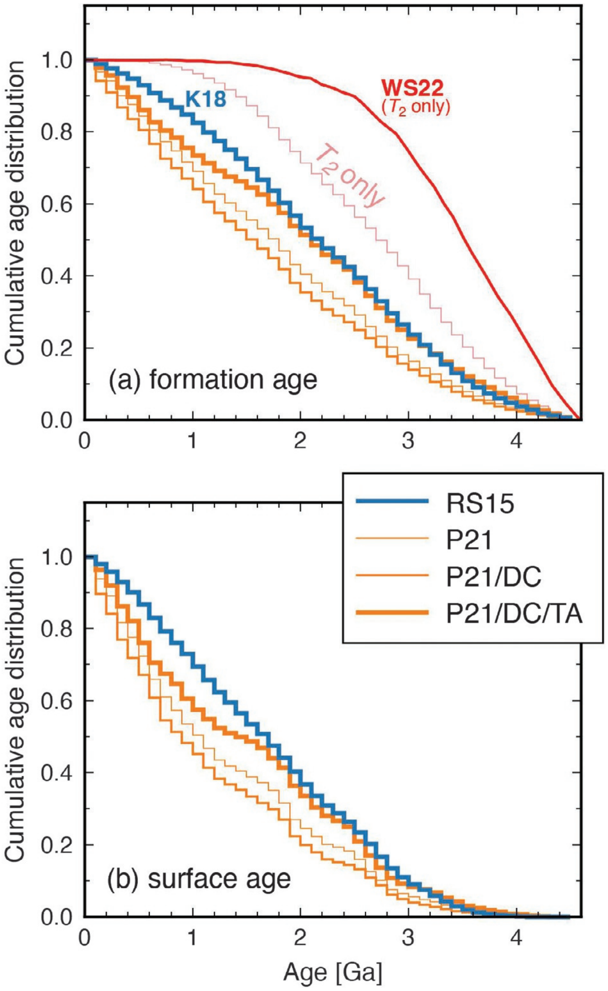

Fig. 5 Cumulative distributions of (a) crustal formation ages and (b) surface ages, based on four different kinds of zircon database: RS15 (Roberts and Spencer, 2015), P21 (Puetz et al., 2021; original data), P21/DC (declustered data), and P21/DC/TA (declustered and temporally averaged). Formation age distributions in (a) are all derived by the unmixing method, and the crust-based model K18 (Korenaga, 2018) is based on RS15. "T_2 only" denotes an incomplete application of the unmixing method to P21/DC/TA, as described in the text. The model WS22 (Wang and Spencer, 2022), is also shown. The difference between "T_2 only" and WS22 is mostly owing to different assumptions made for the reworking index. Surface age distributions in (b) are based simply on U-Pb crystallization ages.

manifestation as oceanic plateaus. These geological features, characterized by the rapid eruption of plume-derived basalts on the ocean floor, ultimately reach a buoyancy threshold, thus attaining the status of continental crust. This process culminates in the accretion of plateaus against existing continents, followed by the emergence of distinctive felsic magmas, which stand as hallmark features of continental crust chemistry. Albarède (1998) discussed aspects of crustal growth that have not received as much attention including ridge subduction and underplating of plume-derived material. While the latter may not be self-initiating in terms of continent formation, it is argued to enhance overall crustal growth efficiency. Oceanic plateau accretion, such as the Ontong-Java plateau, provides additional support for episodic crustal growth as the stochastic nature of mantle plumes that form oceanic plateaus and the unsystematic timing from formation to accretion. The thickness of oceanic plateaus effectively shields it from subduction and preferentially leads to accretion thus contributing to net crustal growth. This intriguing process calls for a deeper investigation into the geological conditions that facilitate such extended periods of crustal growth. Each of these plume-related mechanisms provides mechanisms for episodic net crustal growth that, due to the predominantly mafic nature of the magmatism, adds very little to the zircon record and is therefore missed in studies that focus exclusively on the zircon record.

Recently, based on the new zircon database of Puetz et al. (2021), which contains ~165,000 pairs of U-Pb crystallization age and Hf-depleted mantle model age, Wang and Spencer (2022) presented a new "crustal growth" curve (Fig. 9a), which is similar to the model of Patchett and Arndt (1986), in that there is little growth in the last 1.5 billion years, and to the model of the Dhuime et al. (2012), in that ~50% of the present-day continental mass was achieved gradually in the first one billion years. Unlike earlier studies, Wang and Spencer (2022) do not directly use a chosen zircon database. Taking into account the possibility that existing databases, however extensive they are, can still suffer from incomplete and biased sampling, they applied spatiotemporal bias-canceling to the database of Puetz et al. (2021). To correct for spatial biasing, they applied the declustering scheme of Pyrcz

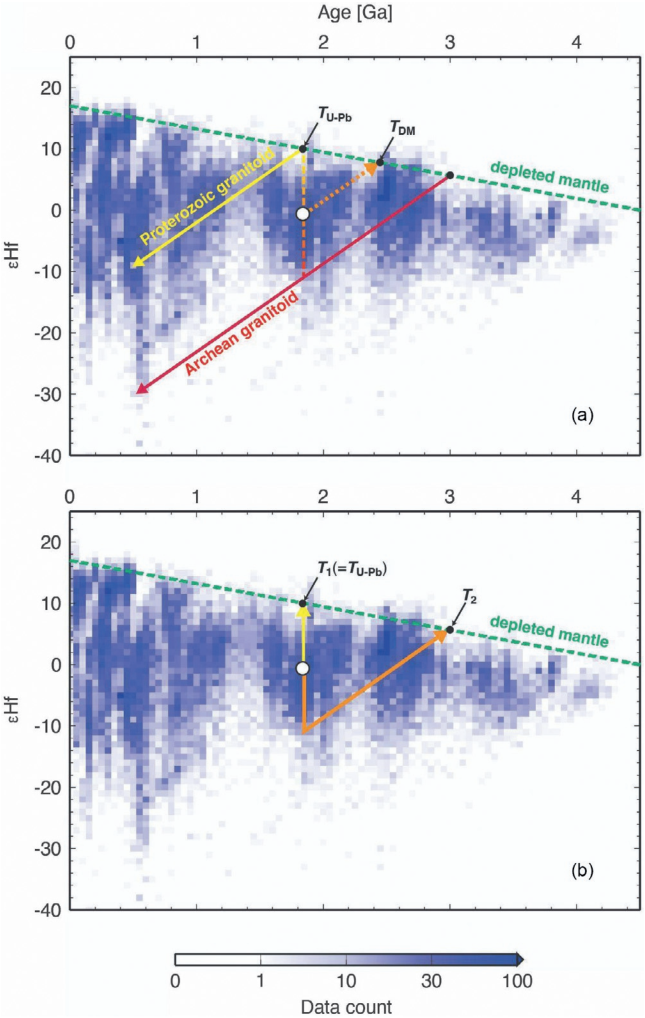

Fig. 6 Distribution of Hf and crystallization age data for the global zircon database of Roberts and Spencer (2015). Hf is defined $[(^{176}Hf/^{177}Hf)_{sample}/(^{176}Hf/^{177}Hf)_{CHUR} - 1] \times 10^4$, where "CHUR" represents chondritic uniform reservoir (Blichert-Toft and Albarede, 1997), calculated at the crystallization age of sample. The evolution of depleted mantle (Vervoort and Blichert-Toft, 1999) is shown as a green dashed line. Two kinds of zircon ages, $T_{U\text{-}Pb}$ and T_{DM}, are indicated for a hypothetical datum (open circle). A sample mixing scenario for the datum is schematically drawn; an Archean crust evolving along the red arrow is reworked by the formation of a Proterozoic crust, which itself evolves along the yellow arrow. (b) How the unmixing method works for the hypothetical datum in the age-εHf space. The reworking index is set to 0.5 in this example. After Korenaga J (2018) Estimating the formation age distribution of continental crust by unmixing zircon age data. *Earth and Planetary Science Letters* **482**: 388–395.

and Deutsch (2003). They divided Earth's surface into 5° × 5° grids, and all grids with some data were treated equally. For example, if one grid contains 100 zircon data and the other has 10 zircons, each of 100 zircons in the former grid receives a relative weight of 1/10 with respect to the data in the latter grid. This declustering helps avoid over-representing the areas that happen to have been more extensively studied than others. Fig. 8 shows that declustering reduces the amplitudes of the prominent peaks seen at crystallization ages of ~0.5, ~1.8, and ~2.5 Ga in the database of Puetz et al. (2021). Their temporal de-biasing procedure may be more controversial. In each of those 5° × 5° grids with data, they averaged εHf values (and thus Hf-depleted mantle model ages) in 100-Myr bins of U-Pb crystallization ages. For example, if there are 30 data and 2 data in the 100–200 and 500–600 Ma bins, respectively, each bin provides just one εHf and Hf-depleted mantle model age after this temporal averaging. This temporal averaging considerably suppresses the peak at ~0 Ga and enhances the subtle temporal pattern (Fig. 8). This temporal averaging in the crystallization age vs. εHf space may inadvertently introduce biases toward points with little observational support.

A more serious issue with the model of Wang and Spencer (2022) is their incomplete application of the unmixing method of Korenaga (2018). They calculated their "growth curve" (or more properly, the formation age distribution) using T_2 pseudodata only. As noted above, for the unmixing method to function, it is essential to use both T_1 and T_2 pseudodata, and using T_2 pseudodata only is equivalent to discarding half of all data, introducing a severe bias toward crustal generation in deep time (Fig. 5a). This is why their formation age distribution shows little crustal formation since the Mesoproterozoic. As for the model of Patchett and Arndt (1986) (Section "Crust-based models"), such behavior is not appropriate for a formation age distribution

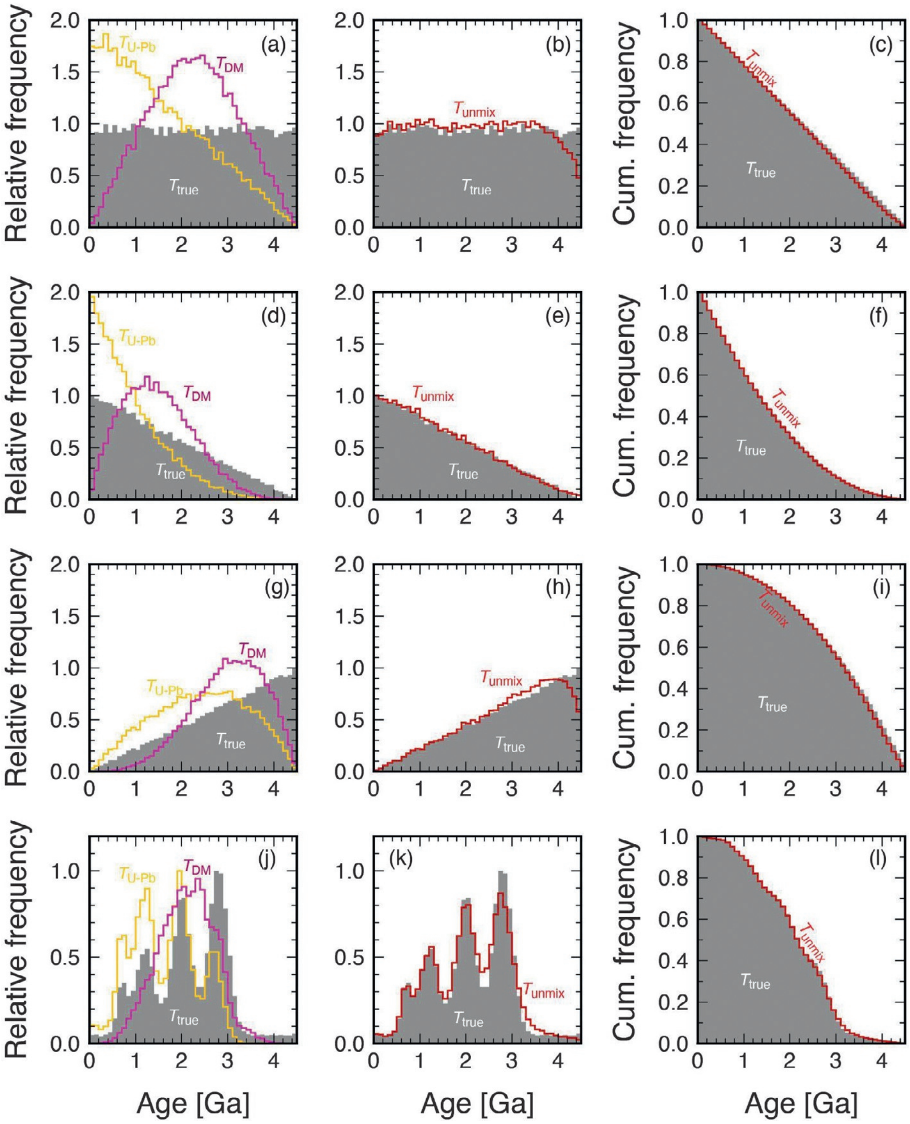

Fig. 7 Demonstration of how the unmixing method works, with four different sets of synthetic data: (first row) constant crust production through time (second row) more production in recent times (third row) less production in recent times, and (fourth row) multiple peaks in crustal production. The first column shows the true distribution (gray) and the corresponding distributions of U-Pb crystallization age ($T_{\text{U-Pb}}$; yellow) and the depleted mantle model age (T_{DM}; magenta). The second column compares the formation age distribution according to the unmixing method with the true distribution of crust production (gray). The third column is a cumulative version of the second column. After Korenaga J (2021) Hadean geodynamics and the nature of early continental crust. *Precambrian Research* **359**: 106178.

because it is not consistent with observational constraints on modern rates of crustal generation and recycling. It is important to remember that what we can estimate from zircon databases of U-Pb crystallization ages and Hf-depleted mantle model ages is a formation age distribution, not net crustal growth, at least in the ways that those databases have been analyzed.

Nevertheless, the spatiotemporal debiasing effort of Wang and Spencer (2022) poses an important question for the fidelity of global zircon databases. The database of Puetz et al. (2021) is about four times larger than that of Roberts and Spencer (2015), and if these databases are treated without any debiasing, they yield notably different results for both surface age and formation age distributions (Fig. 5). This is important because these age distributions, if used together with a model of net crustal growth, can constrain the extents of crustal recycling and reworking (Section "Crust-based models"; Fig. 2). Correctly applying the unmixing method to the database of Puetz et al. (2021), with the spatiotemporal debiasing of Wang and Spencer (2022), actually yields results similar to those of Korenaga (2018), which are based on the database of Roberts and Spencer (2015) with no debiasing. How to deal with global zircon databases clearly warrants further consideration.

The unmixed crustal formation age distribution using the declustering and temporal averaging described by Wang and Spencer (2022) applied to the Puetz et al. (2021) database differs from Korenaga (2018) with a divergence of formation age distribution at

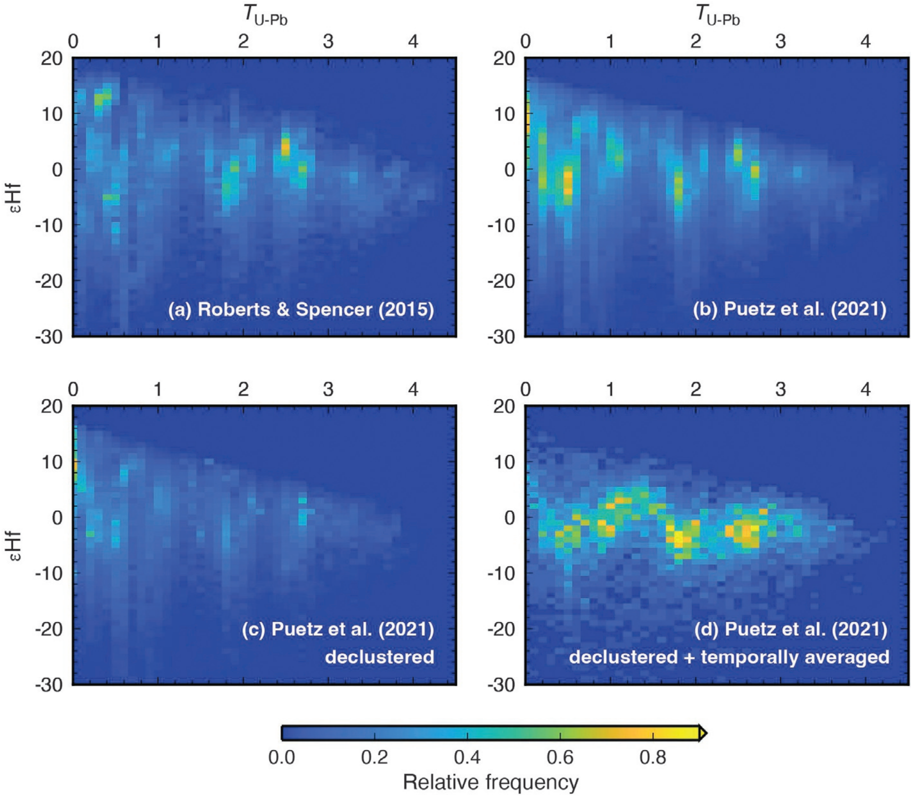

Fig. 8 Global databases of detrital zircons with U-Pb crystallization ages and Hf isotope data: (a) Roberts and Spencer (2015), (b) original, (c) declustered with 5° × 5° grids, and (d) declustered as well as temporally averaged versions of Puetz et al. (2021). Note that declustering conducted here takes into account that grids with different latitudes have different areas.

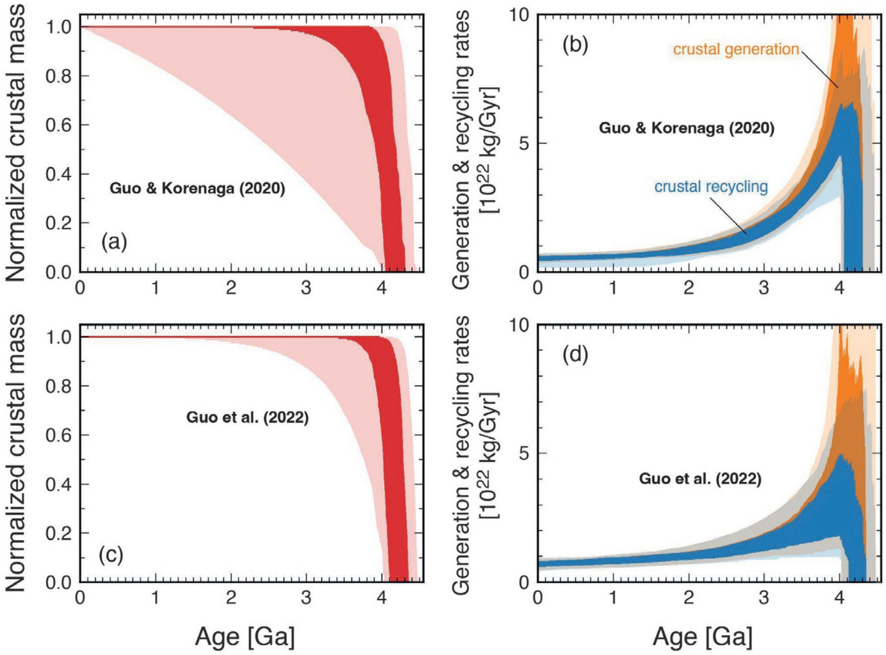

Fig. 9 Recent growth models with indirect approaches. (a, c) Net crustal growth and (b, d) crustal generation and recycling rates. The top row is the model of Guo and Korenaga (2020), which is based on the modeling of atmospheric argon isotopes, and the bottom row is the model of Guo et al. (2022), which is based on the modeling of seawater oxygen isotopes. As in Fig. 8, dark and light shades denote mid-50% and mid-90% of Monte Carlo solutions.

~1.8 Ga, implying a greater proportion of radiogenic (more mantle-like) crust formation in the former. This feature is clearly a function of both spatial declustering and temporal averaging (Figs. 5 and 8). The increase of radiogenic crust formation at ~1.8 Ga coincides with the onset of the Great Proterozoic Accretionary Orogeny (Condie, 2013) that spans every major Proterozoic craton and marks a period of time with a marked increase in Nuna-forming collisional orogens and circum-Nuna accretionary arcs. While the Paleoproterozoic Era has always been characterized by an anomalous drawdown of εHf, crustal formation curves have generally not captured this feature. The spatiotemporally debiased crustal formation curve proposed in Fig. 5 provides a testable hypothesis to further evaluate whether what we are seeing corresponds to some shift in tectonomagmatic style (see Weller and St-Onge, 2017) or is an idiosyncrasy of plate configuration controlled by regional geodynamics.

Recently, Reimink et al. (2023) proposed a modification of the ratio method, which deserves some discussion here. Similar to Korenaga (2018), they highlight some of the issues with the ratio method, i.e., the new crust generation rate calculated as $N_{DM}/(N_{DM}+N_{U\text{-}Pb})$ (Section "Artifacts") is just a "ratio" and not a "rate." As explained in Section "Artifacts," this ratio assumes that N_{DM} and $N_{U\text{-}Pb}$ represent newly generated crust and reworked crust, and with this assumption, the new crust generation rate becomes simply N_{DM}. Reimink et al. (2023) suggest that, multiplying the ratio with N_{DM}, instead of with $N_{DM}+N_{U\text{-}Pb}$, they can obtain an estimate of crustal growth. However, like the original ratio method, their procedure is lacking synthetic tests such as shown in Figs. 3 and 7 to demonstrate an accuracy in reproducing patterns of crustal formation. We recommend that additional work is needed in this regard and that all future proposed attempts to constrain crustal formation should begin with synthetic tests prior to applying said algorithms to empirical data. Treating a crust-based model as an estimate for (net) crustal growth is still common in the literature (e.g., Zhu et al., 2023), but the analysis of detrital zircon data with the crust-based approach can provide us only with the present-day formation age distribution at best.

There is a way to estimate net crustal growth from a global database of detrital zircons, though it is yet to be attempted. The depleted end of the εHf evolution of zircons may be equated to the evolution of the depleted mantle, and the enriched end to the evolution of the continental crust. By using both types of the εHf evolution, it is possible to conduct a geochemical box modeling in a manner similar to the εNd modeling of Jacobsen (1988). If we wish to exploit more details of the εNd vs. crystallization age distribution of detrital zircons, we can do so by extending the box model of Guo and Korenaga (2023) to model the spatial and temporal evolution of continental crust. The model of Guo and Korenaga (2023) treats the continental crust as a singular reservoir, so while it can track convective mixing and thus simulate the temporal evolution of the depleted mantle signals, it cannot model the spread of εNd within the continental crust.

Indirect models

Among the three indirect models reviewed in Section "Indirect models," the approach based on atmospheric argon isotopes (Pujol et al., 2013) can potentially be improved from a modeling perspective, and this is what was attempted by Guo and Korenaga (2020). To estimate the extent of argon degassing due to mid-ocean ridge magmatism and hotspot magmatism, they made use of the thermal evolution model of Earth, which was constrained by the cooling history of the upper mantle (Herzberg et al., 2010), and to estimate the extent of argon degassing due to crustal recycling and reworking, they used the formation age distribution and the surface age distribution of the continental crust, which had been estimated by Korenaga (2018) and Roberts and Spencer (2015), respectively. As in Rosas and Korenaga (2018), they employed Monte Carlo sampling to explore a wide range of crustal evolution scenarios as well as to incorporate various uncertainties associated with thermal evolution and mantle degassing. Their model of net crustal growth (Fig. 9a) is similar to the model of Rosas and Korenaga (2018) but has considerably greater uncertainties, reflecting the uncertainties of all processes involved in argon degassing. Net crustal growth, however, results from the balance between crustal generation and crustal recycling, and each of these processes are characterized by high intensity during the Hadean and gradual decrease afterwards (Fig. 9b). Despite the apparently large uncertainties in net crustal growth, therefore, this argon-based inference suggests that the continuous production of continental crust, which likely requires the concurrent operation of plate tectonics (Section "Modeling constraints and physical feasibilities"), was already underway during the Hadean.

More recently, Guo et al. (2022) attempted another indirect approach based on the secular evolution of the oxygen isotope composition of seawater (Fig. 9c,d). The oxygen isotope composition of seawater is controlled by hydrothermal alteration of oceanic crust, continental weathering, and the subduction of water and crustal materials (e.g., Wallmann, 2001). Whereas it was often assumed that these processes would balance out to maintain a steady-state oxygen isotope composition (e.g., Muehlenbachs and Clayton, 1976; Gregory and Taylor, 1981; Muehlenbachs, 1998), the possibility of secular evolution is difficult to dismiss (e.g., Perry et al., 1978; Walker and Lohmann, 1989; Kasting et al., 2006). The rates of hydrothermal alteration and subduction are controlled by the thermal evolution of Earth, and the extent of continental weathering is affected by the history of crustal formation. By extending the box modeling of Wallmann (2001) to incorporate the effects of thermal evolution and crustal evolution, and by conducting Monte Carlo sampling in a similar manner to Guo and Korenaga (2020), Guo et al. (2022) was able to show that the evolution of the oxygen isotope composition of seawater was sufficiently sensitive to crustal evolution; indeed, the uncertainty of estimated net crustal growth are smaller than that of the argon-based model. It should be noted, however, that their estimate on seawater oxygen isotope composition in the past relies critically on estimates made from marine iron oxides in the Phanerozoic and Proterozoic (Galili et al., 2019). The use of iron oxides is a relatively new approach in the field of marine isotope geochemistry, and the robustness of the work of Galili et al. (2019) remains to be seen.

Qualitative inferences

As mentioned in Section "Mantle-based models," the ^{176}Hf/^{177}Hf data of igneous zircons appear to become suprachondritic only after ~3.8 Ga (e.g., Fisher and Vervoort, 2018; Salerno et al., 2021). Fisher and Vervoort (2018) interpreted this observation as evidence for no planetary-scale mantle depletion prior to 3.8 Ga. In other words, they argue that substantial continental growth must have started after 3.8 Ga. As these authors do not quantify how the crust might have grown after 3.8 Ga, their inference would be best discussed under the category of qualitative inferences. Actually, their 3.8 Ga depleted mantle evolution line is based on a single-stage formation of continental crust, that is, the present-day volume of continental crust is assumed to have formed suddenly at 3.8 Ga. It is unlikely that they are suggesting such instantaneous crustal growth, and the depleted mantle evolution line is likely to be drawn as a mere reference. Also noted in Section "Mantle-based models," however, their interpretation of the Hf isotope data assumes that the evolution of the depleted mantle faithfully tracks the extraction of the continental crust, but this is correct only in a globally averaged sense, and it takes some caution when applying this concept to observations. The extraction of the continental crust at any given time leaves a small fraction of the convecting mantle chemically depleted, and it takes some finite time for this depleted mantle residue to remix with more fertile surroundings so that it can melt again and impart its depleted isotopic signature to observable rocks. As mentioned earlier, Guo and Korenaga (2023) estimated that the timescale of this finite-time convective mixing would have been ~0.7 Gyr in the early Earth. Thus, even if continental growth initiated at 4.5 Ga, the first appearance of depleted mantle signals is likely to be delayed until 3.8 Ga. Also, this time scale should be regarded as a global average; given the complexity of mantle convection, the efficiency of convective mixing is expected to exhibit regional variations. Based on the coupled Nd-Hf isotope evolution of the depleted mantle, Guo and Korenaga (2023) estimated that at least 50% of the present-day continental mass must have already existed by the end of the Hadean. Such rapid continental growth in the early Earth is also consistent with the secular evolution of continental basalt chemistry (Keller and Schoene, 2018), which suggests a nearly constant degree of depletion in the source mantle over the past ~3.8 Gyr.

The effect of finite-time mixing, therefore, leads to a considerable lag, on the order of a few hundred million years, between the extraction of continental crust and the appearance of corresponding depleted mantle signals, and this time lag is expected to vary from place to place. Considering this dynamical perspective, too detailed a reading of zircon Hf data may not be warranted. For example, Bauer et al. (2020) noted that a compilation of igneous and detrital zircons exhibited a secular shift to higher εHf after ~3.8 to 3.6 Ga, and they suggested that this shift reflected the abundant input of more juvenile (near chondritic εHf) components enabled by the onset of mobile-lid tectonics (i.e., plate tectonics) around this time. With the effect of finite-time mixing on the appearance of depleted mantle signals, the Hf isotopic signatures of zircons formed in the early Earth are naturally biased to negative εHf, and therefore caution is needed when translating the timing of the observed secular shift into a change in tectonic regimes. In fact, the upward shift of εHf around 3.8 Ga is not inconsistent with the continuous operation of plate tectonics since the Hadean, if one takes into account that the εHf of juvenile magma can become positive only after ~3.8 Ga (Guo and Korenaga, 2023).

The consideration of finite-time mantle mixing thus influences the way we interpret the evolution of mantle-related isotopic data. Kirkland et al. (2021), for example, focused on the details of how available zircon εHf data are distributed in time during the early Earth, from which they speculated on the secular evolution of crustal rejuvenation and its tectonic implications. This type of exercise needs to be viewed with caution for two reasons. First, their interpretation relies critically on the absence of data in certain domains of the age-εHf space, and the robustness of such absence is unclear given that early Earth data are intrinsically spatially limited (Section "Tectonic background"). Second, the interpretation of the details of εHf data requires a correspondingly detailed understanding of how depleted mantle signals would appear, in space and time, as a result of continental extraction and mantle mixing, but such an understanding is currently beyond our reach.

Differentiation of the crust-mantle system can also be constrained using short-lived radiogenic isotope systems such as ^{146}Sm-^{142}Nd. Given the relatively short half-life of ^{146}Sm (103 Ma), the ^{146}Sm-^{142}Nd system records the earliest phases of crust-mantle differentiation (>4 Gyr) (Caro et al., 2003; O'Neil et al., 2008). Recent studies of ^{142}Nd have established extensive crust-mantle differentiation within the first 200–300 Myr of Earth history (4.4–4.2 Ga; Morino et al., 2017; Maltese et al., 2022). In particular, Maltese et al. (2022) report ^{142}Nd anomalies in Paleoarchean rocks and posit multiple and distinct large-scale tectonomagmatic events that created discrete and long-lived mantle heterogeneities. This is consistent with the recent work of Guo and Korenaga (2023) that indicates large-scale mantle heterogeneities during the early Archean are necessary to explain radiogenic depletion of the mantle. An additional short-lived isotopic system that has proven useful in constraining early Earth processes is ^{182}Hf which decays to ^{182}W with a half-life of 8.9 Ma (Kleine and Walker, 2017). While ^{182}W anomalies that have been discovered in modern ocean island basalts are thought to have been derived from interactions at the core-mantle boundary (Rizo et al., 2019), ^{182}W anomalies found in Paleoarchean (3.55–3.22 Ga) rocks in the Kaapvaal Craton point to the long-term preservation of the Hadean protocrust and large-scale heterogeneity of the mantle leading to perennial remelting of recycled mafic restites derived from the Hadean protocrust (Tusch et al., 2022).

Secular evolution of continental crust composition

The divergent composition of the crust-mantle system is controlled at a first-order level by differentiation and the secular change in the composition of the mantle, and the continental crust has been argued to have a significant bearing on the evolution of the biosphere and atmosphere (Tang et al. 2016; Smit and Mezger, 2017; Keller and Schoene, 2018; Keller and Harrison, 2020). It has long been held that the early Earth was characterized by a predominantly mafic crust that increased in silica content over hundreds of millions to billions of years (Taylor, 1982; Dhuime et al., 2015; Tang et al., 2016). However, recent work suggests a significantly shorter timeframe in the formation of significant volumes of sialic crust. Keller and Harrison (2020) propose that for the past 4 Ga, the average silica content of the crust has remained constant. They further posit that in light of a near-constant average silica content through time, geochemical trends that have previously been interpreted to represent state shifts relating to atmospheric oxygenation (Smit and Mezger, 2017) or the onset of plate tectonics (Dhuime et al., 2015) can be ascribed to the secular cooling of the mantle. Supportive of a predominately felsic crust on the early Earth are Ti isotopes and trace element signatures of terrigenous sedimentary rocks (Greber et al., 2017; Ptáček et al., 2020), Mo isotopes of mafic and ultramafic igneous rocks (McCoy-West et al., 2019), and Nd isotopes of sedimentary rocks (Garçon, 2021). Importantly, the predominance of felsic crust implies either significant amounts of differentiation or remelting of the mafic protocrust. Recent petrological experiments have shown that the remelting of hydrated ultramafic lithologies is able to produce melts that are comparable in composition with those from which the Hadean age Jack Hills may have formed (Borisova et al., 2022).

Discussions related to the composition and evolution of the continental crust is generally limited to the upper crustal composition as this is the most readily exposed part of the crust with lower crustal exposures remaining relatively scant even within deeply eroded Precambrian orogenic cores. These secular compositional trends observed in the continental upper crust, however, do not necessarily indicate that the composition of the continental crust has evolved as well. Even with the same crustal composition through time, the upper crustal composition could exhibit a secular change if the internal structure of the continental crust evolves with time. In fact, it is commonly thought that the continental crust was less internally differentiated in the past (e.g., Taylor and McLennan, 1995; Kemp and Hawkesworth, 2003). Such secular evolution is expected for the long-lived continental crust subject to repeated crustal reworking events.

Constraining possible secular changes in the bulk crustal composition is challenging. Estimating even the present-day bulk crustal composition is already difficult and subject to large uncertainties, because of limited constraints on the lower crustal composition (Rudnick and Gao, 2014, Hacker et al., 2015). Thus, only some indirect approaches seem reasonable for this issue. One way is to evaluate the dynamical plausibility of a given geochemical box model built for continental growth. When box modeling is used to study continental growth, the enrichment of relevant elements in a newly generated batch of continental crust with respect to its source mantle is often assumed to be constant through Earth history (e.g., DePaolo, 1980; Jacobsen, 1988; McCulloch and Bennett, 1994; Caro et al., 2006). This treatment is most likely for the sake of simplicity, and although it does not readily conform to the common notion that the early continental crust was not evolved as much as the present-day continental crust, it would not affect modeling results considerably if the amount of early continental crust is estimated or assumed to be small. When the mass of the early continental crust is substantial (e.g., Armstrong, 1981b), however, this assumption of constant enrichment starts to matter. This is because lower enrichment in the past, corresponding to less evolved, more basaltic crust, requires an even greater continental mass to achieve the same depletion effect of crustal extraction. At present, the continental crust occupies approximately 40% of the total surface area. If geochemical box modeling with the assumption of constant enrichment suggests a similar mass of the early continental crust, but if the early continental crust is half as enriched in compatible elements as the present-day crust (e.g., Ptáček et al., 2020), this could mean that about 80% of the Earth's surface was covered by the continental crust. This poses a serious dynamical challenge to the formation of the continental crust itself because it would leave only 20% of the Earth's surface for the operation of plate tectonics (Korenaga, 2021).

This implausibility argument against the less evolved nature of the early continental crust depends critically on the average thickness of the continental crust, which is assumed to be time-independent in the above. Thicker crust alleviates this dynamical issue. As suggested by Hess (1962), the average thickness of modern continental crust appears to be regulated by isostasy and sea level; continents can keep growing until their surface exceeds the sea level, after which the growth is prevented by erosion. This role of oceans in regulating the mean continental height is manifested as the constancy of the continental freeboard (Wise, 1974; Eriksson, 1999; Korenaga et al., 2017). As the Archean ocean is expected to have been more voluminous and thus deeper than the present ocean (Korenaga, 2008a; Dong et al., 2021), continents could have been correspondingly thicker in the past. However, Galer and Mezger (1998) suggested that, based on the regional metamorphic grade of current exposure in archean greenstone belts, the thickness of the Archean crust could have been thicker only by 5 km or so. Whereas their estimate is valid only back to ~3 Ga, a recent theoretical analysis by Mai and Korenaga (2022) suggests that, instead of sea level, the strength of crustal rocks is the likely limiting factor for crustal thickness in the Archean, and it is difficult to exceed ~50 km in thickness even if isostasy with a deep ocean predicts a greater thickness. Furthermore, whereas the Archean ocean was probably deep, the early Hadean ocean is likely to have been shallower than the present-day ocean, because it would take a few hundred million years for a post-magma-ocean mantle to degas its water to surface (Miyazaki and Korenaga, 2022). In this case, the sea level becomes once again the limiting factor for continental thickness. Taken together, it is difficult to expect that the early continental crust could be thick enough to negate the impact of a less evolved composition on its spatial extent.

The geochemical box modeling of the ^{40}K-^{40}Ar system by Guo and Korenaga (2020) suggests that the continental crust may have reached >80% of the present-day mass by the early Archean. Because their model assumes that the early crust was as enriched in potassium as in the present-day crust, the possibility of less felsic crust in the early Earth is unlikely to be high owing to the above implausibility argument. Whereas a similar suggestion was already made based on the Nd isotope modeling of Rosas and Korenaga (2018), the ^{40}K-^{40}Ar system provides a stronger argument because potassium is much more incompatible than rare earth elements, with a distribution coefficient of ~0.01. However, this indirect argument for a nearly constant composition of the bulk continental crust is only as good as the underlying modeling, and the modeling the ^{40}K-^{40}Ar system is particularly involved because the atmospheric argon is influenced not only by continental growth but also by several other processes as such crustal recycling, crustal reworking, mid-ocean ridge magmatism, and hotspot magmatism. Whereas these processes listed above are considered in the model of Guo and Korenaga (2020), the likely influence of late accretion, that is, the bombardment of leftover planetesimals after the Moon-forming giant impact (Marchi et al., 2014, 2018), was entirely neglected, so it remains to be quantified by future studies. Moreover, the evolution of atmospheric argon isotopes is the key observational constraint, but it is constrained only at two points, the present-day and ~ 3.5 Ga (Pujol et al. 2013). More continuous observational support should supplement future modeling efforts.

Synthesis and outlook

The evolution of the mantle–crust system is fundamentally related to the evolution of plate tectonics, or more broadly, the evolution of mantle convection. As discussed above, recent crustal growth models suggest that initial crustal growth was very rapid with ~50%–100% of present-day continental mass having formed within the first ~500 million years since Earth formation (Rosas and Korenaga, 2018; Guo and Korenaga, 2020, 2023). Coupled to the requirement to grow $\sim 2 \times 10^{22}$ kg of continental crust is the necessity to sequester vast quantities of CO_2 during the early Earth (Sleep et al., 2001; Korenaga, 2021). While the detail of this initial crustal growth is debated, the process of plate tectonics would provide a clear mechanism to sequester a massive amount of atmospheric carbon and generate large quantities of continental crust. Nevertheless, even if plate tectonics played a role, and perhaps even a dominant role in the growth of Earth's continents, the geologic manifestation of this early form of plate tectonics is significantly different from what is seen today. Secular change in mantle temperature led to substantial changes in the composition of mantle-derived igneous rocks and the average extent of mantle melting (Herzberg et al., 2010; Keller and Schoene, 2018). It has been argued that trace element ratios indicative of arc volcanism (e.g., Nb/Th) is present in basaltic rocks throughout the geologic record (<4 Ga) without substantial secular change in arc abundance despite the compositional variation associated with secular mantle cooling (Keller and Schoene, 2018). The gradual decline in ambient mantle temperature and thus the degree of mantle melting is also reflected in the metamorphic record where the record of thermobaric ratios shifts at ~2.2 and ~ 0.85 Ga (Brown and Johnson, 2019; Holder et al., 2019; Brown et al., 2022).

Recent mantle-based models argue for rapid crustal growth (see Section "Mantle-based models"), but crustal growth in these models is parameterized so that crust can grow only in a monotonic manner (e.g., crustal mass cannot fluctuate). Whereas such parameterization may be sufficient to delineate the first-order characteristics of crustal growth, it certainly fails to capture the higher-order complexities of crustal destruction and recycling. Although such details of crustal recycling are generally unconstrained, one can make indirect inferences about crustal recycling based upon the supercontinent cycle (Martin et al., 2020), evolving isotope compositions (Armstrong, 1981b; Shirey and Richardson, 2011), or modeling the frequency changes of geochronologic data (Spencer, 2020). In the present tectonic regime, significant crustal recycling is occurring in convergent systems. It has been proposed that the magnitude of recycling is directly tied to the tectonic setting and "subductibility" of the material at the plate interface of a convergent plate margin (Condie and Kröner, 2013; Brown et al., 2011; Tate et al., 2015). The culmination of global orogenesis has been argued to be directly tied to the supercontinent cycle, which is predicted to have a circum-supercontinental continental arc as epitomized by the earliest phase of circum-Pangea continental arcs encircling the Paleo-Pacific Ocean (Cao et al., 2017; Heron, 2019). It is predicted that, during the period leading up to the formation of the supercontinents, continental arcs would have been dominant (Collins et al., 2011; Spencer et al., 2019). In contrast, following supercontinent assembly and leading to breakup, supercontinental insulation of the mantle and the concomitant mantle upwelling would predict a rollback of the continental arcs leading to a predominance of oceanic arc systems (Spencer et al., 2017). The amount of crustal destruction during the contrasting phases of arc magmatism is likely also tied to crustal recycling, as oceanic arc magmatism is more likely to be characterized by thin crust and is therefore more subductible. The influence and secular change in subductive potential of arc systems is likely difficult to constrain within mantle-based crustal growth models, but, the above geological inferences may provide useful insight into the degree of crustal recycling at various times in geologic time (Fig. 10).

Given the bearing of continental growth on the style of global tectonics, we also stress the importance of discussing continental growth by acknowledging different types of models (crust-based vs. mantle-based). Future discussion would be substantially facilitated by following the two simple guidelines: (1) avoid comparing with the artifact models (Section "Artifacts") and (2) distinguish between net growth models and the formation age distributions. Cawood et al. (2022), for example, correctly acknowledge that the models of Allègre and Rousseau (1984) and Condie and Aster (2010) are crust-based models (Section "Crust-based models") and thus are estimates for formation age distributions, but they also describe the models of Belousova et al. (2010), Dhuime et al. (2012), and Roberts and Spencer (2015) as estimates of "the volumes of continental crust at different times in Earth history, independent of relative volumes preserved today", which is incorrect, as these models are artifacts (Sections "Artifacts" and "Crust-based models"). As another example, Zhu et al. (2023) call their models based on the distribution of Hf-depleted mantle model ages as "growth curves," but it is not appropriate to use the term "growth curve." Their models are estimates of formation age distribution, not net growth.

Although evidence for a Hadean onset of plate tectonics continues to mount, various petrologic and geochemical proxies have also been argued to support either a later onset or secular evolution in the style of plate tectonics and the indication of plate tectonic processes in the geologic record. If the style of plate tectonics and the corresponding geologic manifestations have evolved over time, it follows that the primary driver of this shift can be attributed to secular cooling of the mantle, which in turn affects how the crust and the mantle coevolve (e.g., Chowdhury et al., 2017; Capitanio et al., 2020). The rapidity and nature of cooling of the mantle

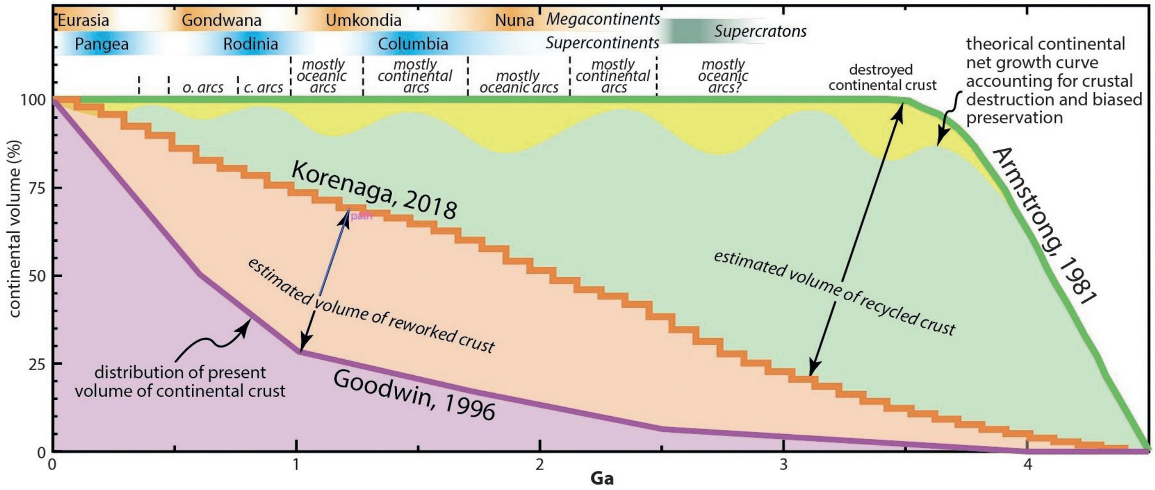

Fig. 10 The lowest (purple) curve is the distribution of extant continental crust (Goodwin, 1996). The area between the surface age distribution of Goodwin (1996) and the formation age distribution of Korenaga (2018) curves represents the estimated volume of reworked continental crust. Whereas the area between the growth l curve of Armstrong (1981a,b) and the curve of Korenaga (2018) represents the estimated volume of recycled crust, in the case of rapid crustal growth in the early Earth. We further hypothesize an oscillation of absolute crustal mass associated with the assembly of supercratons/continents (see Wang et al., 2021), which in turn control the balance of continental vs. oceanic arcs (see Spencer et al., 2017).

remains a perennial challenge, as varying petrological estimates of cooling history have been published (Grove and Parman, 2004; Herzberg et al., 2010; Condie et al., 2016; Ganne and Feng, 2017; Aulbach and Arndt, 2019). It is important to understand, however, that some estimates are more questionable than others (see, for example, discussion in Herzberg, 2019, 2022b). Also, how to interpret petrological estimates in the framework of the thermal evolution of Earth requires a proper understanding of geodynamics; without it, sensible discussion of the literature becomes difficult. For example, Herzberg et al. (2010) compared estimated potential temperatures for the source mantle for non-arc basalts with the thermal evolution model of Korenaga (2008b), and contrary to the claim made by Mitchell and Ganne (2022), this is an adequate comparison, because the model of Korenaga (2008b) tracks the evolution of ambient mantle temperature. In any case, providing more robust constraints on secular cooling of the mantle and its relation to mantle–crust differentiation (e.g., Herzberg, 2022a) are key to augmenting our understanding of the evolution of plate tectonics.

Previous estimates for the onset of plate tectonics are based on a variety of mineralogical and compositional proxies for plate tectonics, ranging from >4.2 Ga (Hopkins et al., 2008) to ~0.85 Ga (Hamilton, 2011; Stern and Miller, 2018). Importantly, these estimates are based on the presence of mineralogical compositions (muscovite inclusions in Hadean zircon) or appearance to petrological associations (earliest occurrence of low-pressure, (ultra)high-temperature metamorphism) akin to modern-day plate tectonic scenarios, along with geochronological data providing a direct temporal constraint for the observed shift. However, it must be noted that while the confluence of plate tectonic proxies (ophiolites, blueschist occurrences, and ultra-high pressure metamorphism as in Stern, 2005) may be seen as more robust in constraining the onset of plate tectonics, the earliest occurrence of any robust plate tectonic proxy still indicates the possibility of plate tectonics. At the same time, we also need to be careful when the earliest occurrence of a particular proxy, however rare, is taken as a minimum age for its emergence. Like the fossil record, there are conflicting views on the robustness of any one proxy (fossil records vs. genetic records; Peterson et al., 2008). Furthermore, the modern (or Cenozoic) plate tectonic milieu is extremely diverse even within the highly oversimplified and idealized view of convergent plate boundaries (oceanic and continental subduction zones and continental collision zones). It is important to note that while the presence of primary muscovite inclusions in zircon may be an indication of magmatism associated with Himalayan-style continental collisions (despite diverse arguments questioning the primary nature of said inclusions; Hopkins et al., 2010; Bell et al., 2015; Rasmussen et al., 2011; Cavosie et al., 2018), not every continental collision produces sedimentary-derived melts as is seen by the near lack of collisional-related magmatism in the Alpine orogeny. Nevertheless, the presence of primary muscovite inclusions indicates the possibility of continent collision-related magmatism. By this same logic, it can be said that by identifying the earliest occurrence of low-temperature, high-pressure metamorphism one can define the the earliest evidence for subduction-related metamorphism and by proxies onset of "modern-style" plate tectonics (Holder et al., 2019). However, as with continent collision-related magmatism, it is important not to neglect the lack of exposed/preserved blueschist-facies metamorphism along numerous recent/Cenozoic subduction zones, including the central Andes and New Zealand.

A potential solution to the quandary of the onset of plate tectonics is coming to see plate tectonics as an evolving system whose manifestations (i.e., proxies) have changed through time. Applying a single proxy to argue for global distribution and a fully fledged plate tectonic network may be flawed because a single proxy is insufficient to constrain even the processes of plate tectonics in the Cenozoic Era. Conversely, by requiring an array of plate tectonics proxies to be present in the geologic record before accepting the operation of plate tectonics neglects how a mineralogical and petrological evolution may have expressed plate tectonics differently throughout geologic time. Perhaps a solution can be found through the evaluation of how secular changes in Earth's interior have evolved over 4.5 billion years and explore how evolution of Earth's interior may have influenced the expression of plate tectonics over time. Such an endeavor requires substantial advance on the theoretical front. Our theoretical understanding of how Earth's mantle would differentiate and evolve under a wide range of physical and chemical conditions needs to be improved so that theoretical predictions can be reliably compared with field observations. Numerical modeling of mantle convection still suffers from considerable uncertainties regarding rock rheology, and this difficulty is further aggravated by the need to incorporate the effects of chemical differentiation. Given the magnitude of such theoretical difficulties, it will remain prudent, at least for a while, to keep open-minded about possible tectonic regimes when interpreting early Earth observations, which are necessarily local, in terms of global tectonics.

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