ANNUAL REVIEWS

Annual Review of Earth and Planetary Sciences

Plate Tectonics and the Archean Earth

Michael Brown,[1] Tim Johnson,[2,3] and Nicholas J. Gardiner[4,5]

[1]Laboratory for Crustal Petrology, Department of Geology, University of Maryland, College Park, Maryland 20742, USA; email: mbrown@umd.edu

[2]School of Earth and Planetary Sciences, The Institute for Geoscience Research (TIGeR), Space Science and Technology Centre, Curtin University, Perth, Western Australia 6845, Australia

[3]State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan, Hubei Province 430074, China

[4]School of Earth and Environmental Sciences, University of St Andrews, St Andrews KY16 9AL, United Kingdom

[5]School of Earth, Atmosphere and Environment, Monash University, Melbourne, Victoria 3800, Australia

Annu. Rev. Earth Planet. Sci. 2020. 48:291–320

First published as a Review in Advance on January 17, 2020

The *Annual Review of Earth and Planetary Sciences* is online at earth.annualreviews.org

https://doi.org/10.1146/annurev-earth-081619-052705

Keywords

tectonic mode, subduction, plume, metamorphism, mantle T_P, geochemistry

Abstract

If we accept that a critical condition for plate tectonics is the creation and maintenance of a global network of narrow boundaries separating multiple plates, then to argue for plate tectonics during the Archean requires more than a local record of subduction. A case is made for plate tectonics back to the early Paleoproterozoic, when a cycle of breakup and collision led to formation of the supercontinent Columbia, and bimodal metamorphism is registered globally. Before this, less preserved crust and survivorship bias become greater concerns, and the geological record may yield only a lower limit on the emergence of plate tectonics. Higher mantle temperature in the Archean precluded or limited stable subduction, requiring a transition to plate tectonics from another tectonic mode. This transition is recorded by changes in geochemical proxies and interpreted based on numerical modeling. Improved understanding of the secular evolution of temperature and water in the mantle is a key target for future research.

- Higher mantle temperature in the Archean precluded or limited stable subduction, requiring a transition to plate tectonics from another tectonic mode.

- Plate tectonics can be demonstrated on Earth since the early Paleoproterozoic (since c. 2.2 Ga), but before the Proterozoic Earth's tectonic mode remains ambiguous.
- The Mesoarchean to early Paleoproterozoic (3.2–2.3 Ga) represents a period of transition from an early tectonic mode (stagnant or sluggish lid) to plate tectonics.
- The development of a global network of narrow boundaries separating multiple plates could have been kick-started by plume-induced subduction.

1. INTRODUCTION

After the Moon-forming impact, Earth had a core of similar size to that of the present day, a silicate mantle and crust of largely unknown compositional and mineralogical structure, and temperate surface conditions (Carlson et al. 2014). Sometime thereafter plate tectonics emerged. What tectonic mode preceded plate tectonics, how and when plate tectonics emerged, and how plate tectonics evolved are fundamental questions in geology. However, they are questions that have proven difficult to answer.

The theory of plate tectonics developed from geophysical studies of the ocean basins and was confirmed by interpretations of contemporary earthquake activity (Oreskes 2002). Plate tectonics is widely considered to have emerged on Earth sometime during the late Archean or early Proterozoic (e.g., Brown 2006, Cawood et al. 2006, Sizova et al. 2010, van Hunen & Moyen 2012, Hawkesworth et al. 2016, Brown & Johnson 2018, Cawood et al. 2018, Hawkesworth & Brown 2018). However, some argue for plate tectonics as early as the Hadean (e.g., Harrison 2009), or at least for subduction at that time (Turner et al. 2014), although the style may have been different (Foley 2018). Others argue that the modern episode of plate tectonics began in the Neoproterozoic, requiring one (or more) alternative tectonic mode before this time (e.g., Stern 2018) (see the sidebar titled Major Divisions of Geologic Time).

If a critical condition for plate tectonics is the creation and maintenance of a global network of narrow plate boundaries separating multiple plates of rigid lithosphere (Bercovici et al. 2015, Mallard et al. 2016, Lenardic 2018), then regions of localized subduction that were not part of a network of plate boundaries, such as may exist on Venus (Davaille et al. 2017), are not a priori evidence for plate tectonics (Smrekar et al. 2018). At the outset, we emphasize this fundamental distinction between plate tectonics and subduction—the former, which necessarily includes subduction as a component, is of global (planetary) extent (**Figure 1**), whereas the latter may be only a regional feature on a planet without plate tectonics.

MAJOR DIVISIONS OF GEOLOGIC TIME

In chronostratigraphy, the Precambrian is the period of time from the formation of Earth around 4,567 millions of years (Ma) to the first appearance of hard-bodied fossils in the rock record about 541 Ma (the base of the Cambrian Period at the beginning of the Phanerozoic Eon). The Precambrian is subdivided into the Hadean (pre-4,000 Ma), the Archean (from 4,000 to 2,500 Ma), and the Proterozoic (from 2,500 to 541 Ma) eons. In turn, the Archean and Proterozoic eons are further subdivided into the Eoarchean (from 4,000 to 3,600 Ma), Paleoarchean (from 3,600 to 3,200 Ma), Mesoarchean (from 3,200 to 2,800 Ma), and Neoarchean (from 2,800 to 2,500 Ma) eras, and the Paleoproterozoic (from 2,500 to 1,600 Ma), Mesoproterozoic (from 1,600 to 1,000 Ma), and Neoproterozoic (from 1,000 to 541 Ma) eras, respectively.

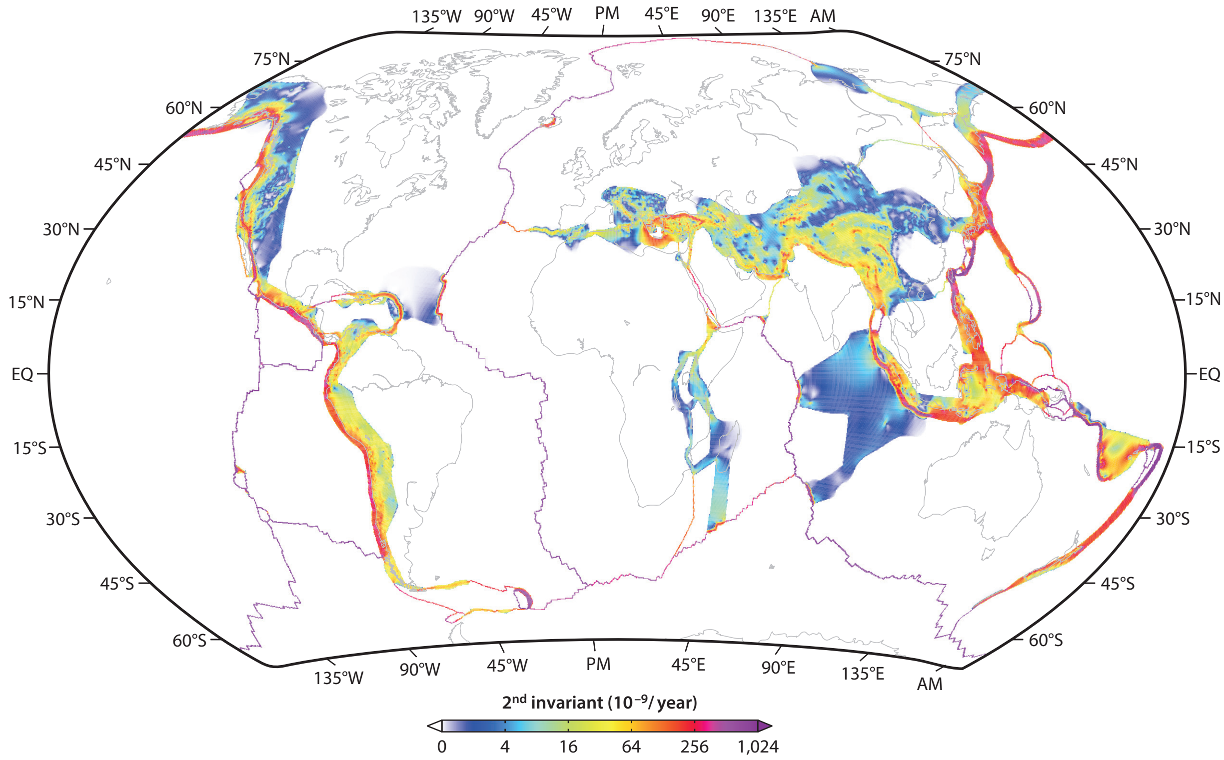


Figure 1

Map of present-day plate boundary deformation zones. White areas were assumed to be rigid plates, and the rigid body rotation of these plates was imposed as a boundary condition when solving for plate boundary strain rates from geodetic velocities. Figure adapted from Kreemer et al. (2014).

Before the Proterozoic, whether plate tectonics operated on Earth is contentious for two main reasons. First, Earth's mantle has likely been cooling since the Mesoarchean (Labrosse & Jaupart 2007, Korenaga 2013). Therefore, there may be differences in the geochemical, petrological, structural, and metamorphic features preserved in the Archean crust compared to those based on studies of contemporary convergent plate boundaries due to plate tectonics (van Hunen & Moyen 2012). Second, the amount of preserved continental lithosphere diminishes back through time and is particularly scarce before the Neoarchean. Given the likelihood of a strong survivorship bias, cratons may be atypical of the lithosphere that existed in the Neoarchean (Kamber & Tomlinson 2019). In short, the limited Archean rock record has made it difficult to demonstrate the existence of a global network of narrow plate boundaries separating multiple plates, such that it may not be possible to determine if the Archean Earth had plate tectonics (Lenardic 2018).

After we consider what potential tectonic modes could have operated on Earth and discuss the transitions between them, our strategy is to identify a lower limit to the emergence of plate tectonics on Earth from evidence preserved in the geological record. To do this we identify the two essential characteristics of plate tectonics—large horizontal displacements between continental fragments and bimodal metamorphism—and trace them back in time. These demonstrate the probable existence of a global network of plate boundaries and multiple plates since the early Paleoproterozoic, providing a minimum age for the emergence of plate tectonics. Then, we discuss the use of geochemical proxies in crustal rocks. During the Archean, some of these have been applied to infer a local tectonic mode, such as subduction; in these cases, it may be inappropriate to infer global changes from the spatially limited data. However, for those geochemical proxies that are likely to record a global signature, this approach may provide an upper limit for the first imprint of plate tectonics in the geological record.

2. TECTONIC MODES ON PLANETS

2.1. Potential Tectonic Modes

According to Lenardic (2018), tectonic modes that may operate on terrestrial planets are (*a*) an active (mobile) lid mode, either with narrow plate boundaries or with distributed deformation; (*b*) a sluggish lid mode, either with ridges or sublithospheric convection-driven tectonics; (*c*) an episodic (transient) mode; and (*d*) a stagnant lid mode, involving heat pipe volcanism or plume tectonics. Any of the last three is a potential precursor to plate tectonics.

Plate tectonics is an active lid mode because the cold upper boundary layer of mantle convection (the lithosphere) participates in convective overturn via formation of weak zones that define narrow boundaries (Bercovici et al. 2015, Crameri & Tackley 2016), allowing it to sink (subduct) back into the interior and drive deformation (orogenesis) at convergent boundaries. If the cold upper boundary layer does not take part in convective overturn, as in a stagnant lid mode, the rate of heat loss will be slower and the style of deformation different (Korenaga 2013, Lenardic 2018). In this mode, a plutonic squishy lid is compatible with the persistence of melt-bearing lower crust for hundreds of millions of years (Taylor et al. 2020, Vanderhaeghe et al. 2019), whereas a heat pipe regime generates crust that is too cold (Sizova et al. 2015, Rozel et al. 2017). An episodic mode reflects alternating states of active and stagnant lid behavior (O'Neill et al. 2016, Lenardic 2018). In a sluggish lid mode the velocity of the lithosphere is lower than that of the convecting mantle, and mobility is driven by convective traction on the base of the lithosphere rather than by subduction (Foley 2018). Alternatively, a mixed mode, in which a poorly mobile lid domain coexists with a pseudoplate tectonics domain, could have existed between a Hadean stagnant lid and modern plate tectonics (Capitanio et al. 2019).

2.2. Mantle Temperature and Tectonic Mode

To compare mantle temperature in space and time, McKenzie & Bickle (1988) proposed the concept of mantle potential temperature (T_P)—the temperature the mantle would have at the surface if extrapolated along an adiabat without melting. According to Herzberg et al. (2007), the present-day range of T_P for mid-ocean ridge basalt (MORB) is ~120°C (1280–1400°C). However, a warmer mantle in the past, with T_P varying from place to place as it does today, may have resulted in an alternative tectonic mode during part or all of the Archean.

In principle, secular cooling of Earth may be deduced from compositional variations of mantle melts through time and from conditions at the start of mantle convection in the Hadean, when T_P may have been ~200°C warmer than at present ($\Delta T_P = +200$°C; Labrosse & Jaupart 2007). Calculations suggest T_P peaked at about 3 Ga but cannot be extrapolated further back in time (Labrosse & Jaupart 2007). For the Archean, estimates of ambient T_P based on petrology vary according to the assumptions made and the method used ($\Delta T_P = +100$–250°C; Herzberg et al. 2010, Condie et al. 2016, Putirka 2016, Ganne & Feng 2017, Aulbach & Arndt 2019), so although it is agreed that ambient mantle was warmer in the past, by how much remains an important unanswered question.

Hotter mantle has a lower viscosity, leading to more vigorous convection, and will melt to a greater extent, producing lithosphere with thicker primary (oceanic) crust—more magnesian than

WATER IN THE EARTH

An additional complication is the critical control of water on the viscosity of the mantle. Unfortunately, how water has been distributed between the interior and surface of Earth through time is uncertain. Some have argued that present-day Earth's mantle may be highly outgassed, containing only a small fraction of its original water content. Others have suggested that Earth in the Hadean had abundant surface water and a dry mantle, implying that regassing of the mantle has dominated Earth evolution. However, recent research has demonstrated that a deep hydrous mantle reservoir has been present in Earth's interior since at least the Paleoarchean. This is another unsolved and highly contentious issue that is fundamental to the question of whether plate tectonics could have operated on the Archean Earth, but one that is beyond our scope here.

present-day primary crust—above a more strongly depleted residue. Both the structure and composition of the lithosphere control its buoyancy, although not sufficiently to inhibit the viability of subduction during the Neoarchean (Korenaga 2013, 2017; Johnson et al. 2014; Weller et al. 2019). Subduction has been shown to be stable at ΔT_P up to +100°C if shear stress at the subduction interface is low (<5 MPa); if high (~30 MPa), subduction is stable only at present-day T_P (van Hunen & van den Berg 2008). At $\Delta T_P > +100$°C, subduction is inferred to become increasingly less stable with earlier slab breakoff (van Hunen & van den Berg 2008, Sizova et al. 2010) (see the sidebar titled Water in the Earth).

We illustrate the ambiguity in resolving when plate tectonics could have emerged on Earth by reference to the thermal evolution of the mantle as modeled by Korenaga (2013, 2017) in relation to the T_P data from Herzberg et al. (2010). Assuming a low present-day Urey ratio (ratio of internal heat production to surface heat flux), the results show the T_P data are consistent with either a plate tectonic mode modeled with constant surface heat flow or a switch in heat-flow scaling from stagnant lid to plate tectonics at 3 Ga or 2 Ga, but not more recently.

2.3. Transitions Between Tectonic Modes

The critical parameters that control tectonic mode evolve with secular cooling—for example, internal energy decreases and lithospheric strength increases—potentially leading to a change in mode (Lenardic 2018). A transition from one mode to another—for instance, from stagnant to active lid—may take hundreds of millions of years (Bercovici & Ricard 2014). Alternatively, a planet could exhibit multiple tectonic modes in which the proportion of one relative to the other changes. For example, Earth currently has a bimodal distribution of plate sizes in which large plates are driven by the negative buoyancy of the subducting plate, whereas small plates are driven by convective tractions at their base (Hoink et al. 2013). With a higher mantle temperature and lower viscosity in the past, the sluggish lid component could have been larger such that the overall behavior was indistinguishable from a stagnant lid (Lenardic 2018). Turning the argument around, there could have been a smooth transition from a sluggish to an active lid mode with secular cooling (Foley 2018), consistent with the hypothesis that plate tectonics is part of an emergent, self-sustaining system as mantle convection evolves with time (Lenardic et al. 2019).

3. PLATE TECTONICS BACK TO THE ARCHEAN

3.1. How Do We Identify Plate Tectonics from the Geological Record?

There are clear similarities (e.g., Kusky et al. 2018) and differences (e.g., Gapais et al. 2009, Bédard 2018) between the geological features of Archean cratons and those of Paleoproterozoic and younger orogenic belts. Critical to identifying a lower limit on the emergence of plate tectonics is the choice of geological information that may provide reliable evidence of a global network of narrow boundaries and multiple plates. Two types of information potentially fill this need: first, the demonstration of large, contemporaneous horizontal displacements between several continental fragments, consistent with multiple plates and the creation and destruction of oceanic lithosphere (e.g., Mitchell et al. 2014), and, second, the demonstration of widespread, contemporaneous bimodal metamorphism, which is the hallmark of asymmetric subduction at convergent plate boundaries at the present day (Brown 2006, Holder et al. 2019).

3.2. Supercontinents and Supercratons: Evidence for Large Horizontal Displacements

Based on widespread evidence of active convergent margins during the Proterozoic (e.g., Karlstrom et al. 2001, Giles et al. 2004, Roberts & Slagstad 2015, Pehrsson et al. 2016), we contend that plate tectonics has been continuous since its (last) emergence, as recorded by the supercontinent cycle (Nance et al. 2014). Proposals for plate tectonic shutdowns during the Proterozoic (Silver & Behn 2008, Stern 2018) may reflect a slower tempo (Sobolev & Brown 2019) or survivorship bias rather than a change in tectonic mode (see the sidebar titled The Supercontinent Cycle).

Seams in supercontinents are marked by orogenic belts, comprising variably deformed rocks with distinctive distributions of (mainly) marine facies sedimentary strata, igneous rocks, deformational structures, and metamorphic patterns that are commonly aligned subparallel to the belt (Cawood et al. 2009). These features are preserved during collisional orogenesis, marking where former ocean basins were eliminated. In the Phanerozoic and Proterozoic, abundant geological and paleomagnetic data provide evidence for large horizontal displacements since the beginning of the assembly of Columbia at c. 2.2 Ga (Mitchell et al. 2014, Li et al. 2016, Meert & Santosh 2017), in which at least 20 (of more than 30) major Archean cratons were ultimately sutured together by the Mesoproterozoic (Bleeker 2003, Pehrsson et al. 2013). However, before Columbia, large horizontal displacements are difficult to demonstrate globally. The cratons that formed Columbia were derived from the breakup of a few supercratons, which themselves formed during the late Mesoarchean to early Paleoproterozoic (Bleeker 2003, Pehrsson et al. 2013). The breakup is evidenced by late Neoarchean to early Paleoproterozoic mafic dike swarms associated with plumes (Bleeker & Ernst 2006, Ernst et al. 2013), and large horizontal displacements are supported by the abundance of passive margins at 2.2–1.8 Ga (Bradley 2008). Large horizontal displacements are also implied by the occurrence of a smaller number of passive margins at 2.7–2.4 Ga (Bradley 2008), but whether these reflect an active lid mode of global extent is uncertain.

THE SUPERCONTINENT CYCLE

The supercontinent cycle refers to the periodic aggregation of most of the extant continental lithosphere into a single entity. Several supercontinents are recognized: Pangea in the Mesozoic, Pannotia (including Gondwana) in the late Neoproterozoic, Rodinia in the early Neoproterozoic, and Columbia (including Nuna) in the Paleoproterozoic. In the Archean, fundamental differences between some of the better-known cratons suggest it is unlikely the extant continental lithosphere was ever aggregated into a single Archean supercontinent. Notwithstanding, most Archean cratons preserve evidence of rifted margins of Proterozoic age, which suggests they were once fragments of several larger entities or supercratons.

Were the number and size of the plates that existed in the Paleoproterozoic comparable to those that have existed since the breakup of Pangea? Based on results from three-dimensional spherical models of mantle convection, Mallard et al. (2016) proposed that, due to the feedback between mantle convection and lithosphere strength, the size distribution of plates has evolved with secular cooling of the mantle, such that Earth has fewer, larger plates now than earlier. This postulate supports a study suggesting that the global plate boundary network during the formation of Columbia was ~2.2 times the present length (Abbott & Menke 1990).

3.3. Indicators of Subduction in the Geological Record

Markers of subduction in the geological record are the most commonly used evidence of plate tectonics (Kusky et al. 2018). If widespread and contemporaneous, this evidence could be considered representative of a global network of plate boundaries (van Hunen & Moyen 2012). Widely used markers of subduction and collision are calc-alkaline igneous rocks, structural style in orogenic belts, and contemporaneous low-temperature–high-pressure metamorphism.

On contemporary Earth, igneous rocks generated above a subducting slab generally have particular trace element patterns (Pearce 2008), informally termed an arc signature. However, linking source, melting environment, and tectonic mode in variably metamorphosed igneous rocks preserving such a signature is highly contentious, particularly in the Archean (Pearce 2008, van Hunen & Moyen 2012, Bédard et al. 2013, Pearce 2014, Johnson et al. 2017, Smithies et al. 2018). Consequently, we do not rely on this signature as evidence of subduction, although its relevance in Archean rocks is discussed later.

Phanerozoic mountain belts include accretionary orogens related to continuous subduction in intraoceanic settings and at continental margins, and collisional orogens related to continent–continent or arc–continent collision that terminate subduction. The collisional type commonly overprints the accretionary type, creating complexity in the geological record. A common feature of collisional orogens is strong strain localization along lithospheric-scale thrusts that juxtapose units recording different types of metamorphism (Gapais et al. 2009). Similar features occur in some Neoarchean and Paleoproterozoic orogens (e.g., Weller & St-Onge 2017, Zibra et al. 2017), implying that the lithosphere was strong enough to allow modern-style tectonic processes. However, in Archean terrains tectonostratigraphic sequences in which older crustal units overlie younger crustal units across high-strain zones are rare. In southern West Greenland, examples include Mesoarchean–Neoarchean structures in the Nuuk region (Dziggel et al. 2014) and late Eoarchean structures in the Isua region (Nutman et al. 2013), although the latter example has been questioned (Webb et al. 2020). More commonly, the structural and metamorphic patterns of Archean and Proterozoic orogens imply distributed thickening and limited lateral variation in metamorphic grade (Gapais et al. 2009), consistent with a hotter lithosphere (Sizova et al. 2014).

The widespread occurrence of blueschists, low-temperature eclogites, and ultrahigh pressure metamorphic rocks in the geological record since the Neoproterozoic is unambiguous evidence of subduction (Brown 2006). However, these rock types are not ubiquitous in Phanerozoic orogenic belts, so their occurrence is not a requirement of subduction-driven collisional orogenesis, and they are scarce prior to the Neoproterozoic, suggesting their relatively recent appearance may be related to secular cooling (Brown 2006, van Hunen & van den Berg 2008, Sizova et al. 2014). Therefore, although metamorphism offers the possibility of tracing subduction back through time, we must first assess how metamorphism in collisional orogens changes with secular cooling of the mantle.

Information routinely retrieved from mineral assemblages in metamorphic rocks includes the temperature (T), pressure (P), and age of equilibration. Plotting the thermobaric ratio (T/P) against age permits evaluation of secular change in metamorphism (Brown & Johnson 2019a,c).

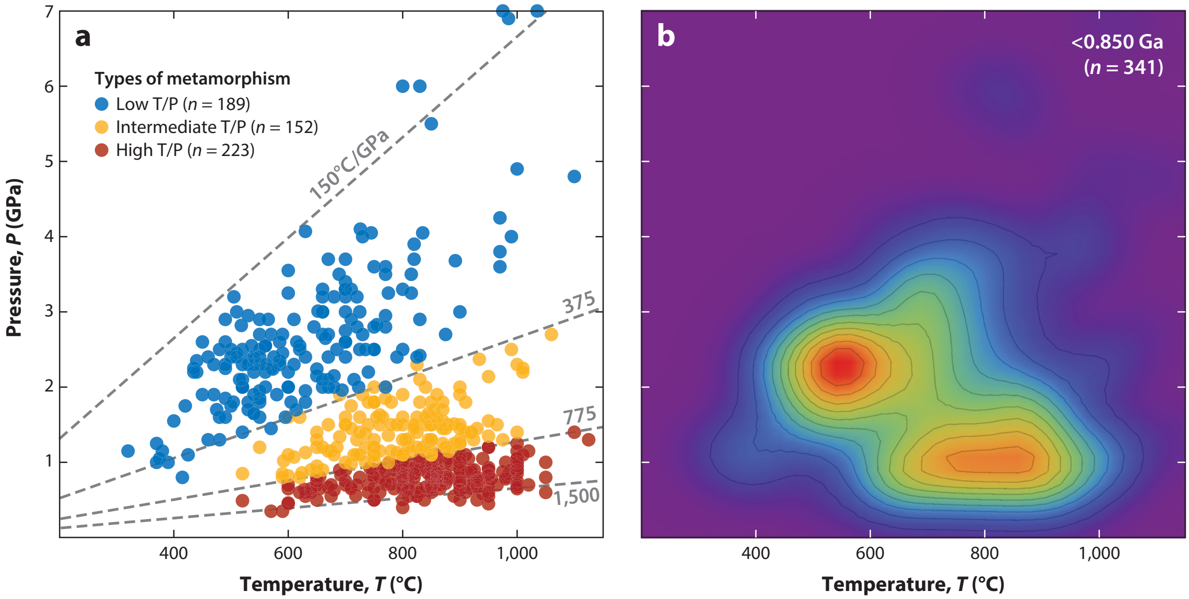


Figure 2

(*a*) Conditions of peak metamorphism for 564 localities with robust pressure (P), temperature (T), and age grouped by type, with representative thermal gradients (*thin gray dashed lines*). Three types of metamorphism are distinguished based on thermobaric ratios (T/P). (*b*) A plot of data <850 Ma in age contoured for density (contours are smooth kernel density estimates for which the bandwidth was computed automatically using DensityPlot in Wolfram Mathematica) to emphasize the characteristic bimodality of crustal metamorphism since 850 Ma. Panel *a* data from Brown & Johnson (2019b). Figure adapted with permission from Brown & Johnson (2019a).

Such data compiled for 564 localities from the Cenozoic to the Eoarchean (Brown & Johnson 2019b) define three types of metamorphism that are associated with particular tectonic settings on contemporary Earth (**Figure 2**): (*a*) low T/P metamorphism, comprising blueschists, and low-temperature and ultrahigh pressure eclogites, as found in subduction channels, accretionary orogens, and sutures in collisional orogens; (*b*) intermediate T/P metamorphism, comprising high-pressure granulites and medium-temperature and high-temperature eclogites, as found in collisional orogens; and (*c*) high T/P metamorphism, comprising migmatites and common and ultrahigh-temperature granulites, as found in orogenic hinterlands (orogenic plateaus or backarcs).

Based on the occurrence of intermediate and high T/P metamorphism, Brown & Johnson (2018; 2019a,c) argued that bimodal metamorphism can be recognized in the rock record since the beginning of the Neoarchean (**Figure 3*a*,*b***). However, a statistical evaluation of T/P through time shows that global metamorphism >2.2 Ga can be fitted by a unimodal Gaussian distribution, whereas metamorphism ≤2.2 Ga is well described by bimodal mixed-Gaussian distributions (paired metamorphism) that become increasingly distinct with decreasing age (Holder et al. 2019). Thus, the Neoarchean might best be thought of as a period of transition between tectonic modes (cf. Cawood et al. 2018, Condie 2018), with the emergence of plate tectonics being complete by the early Paleoproterozoic.

During this transition, intermediate T/P metamorphism records subduction-driven collisional orogenesis, although maximum pressure was limited by shallow slab breakoff, whereas high T/P metamorphism records postbreakoff extension of the overriding plate in the orogenic hinterland

(Sizova et al. 2014, Chowdhury et al. 2017). The occurrence of subduction-driven collisional orogenesis in the Neoarchean is consistent with the sporadic occurrence of what, in seismic reflection profiles, are interpreted to be relict slabs beneath collisional belts in the Superior Craton (Percival et al. 2012). Alternatively, these features have been interpreted as due to overthrusting of oceanic crust by drifting proto-continents (Bédard 2018).

4. THE ARCHEAN ROCK RECORD

Plate tectonics has allowed us to make sense of almost all the large-scale features on Earth's surface. However, moving back in time, unambiguous recognition of volcanic arcs or their eroded remnants, or forearc sedimentary sequences, becomes increasingly difficult—particularly in the Archean, where field evidence is complex and ambiguous, and what remains of the crust is generally multiply deformed, fragmented, and metamorphosed. Because the rock record is limited and survivorship bias is a major concern, and Archean cratons generally do not preserve the uppermost levels of crust, where a record of subduction (for example, in the form of accretionary prisms and ophiolites) is more commonly preserved, evidence for the operation of plate tectonics in the Archean largely depends on geochemical indicators for subduction.

4.1. Survivorship Bias and the Geological Record in the Archean

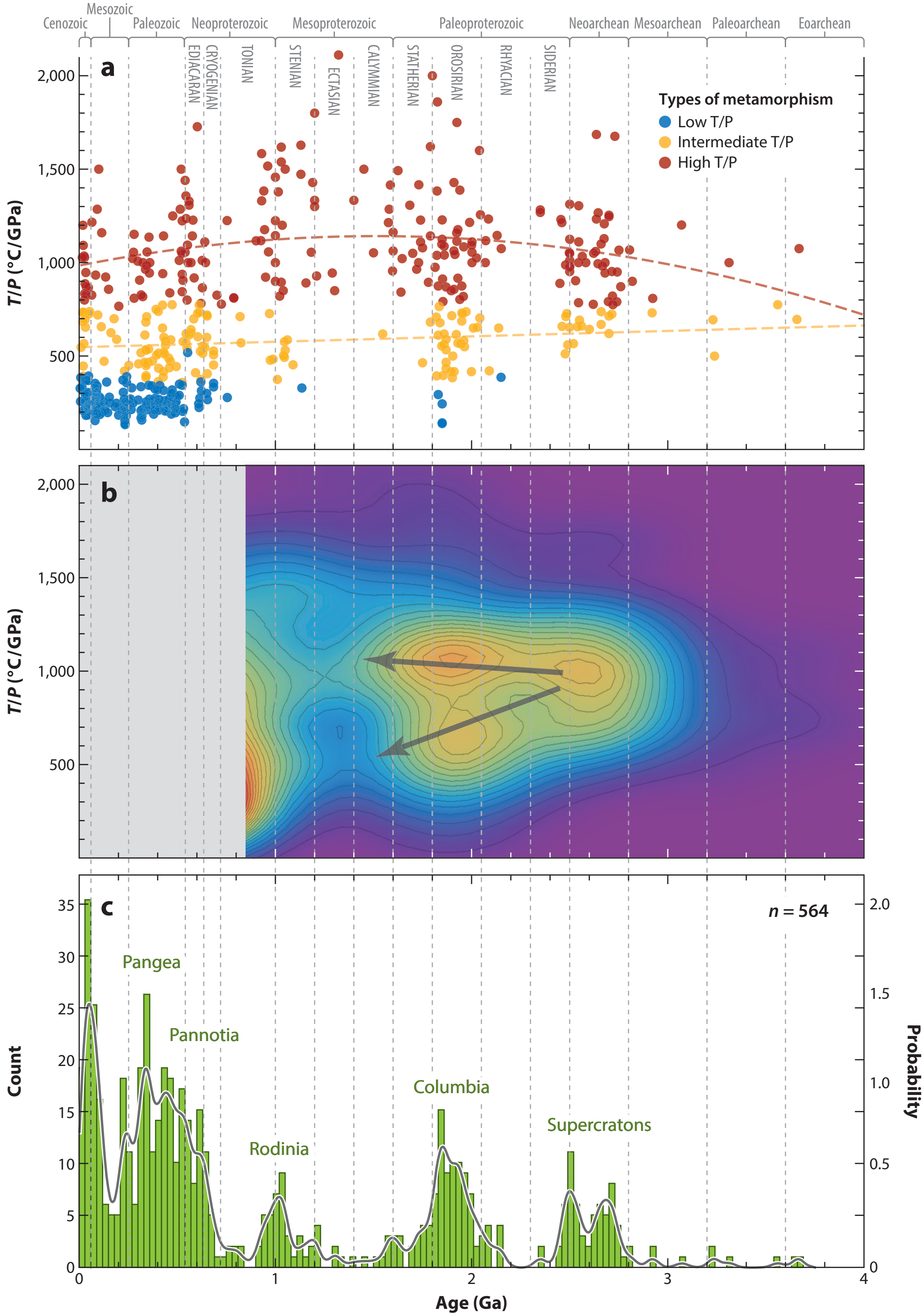
Rocks older than Paleoarchean in age (>3.6 Ga) are rare. Furthermore, the age distribution of detrital zircon grains and magmatic rocks (e.g., Roberts & Spencer 2015, Johnson et al. 2019) shows a marked decline in the amount of preserved crust older than Neoarchean (>2.8 Ga). Thus, we may question to what extent preserved crust older than Neoarchean is representative, in terms of either relative volume of rock types or the processes it records. Is this crust the surviving remnants of a much larger volume that was destroyed (Hawkesworth et al. 2017, 2019; Dhuime et al. 2018, Korenaga 2018), or was there only ever a small volume produced (Condie et al. 2018)? How significant are the scarcity of Eoarchean crustal rocks and the almost complete absence of a Hadean rock record? In addition, there has been a strong geographic bias in studies of Archean crust, with the oldest known rocks attracting more attention. For these and other more practical reasons, much Archean and early Earth research has concentrated on a relatively small number of key localities.

4.2. Key Features of Archean Geology That Must Be Explained

Planetary differentiation is irreversible. Regardless of Earth's compositional and mineralogical structure immediately following the Moon-forming impact, the silicate Earth today is immeasurably more compositionally, mineralogically, and structurally complex. That Archean rocks are different from post-Archean geology is inevitable, irrespective of the tectonic mode in which they formed. With this in mind, we discuss some key features of Archean geology that warrant examination.

4.2.1. Lithological differences between pre- and post-Archean geology. Archean continental crust not only looks different, and was mapped as such by early geologists, but also is compositionally distinct from younger andesitic continental crust (Rudnick 1995). Furthermore, Archean upper crust may have been more mafic than post-Archean emergent crust (e.g., Taylor & McLennan 1985, Dhuime et al. 2015, Tang et al. 2016, Large et al. 2018, Chen et al. 2019).

Exposed Archean crust mostly comprises higher-grade gray gneiss terrains and lower-grade granite–greenstone belts with an archetypical dome-and-basin structure. These probably represent the lower and upper levels of the ancient continental crust, respectively (Johnson et al. 2016),



(Caption appears on following page)

Figure 3 (*Figure appears on preceding page*)

(*a*) Metamorphic thermobaric ratios [temperature (T), pressure (P) (T/P)] for 564 localities grouped by type plotted against age. Three types of metamorphism are shown. The dashed lines show a second-order polynomial regression of the data for the high T/P (*red*) and a linear regression of the data for the intermediate T/P (*orange*) types, respectively. (*b*) T/P data for localities >850 Ma in age contoured for density (contours are smooth kernel density estimates for which the bandwidth was computed automatically using DensityPlot in Wolfram Mathematica) to emphasize the development of bimodality from the Neoarchean through the Proterozoic. (*c*) Histogram of ages and probability density function for metamorphism at 564 localities. Panels *a* and *c* adapted with permission from Brown & Johnson (2019a). Panel *b* adapted with permission from Brown & Johnson (2019c).

but they have also been interpreted as analogs of modern active continental arc margins and associated backarcs (Windley & Smith 1976).

Gray gneiss terrains are volumetrically dominated by sodic granitoids of the tonalite–trondhjemite–granodiorite (TTG) series. TTGs are compositionally similar to, but subtly different from, modern adakites that mostly form by partial melting of subducting hydrated oceanic crust (Smithies 2000, Condie 2005, Martin et al. 2005). Were TTGs also products of slab melting, or are other tectonic settings permissible? (See the sidebar titled The Tonalite–Trondhjemite–Granodiorite Suite of Rocks.)

In addition to felsic domes, granite–greenstone belts comprise sequences of mainly (metamorphosed) basalt, with subordinate ultramafic to felsic volcanic rocks and various sedimentary rocks. A significant feature is the common occurrence of komatiites, high-magnesian ($MgO > 18$ wt%) lavas that are rare in the post-Archean rock record. The unusually high mantle temperatures required to form komatiites (ΔT_P of +200–300°C; Herzberg et al. 2007) are commonly explained by invoking more vigorous plume activity promoted by higher temperatures at the core–mantle boundary.

Most Archean lavas were erupted subaqueously, suggesting very little land had emerged before the late Archean–early Proterozoic (Flament et al. 2008, Rey & Coltice 2008, Bindeman et al. 2018). If the development of significant topography in the Proterozoic reflects strengthening of the continental lithosphere, was the Archean lithosphere too weak to focus deformation and break into plates?

4.2.2. Differences in the character of the Archean and post-Archean lithosphere. Crust that stabilized during the Mesoarchean–Neoarchean and has been largely undisturbed since is generally thinner than post-Archean crust and has fewer internal seismic discontinuities, slower seismic velocities in the lower part reflecting a more felsic composition, and a sharper, flatter Moho (Abbott et al. 2013). Given that Archean cratonic crust is dominated by TTGs mainly derived through partial melting of hydrated mafic sources, where is the (substantial) residual mafic lowermost crust and how and when was it lost? Could it have been returned to the mantle through

THE TONALITE–TRONDHJEMITE–GRANODIORITE SUITE OF ROCKS

Archean rocks are generally found in cratons, which form the stable interiors of continents. Archean cratons are dominantly composed of gneisses derived from a variety of initial rock types, but mostly of igneous origin, many of which have been tectonically transposed during strong deformation, obscuring their original relationships. Within these gneisses, an important group of igneous rocks is the tonalite–trondhjemite–granodiorite (TTG) suite, which is largely confined to the Archean. TTGs are silica-rich ($SiO_2 > 64$ wt%, but commonly ~70 wt% or greater) rocks with high Al_2O_3 (15.0–16.0 wt%) and Na_2O (3.0–7.0 wt%) contents, low K_2O/Na_2O (<0.5) ratios, and low total ferromagnesian oxide (Fe_2O_3 total + MgO + MnO + $TiO_2 \leq 5$ wt%) contents. TTGs generally have fractionated rare earth element (REE) patterns and low heavy REE contents.

density-driven delamination at a level corresponding to the garnet-in isograd (Abbott et al. 2013) or peeled off during subduction-driven collisional orogenesis on a hotter Earth (Chowdhury et al. 2017)?

Based on zircon ages and radiogenic isotopes, estimates of the overall volume of crust extracted from the mantle during the Hadean–Archean, the proportion of this crust returned to the mantle during the same period, and the volume of continental crust remaining at the surface at 3 Ga are equivocal (Dhuime et al. 2018, Korenaga 2018). In a recent study using molybdenum isotopes, McCoy-West et al. (2019) argued that, since 3.5 Ga, the composition of depleted mantle has essentially remained unchanged, implying that, since that time, the rates of crustal extraction and return have been in balance. If correct, such early depletion of the mantle requires extraction of a far greater volume of crust and higher rates of crustal growth and destruction prior to 3.5 Ga than generally expected. Dhuime et al. (2012, 2018) argued that 60–80% of the present volume of continental crust was present by 3 Ga. However, there is little if any evidence for the complementary mafic to ultramafic residues, which presumably were recycled back into the mantle (Abbott et al. 2013, Johnson et al. 2014, Chowdhury et al. 2017, Bédard 2018).

The thickness and composition of the continental lithospheric mantle (CLM) have changed through time (e.g., Pearson & Wittig 2014, Griffin & O'Reilly 2019). Archean CLM is thicker (up to ~250 km thick) and significantly more depleted (residual) than younger CLM, consistent with higher mantle temperatures and more extensive mantle melting (Lee 2003, Griffin et al. 2008). Importantly, the lower FeO content of more depleted Archean CLM means it has a lower density than younger CLM (e.g., Lee 2003, Johnson et al. 2014) and is buoyant with respect to the underlying asthenosphere, making it difficult to subduct or otherwise delaminate (Djomani et al. 2001, Lee et al. 2011). The Re–Os isotope composition of the oldest sulfide grains from mantle xenoliths, which likely date the timing of formation of the CLM, yields ages with a pronounced peak at c. 3.0–2.5 Ga (Pearson & Wittig 2008, Griffin & O'Reilly 2019), reflecting preservation of the oldest cratonic lithosphere during a transition to plate tectonics.

4.3. The Petrogenesis of Archean Crust

Modern arc basalts have characteristic compositions reflecting partial melting, on average at ~100 km depth below the active magmatic arc, of depleted mantle that was hydrated and enriched in incompatible elements through interaction with fluids derived from subducted materials (Pearce 2008). Relative to MORB, arc basalts are enriched in large ion lithophile elements (LILE); show fractionated rare earth element (REE) patterns, with preferential incorporation of light REE (LREE) over heavy REE (HREE); and are depleted in high field strength elements, leading to pronounced negative anomalies in Nb, Ta, Zr, Hf, and Ti. Although these characteristics are taken as a reliable proxy for subduction in many studies, they also occur in basalts derived from subduction-modified lithospheric mantle (Pearce 2008). However, the fundamental question here is whether modern arc basalts really do provide the key to the genesis of Archean basalts with similar compositional characteristics, or whether there are plausible mechanisms by which hydrated crust can be recycled into the mantle other than by subduction. Numerical modeling suggests that sagduction and dripping of the lowermost crust and crustal overturns may represent plausible alternatives (Johnson et al. 2014; Sizova et al. 2015; Fischer & Gerya 2016a, 2016b; Nebel et al. 2018; Roman & Arndt 2019).

The so-called arc signature is also found in most TTGs, which show extreme REE fractionation, with high chondrite-normalized La/Yb ratios ($La_N/Yb_N > 15$) and preferential enrichment of Sr over Y ($Sr_N/Y_N >$ or $\gg 20$; Martin et al. 2014, Hoffmann et al. 2019). Notwithstanding that some TTGs may have formed through fractional crystallization (Liou & Guo 2019), the pronounced HREE and Y depletion in most TTGs (~80%; Moyen 2011) is interpreted to record partial melting of hydrated basaltic rocks (amphibolite) at depth within the stability field of garnet. Although garnet may indicate pressures >1.5 GPa based on experimental studies of amphibolite (Moyen & Stevens 2006), its stability is highly sensitive to bulk rock Mg# [atomic $Mg/(Mg + Fe^{2+})$] and garnet may be stable at pressures as low as 0.7 GPa (Johnson et al. 2017). This lower pressure is within the range of thickness for primary crust generated during the Archean (Dhuime et al. 2015), and melting this crust may not require subduction (Sizova et al. 2015; also see Hoffmann et al. 2019, table 7.2).

Around 20% of TTGs record a high-pressure signature, considered to record extraction from an eclogite residue at pressure >2.0 GPa (Moyen 2011), corresponding to the extreme depths (>60 km) experienced by younger crustal rocks only during deep subduction (Brown & Johnson 2018). However, such high-pressure TTGs have recently been interpreted to represent fractionated sanukitoid (high-magnesian diorite) melts derived by partial melting of chemically enriched hydrated lithospheric mantle (Smithies et al. 2019).

5. COMPOSITIONAL CHARACTERISTICS OF THE ARCHEAN ROCK RECORD

5.1. The Eoarchean (4.0–3.6 Ga)

Earth's oldest known crustal rocks are 4.02–3.96 Ga magnetite-rich felsic gneisses that form a component of the Acasta Gneiss Complex, part of the Slave Craton in northwest Canada (Reimink et al. 2016, and references therein). These gneisses have compositions that are clearly distinct from TTGs and are considered to have formed through in situ partial melting of Fe-rich amphibolite at extremely low pressures, equating to the uppermost few kilometers of hydrated mafic crust (Johnson et al. 2018). Melting under such extreme thermal gradients is most easily explained through meteorite impact, which may have been the predominant mechanism for generating felsic rocks in the Hadean and early Eoarchean (Johnson et al. 2018). That the end of the purported late heavy bombardment (Koeberl 2006, Marchi et al. 2014) broadly coincides with survival of the oldest rocks in most cratons seems unlikely to be a coincidence. Furthermore, numerical simulations have shown that large bolide impacts may induce mantle upwellings capable of driving short-lived (>10 Ma) localized subduction events in a dominantly stagnant lid mode (O'Neill et al. 2017).

Earth's most extensive tract of Eoarchean crust (~3,000 km^2) is the 3.89–3.65 Ga Itsaq Gneiss Complex (IGC) in southwest Greenland (Hoffmann et al. 2014, Nutman & Bennett 2019), which is spatially associated with the 3.8–3.7 Ga Isua Supracrustal Belt (ISB) that includes amphibolites with tholeiitic and island arc affinities and even boninite-like compositions (Polat et al. 2002, Polat & Hofmann 2003, Jenner et al. 2009, Hoffmann et al. 2010). Together, the IGC and ISB form the Eoarchean core to the North Atlantic Craton—a collage of Eoarchean to Mesoarchean terranes defined on the basis of structural relationships, metamorphic grade, and protolith age—which was assembled during the Neoarchean (Friend & Nutman 2019, and references therein).

Southwest Greenland has become a classic model for terrane accretion during the Mesoarchean and Neoarchean, and subduction has been invoked to explain formation of even its earliest constituents (Polat et al. 2015, Windley & Garde 2009, Friend & Nutman 2019). On modern Earth, boninites are volcanic rocks associated with subduction initiation, and boninite-like rocks in the ISB have been argued to be a direct analog (Polat et al. 2002, Hoffmann et al. 2010). However, many Archean boninite-like rocks are silicious high-Mg, low-Ti basalts that could have formed in variably depleted plumes (Smithies et al. 2004, Pearce & Reagan 2019) or from otherwise anomalously hot upwelling mantle.

In **Figure 4** we show plots of Th/Yb versus Nb/Yb for basalts from various Archean localities, including those of Eoarchean and Mesoarchean age from southwest Greenland. This plot

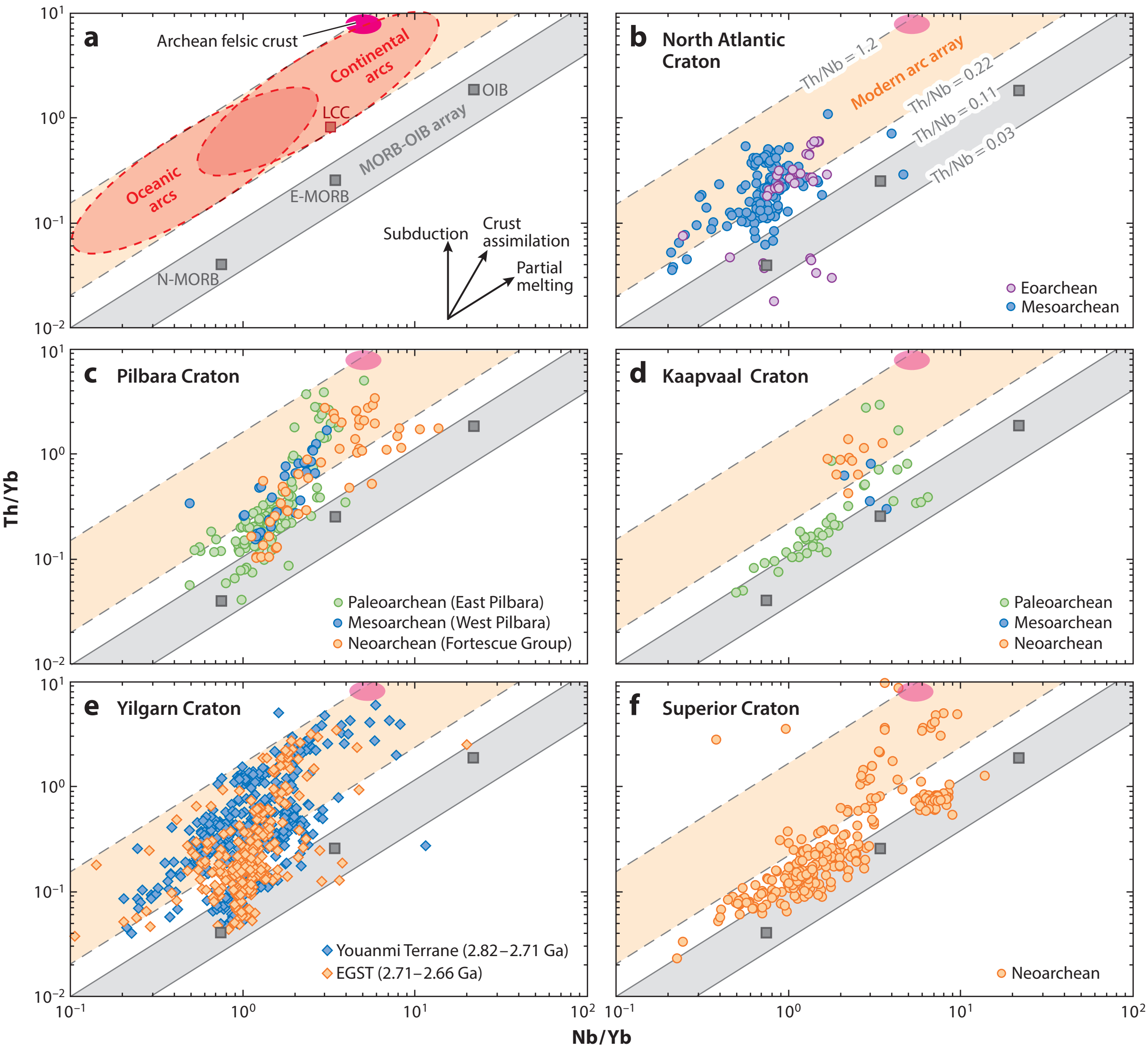


Figure 4

(*a*) The Th/Yb–Nb/Yb plot of Pearce (2008) showing main fields as well as composition vectors expected during subduction enrichment of a mantle source, crustal assimilation, and partial melting. Panel *a* adapted from Smithies et al. (2018). Copyright 2018, with permission from Elsevier; data for ocean floor basalt compositions (N-MORB, E-MORB, and OIB) from Sun & McDonough (1989); for the average composition of Archean felsic crust from Moyen (2011); and for modern LCC from Rudnick & Gao (2014). (*b*)–(*f*) Plots of Th/Yb versus Nb/Yb for basalts from the North Atlantic Craton (southwest Greenland), the Pilbara Craton, the Kaapvaal Craton (Barberton Granite–Greenstone Belt), and the Superior Craton (Abitibi Greenstone Belt) colored by age, and for the Yilgarn Craton colored by terrane. Data for panels *b*–*f* from GeoRoc (**http://georoc.mpch-mainz.gwdg.de/georoc/**) and GSWA (2019), filtered by MgO (<18 wt%) and SiO_2 (>45 and <57 wt%) content. Abbreviations: EGST, Eastern Goldfields Superterrane; E-MORB, enhanced mid-ocean ridge basalt; LCC, lower continental crust; MORB, mid-ocean ridge basalt; N-MORB, normal mid-ocean ridge basalt; OIB, ocean island basalt.

potentially allows distinction between basalts derived from mantle enriched in crustally derived Th—for example, by recycling through subduction—versus enrichment of basalts in both Th and Nb through crustal assimilation (Pearce 2008). Melting of a subduction-modified source and fractional crystallization generate an array of compositions with constant Th/Nb within the modern arc array (orange band, **Figure 4*a***), which is parallel to but above the mid-ocean ridge basalt–ocean island basalt (MORB–OIB) array (gray band, **Figure 4*a***). By contrast, mixing between MORB and a crustal component generates an array of compositions with variable Th/Nb that is steeper than either array and is unrelated to subduction (**Figure 4*a***). Notwithstanding the difference in Th/Nb trends, caution should be exercised when attempting to fingerprint Archean tectonic settings (Pearce 2014).

Although the data are limited in number, the Th/Nb trends for Eoarchean basalts from southwest Greenland are offset from MORB and mostly plot within the modern arc array. Thus, these data appear to support mantle enrichment, which may be consistent with subduction-like processes (**Figure 4*b***). Mantle enrichment in LREE through crustal recycling has also been proposed as the mechanism by which εHf was decoupled from εNd, as measured in some Eoarchean ISB tholeiites (Hoffmann et al. 2011). Modeling suggests an upper limit of 5% on the amount of crustal contaminant, consistent with the extracted basalts and TTG crust (Gardiner et al. 2019a). However, others propose that such isotopic decoupling is an artifact of later LREE mobilization during metamorphism (Kemp et al. 2019) and is not indicative of subduction. In summary, although there is strong evidence for a recycled component in the source of Eoarchean mafic rocks from southwest Greenland, the tectonic process by which this occurred remains ambiguous.

5.2. The Paleoarchean (3.6–3.2 Ga)

The East Pilbara Terrane (EPT) in Western Australia and the Barberton Granite–Greenstone Belt (BGGB) in the Kaapvaal Craton of southern Africa are among the most intensively studied Archean granite–greenstone terranes.

The EPT forms the Paleoarchean core to the Pilbara Craton and has a well-developed dome-and-keel architecture comprising steeply dipping supracrustal sequences surrounding domal granitoid complexes. A mafic substrate is proposed to have formed through episodic volcanic resurfacing from 3.8 to 3.5 Ga until it reached a critical depth (>30 km) allowing intracrustal melting to produce TTG magmas (Van Kranendonk et al. 2007). Composite TTGs form domes developed via punctuated magmatic events from c. 3.5 to 3.2 Ga (Smithies et al. 2005b). Hf and Nd isotopes measured in the 3.5–3.2 Ga TTG suites show an increase in unradiogenic εHf and εNd with time, with consistent model ages of c. 3.8–3.7 Ga (Smithies et al. 2003, Gardiner et al. 2017), implying derivation from an Eoarchean mafic source. These trends support a tectonic model in which sagduction episodically delivered (hydrated) mafic volcanic rocks into a deep melting zone largely comprising an older residual mafic substrate.

A petrogenetic model for the EPT must account for the TTGs being too enriched in LILE and LREE to have been derived from a primary mantle melt. Their source was likely an enriched basalt—either the product of multistage crustal reworking (Johnson et al. 2017) or extracted at c. 3.5 Ga from a mantle pre-enriched through recycling of a now-absent c. 3.7 Ga felsic crust (Smithies et al. 2009). The trace element composition of the TTGs requires 20–30% melting of this enriched source at thermal gradients much warmer than those associated with modern subduction (Johnson et al. 2017), suggesting an alternative tectonic setting. The existence of earlier felsic crust is supported by the detrital zircon Hf isotope record, which extends back to at least 3.65 Ga (Gardiner et al. 2019c, and references therein), and the variable Th/Nb trends of Pilbara basalts (**Figure 4*c***), which are consistent with crustal assimilation rather than derivation from mantle enriched through subduction.

Paleoarchean domal granitoid complexes in the BGGB have been compared to those in the EPT in terms of a volcanic plateau origin (e.g., Van Kranendonk et al. 2015), but they differ in detail. Generally the BGGB granites are not polychronic composite intrusions, and where they comprise more than one component, these have similar magmatic ages (e.g., Kamo & Davis 1994). Based on Hf isotopes, TTGs that crystallized at c. 3.2 Ga in the northern Barberton region were derived from a predominantly juvenile source, distinguishing them from an older suite of TTGs (c. 3.5–3.4 Ga) in the southern Barberton region that exhibits less radiogenic Hf isotope values, implying some crustal assimilation (Zeh et al. 2009). However, in general TTGs in the BGGB are less enriched than those from the EPT (e.g., Moyen et al. 2019), suggesting crustal assimilation was limited. Limited crustal assimilation is also implied by the Th/Yb versus Nb/Yb plot, where Paleoarchean basalts largely follow constant Th/Nb trends with slightly elevated values at higher Nb/Yb (**Figure 4*d***). It is unclear whether these distinctions between the EPT and the BGGB genuinely reflect formation within different tectonic settings (i.e., intraplate versus subduction; Kisters et al. 2010, and references therein; Schneider et al. 2019, and references therein) or simply a different prehistory of crustal recycling.

5.3. The Mesoarchean (3.2–2.8 Ga) and Neoarchean (2.8–2.5 Ga)

The late Archean was a crucial period for potential changes in tectonic mode because it witnessed shifts in various proxies that have been linked to the emergence of plate tectonics (e.g., Taylor & McLennan 1985; Condie 1993; Dhuime et al. 2012, 2015; Næraa et al. 2012; Tang et al. 2016; Greber et al. 2017; Large et al. 2018; Moyen & Laurent 2018; Nebel-Jacobsen et al. 2018; Chen et al. 2019; Greber & Dauphas 2019; Johnson et al. 2019; Ravindran et al. 2020). However, the interpretation of proxies reminds us of the parable of the blind men and an elephant. Studies based on proxies have obvious merit, but do they all address the problem as a whole? Are some of the so-called global data sets really only local—for example, due to survivorship bias or the late Archean rise of the continents—and do some data sets record an increased proportion of subduction (e.g., in a sluggish lid mode) rather than a change to plate tectonics? Does the spread of ages centered around c. 3.0 Ga that has been argued to record the emergence of plate tectonics simply reflect the beginning of a long transition from a sluggish lid to plate tectonics? Certainly, a change around 3.0 Ga is not clearly recorded by basalts from several cratons, including Pilbara, Yilgarn, and Superior (Smithies et al. 2018; cf. Moyen & van Hunen 2012), where the record appears to vary between magmatism with arc and nonarc characteristics (**Figure 4**). Maybe those proxies that are global record the onset of the transition, and differences between cratons reflect the nature of the transition.

In the Pilbara Craton, a change in tectonic style from sagduction to subduction and terrane accretion has been proposed at c. 3.2–3.0 Ga (e.g., Hickman 2004, Smithies et al. 2007) and linked with an inferred Wilson cycle and craton assembly at c. 3.0 Ga (Van Kranendonk et al. 2010). Evidence for this transition includes a shift toward more juvenile Nd isotope compositions after c. 3.2 Ga and lithological evidence of subduction-related magmatism, including sanukitoids, Nb-enriched tholeiites, and adakites (Smithies et al. 2005a). Nevertheless, an investigation of secular change in the composition of Pilbara basalts using variation in Th/Yb versus Nb/Yb identified two contrasting trends (Smithies et al. 2018). Basalts with constant Th/Nb trends that might imply melting of a subduction modified source are only seen in the Mesoarchean (c. 3.13–2.95 Ga in the West Pilbara Terrane; **Figure 4*c***), whereas most of the older (Paleoarchean of the EPT) and younger (Neoarchean of the Fortescue Group) basalt sequences have variable Th/Nb trends that do not appear subduction-like (**Figure 4*c***).

Much of the Yilgarn Craton formed between c. 3.1 and 2.6 Ga. Magmatic rocks vary in composition from TTG to monzogranite with decreasing age and commonly record geological and geochemical characteristics considered consistent with subduction, including the presence of sanukitoids. In the Th/Yb versus Nb/Yb plot (**Figure 4*e***), c. 2.82–2.71 Ga basalts from the western Youanmi Terrane define subduction-like trends, whereas c. 2.71–2.66 Ga basalts from the Eastern Goldfields Superterrane do not (Smithies et al. 2018). These data support the idea of short-lived episodes of subduction that may not record plate tectonics (O'Neill et al. 2018) but may be characteristic of the transition to plate tectonics (O'Neill et al. 2019).

We note that subduction-related rocks such as sanukitoids occur in many late Archean terranes, but are not present in pre-3.0 Ga crust (Smithies 2000). Furthermore, statistical interrogation of large geochemical and isotopic data sets has identified shifts during this period that may reflect changing tectonic modes. According to Condie (2018), the proportion of basalts derived from hydrated mantle sources (i.e., arc-like) increased significantly during the Mesoarchean–Neoarchean, interpreted as a transition to plate tectonics. There was also an increasing proportion of basalts derived from clearly depleted or enriched mantle sources from the Archean to the Proterozoic, suggesting that the distinction between magma sources was less significant during the Archean (Condie 2018, Moyen & Laurent 2018). However, using weighted bootstrap resampling to minimize any preservation and/or sampling bias, Keller & Schoene (2018) found that basalts show a gradational change though the Archean, consistent with secular cooling, but with no requirement for a sharp change in tectonic mode. This type of change may be consistent with an evolution from a sluggish lid to an active lid tectonic mode.

During the Mesoarchean–Neoarchean, a secular evolution of magma type from early TTGs to sanukitiods to potassic two-mica granites is recognized in many cratons, albeit at different times (Cawood et al. 2018). Furthermore, the chemical composition of TTGs shows an increasing spread through the Archean, reflecting the irreversible differentiation of the lithosphere (Gardiner et al. 2017, Johnson et al. 2019). Despite a high degree of scatter, the ratios of several important geochemical proxies—particularly K_2O/Na_2O, Sr/Y, and La_N/Yb_N—show statistically significant change in the interval 3.3–3.0 Ga (Johnson et al. 2019) that may identify the appearance of continental arcs and the beginning of the transition to plate tectonics.

In summary, there is geochemical evidence for subduction initiation and periods of stable subduction at multiple localities between c. 3.2 and 2.5 Ga. This period also marks the assembly of proto-continents into supercratons via accretion of proto-continents (e.g., Bleeker 2003, Smithies et al. 2007, Percival et al. 2012, Cawood et al. 2018, Friend & Nutman 2019). We interpret these data as recording a transitional period that ultimately led to plate tectonics.

6. DISCUSSION: SUBDUCTION AND PLATE TECTONICS IN THE ARCHEAN

If we accept a Columbia supercontinent composed of Archean cratons with passive margin sequences that were sutured by orogenic belts, the earliest of several supercontinent configurations, then Earth has operated according to plate tectonic theory since at least the early Paleoproterozoic. To assess what tectonic mode preceded plate tectonics, we refer to numerical modeling studies of tectonics in the Archean so that we may evaluate them against the geological record (Gerya 2014, 2019) (see the sidebar titled Numerical Modeling).

6.1. What Preceded Plate Tectonics?

A prerequisite for plate tectonics is the ability to break the lithospheric lid and initiate plate boundaries. With increasing temperature, the viscosity of the mantle is lowered, such that viscous coupling between the convecting mantle and the overlying lithosphere is reduced. In mantle

NUMERICAL MODELING

Over the past two decades, much of the progress in evaluating plausible tectonic modes for early Earth has stemmed from numerical modeling. The exponential rise in computer processing power has permitted consideration of increasingly complex rheological and material properties that more closely simulate nature, using input criteria based on existing geological, geochemical, geophysical, and petrological data. This has allowed exploration and quantitative testing of various geodynamic hypotheses. Of particular importance to the input parameters is the development of thermodynamic models appropriate to partial melting of a wide spectrum of compositions ranging from ultrabasic to granitic. These advances allow calculation of the changes in phase assemblage, the abundance and composition of phases, and the densities of phase assemblages in crust–mantle systems that include solid, melt, and volatile phases, all as a function of pressure, temperature, and protolith composition.

convection models that use a pseudoplastic rheology for the lithosphere, higher T_P favors a stagnant lid for the early Earth (e.g., O'Neill et al. 2016). By contrast, models in which plate boundaries develop by grain size reduction favor a sluggish lid for the early Earth (e.g., Foley 2018). Higher temperature also weakens the slab, leading to more frequent slab breakoffs (van Hunen & van den Berg 2008) and, at ΔT_P around +175°C, subduction may no longer be possible (Sizova et al. 2010). At ΔT_P higher than +200°C, foundering by Rayleigh–Taylor instabilities (drips) of overthickened crust (Johnson et al. 2014, Nebel et al. 2018) is likely. Thus, a stagnant or sluggish lid mode, with a deformable (squishy) lithosphere (Rozel et al. 2017) punctuated by episodes of short-lived subduction (Sizova et al. 2015), may have preceded plate tectonics. The earlier mode may have been linked to plate tectonics via an episodic lid mode (O'Neill et al. 2016, 2018), which may be reflected in changes from arc to nonarc magmatism in the Mesoarchean–Neoarchean rock record of some cratons.

6.2. Formation and Breakup of Supercratons: The Transition to Plate Tectonics in the Neoarchean–Early Paleoproterozoic

Age-constrained geological and geochemical data retrieved from cratons demonstrate differences in petrogenesis and tectonic style from one to another without a uniform pattern. Prior to the Mesoarchean, the formation and evolution of some Archean crust (e.g., the North Atlantic Craton) may have been related to subduction-driven tectonics, whereas the development of other Archean crust (e.g., the EPT in the Pilbara Craton) appears to have been related to intraplate activity. Such differences may also occur between terranes within the same craton. For example the Mesoarchean Akia Terrane, now part of the North Atlantic Craton, may have formed in a stagnant lid mode (Gardiner et al. 2019b), whereas the Eoarchean IGC may have had a subduction origin. Potentially, these differences can be accommodated in more than one tectonic mode, such as sluggish lid (Foley 2018) or lid and plate tectonics (Capitanio et al. 2019).

In a sluggish lid mode, assuming weak plate boundaries can form during mantle convection at Archean conditions (Foley 2018), subduction may occur on a locally confined scale associated with lithospheric mobility, whereas intraplate magmatism may occur elsewhere due to passive mantle upwelling. On secular cooling, as subduction became more widespread, intraplate magmatism waned, and subduction-related magmatism increased during a transition to an active lid mode (Foley 2018). However, it remains unclear when this transition began or was completed. The beginning of such a transition may be what is recorded in the geology of the North Atlantic Craton and in the BGGB during the Mesoarchean–Neoarchean. By contrast, during the same period in other cratons (Pilbara, Yilgarn, and Superior), the evidence suggests only short-lived

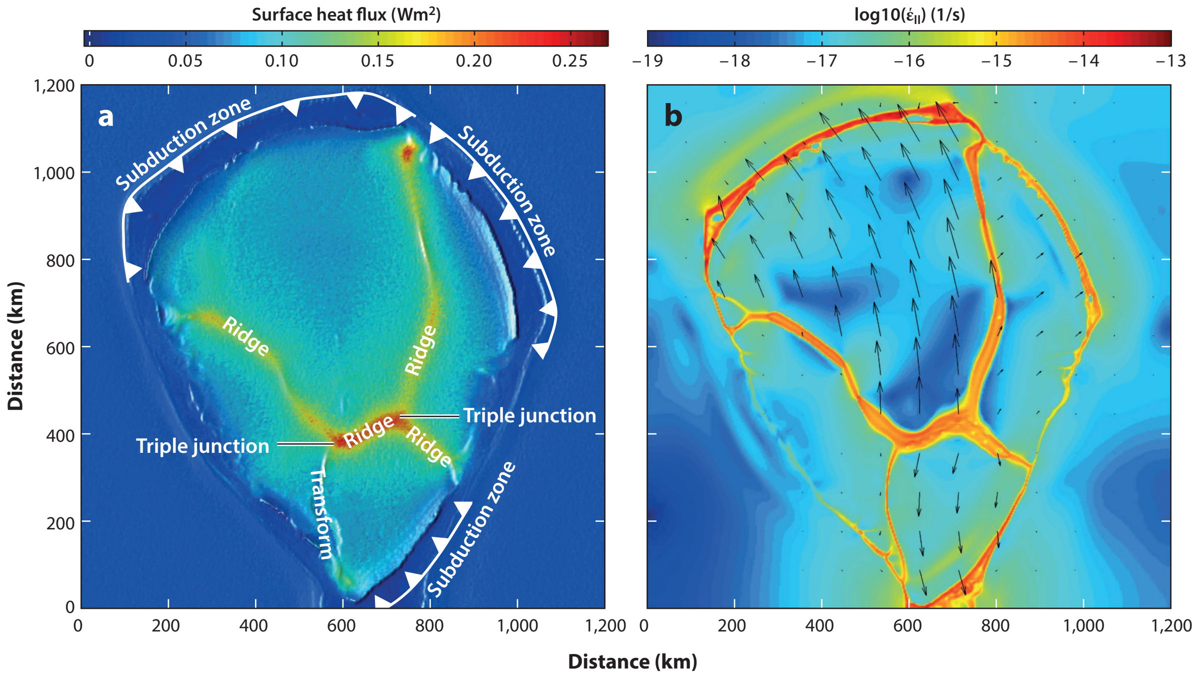


Figure 5

Development of an embryonic mosaic of plates separated by spreading centers (ridges), triple junctions, and transform faults at the latest stage of plume-induced subduction. (*a*) Surface heat fluxes projected onto the modeled surface topography, showing a pattern of spreading centers (*white lines with triangles* show dip directions of retreating subducting slabs). (*b*) Spatial distribution of the second strain rate invariant at a depth of 20 km (*arrows* show horizontal velocities of individual, young, nonsubducting plates moving toward retreating subducting slabs). Figure adapted from Gerya et al. (2015); copyright 2015, with permission from Springer Nature.

episodes of subduction that cannot necessarily be used to argue for plate tectonics (O'Neill et al. 2018, 2019). Thus, the Mesoarchean–Neoarchean may register the mixed signals we might expect of a transition to plate tectonics that was not completed until the early Paleoproterozoic.

How the transition to plate tectonics occurred remains cryptic, but during converging mantle flow a general requirement for initiation of subduction is thought to be the development of heterogeneities in rheology, buoyancy, and composition along the margins of early-formed protocontinents (Bercovici & Ricard 2014, Rey et al. 2014). In addition, other mechanisms may have contributed to the emergence of plate tectonics within a sluggish lid tectonic mode, such as subduction induced through intraplate plume activity (Gerya et al. 2015) (**Figure 5**). In the Archean, plume activity could have led to the formation of retreating subduction zones similar to those associated with the Caribbean large igneous province in the Cretaceous (Gerya et al. 2015). At higher ΔT_P of +200°C, models of plume–lithosphere interactions show that plume-induced subduction is feasible for older lithosphere (80 Myr), whereas plume interaction with younger lithosphere (20 Myr) favors episodic dripping rather than stable subduction (Gerya et al. 2015) (**Figure 6**).

According to Perchuk et al. (2019), at higher ΔT_P of +150°C, retreating subduction, as occurs in the plume model, could lead to an initial arc-free regime as formation of magma by fluid-fluxed melting in the wedge is depressed during rapid trench rollback and vigorous upwelling of asthenospheric mantle. Instead, decompression melting of the upwelling asthenospheric mantle results in widespread development of voluminous hydrous intraplate basalts (Perchuk et al. 2019). In this context, TTG crust could be generated by partial melting of the intraplate basalts

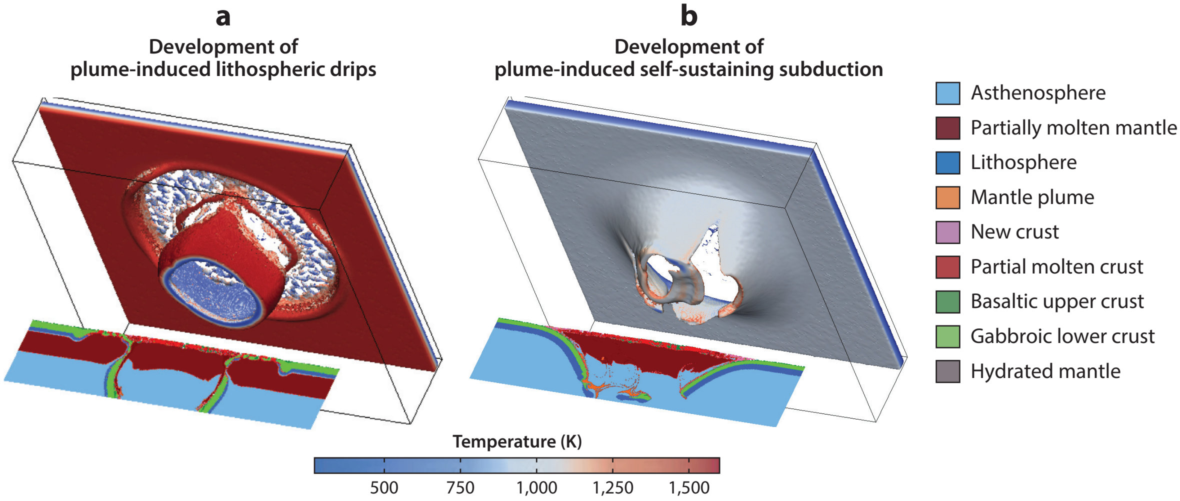


Figure 6

Plume–lithosphere interaction for hotter mantle temperature (ΔT_P of +200°C) and thicker oceanic crust. (*a*) Development of plume-induced lithospheric drips for 20-Myr oceanic plate with 30-km-thick crust. (*b*) Development of plume-induced self-sustaining subduction for 80-Myr oceanic plate with 20-km-thick crust. Figure adapted from Gerya et al. (2015); copyright 2015, with permission from Springer Nature.

(Johnson et al. 2014, 2017; Sobolev & Brown 2019) (**Figure 7*a***). Collision between these nascent proto-continental crustal domains and thickening of the lithosphere to create proto-continents could have occurred as mantle downwelling eliminated the intervening ocean between a pair of retreating subduction cells (cf. Wang et al. 2018, Tang et al. 2019) (**Figure 7*b***).

According to Sobolev & Brown (2019), the emergence and evolution of plate tectonics on Earth could have been related to the rise of the continents (Flament et al. 2008, Rey & Coltice 2008) and the accumulation of sediments at continental edges, and subsequently in trenches, to lubricate and stabilize subduction. In southern Africa, glaciation is recorded in the Mesoarchean Mozaan Group (c. 2.9 Ga; the upper part of the Pongola Supergroup) on the passive margin of the Kaapvaal Craton (Young et al. 1998). This combination of events may have allowed a spreading proto-continent to initiate subduction at its edge, as proposed by Rey et al. (2014) and documented for young subduction zones near Sulawesi in the Southwest Pacific (Hall 2019). Therefore, an early record of plate tectonics in the amalgamation of the Kaapvaal Craton is not surprising (Shirey & Richardson 2011).

We posit that the emergence of plate tectonics on Earth could be related, at least in part, to the development of regional networks of plate boundaries formed by intraplate plume-induced subduction initiation, formation of proto-continents, and initiation of subduction at the edges of these proto-continents. Thus, as a sluggish lid evolved toward an active lid, plume-induced regional networks could have linked with existing subduction sites gradually developing a global network of plate boundaries. During this late Mesoarchean to early Paleoproterozoic transition to plate tectonics, as secular cooling of the mantle became dominant over heating, proto-continental lithosphere was aggregated into a small number of supercratons. This process took hundreds of millions of years to accomplish, and there is no evidence of a single global supercraton-forming event. Subsequently, the supercratons were fragmented in response to mantle insulation (Lenardic 2017, and references therein) and/or possibly by plumes triggered by subduction around the supercraton margins.

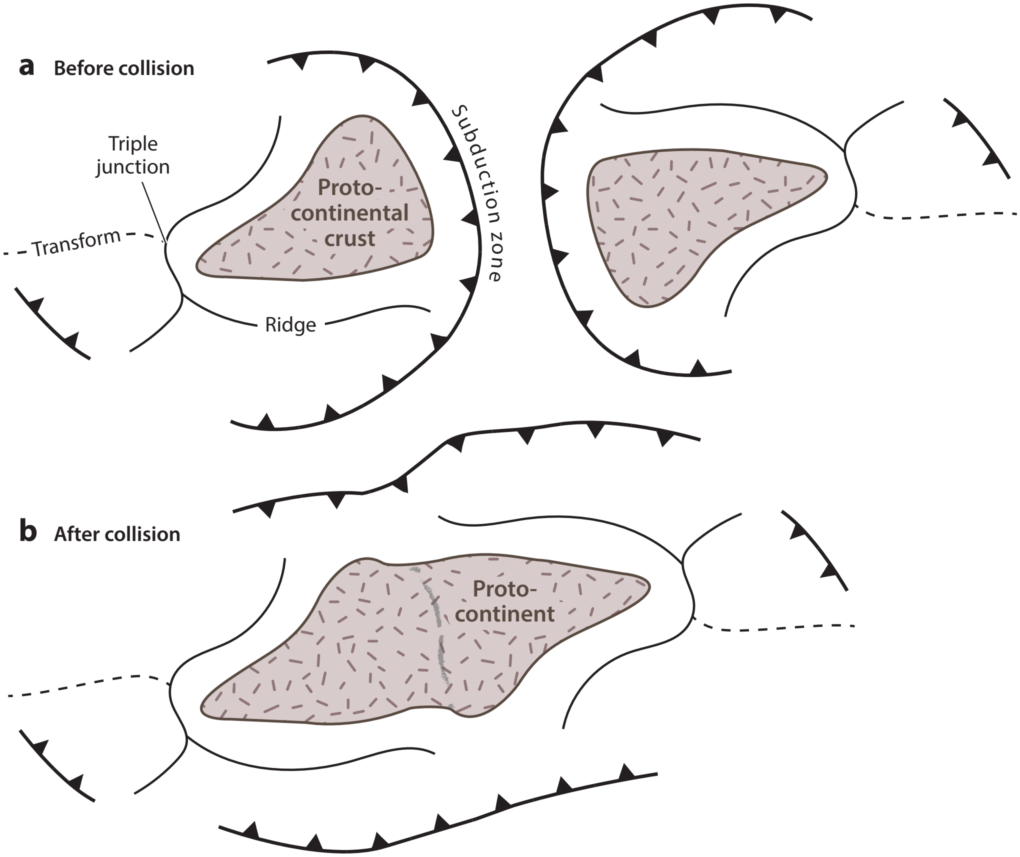


Figure 7

Sketches showing approaching plume-induced subduction cells (*a*) before elimination of the intervening oceanic lithosphere and collision and (*b*) after collision and formation of a proto-continent.

SUMMARY POINTS

1. Before the Mesoarchean–Neoarchean, a stagnant lid or sluggish lid or lid and plate tectonics mode, with a deformable (squishy) lithosphere and either intermittent (unstable) subduction or subduction on a locally confined scale, may have been dominant. A hotter mantle prohibited widespread stable subduction and plate tectonics, and magmatism was largely due to upwelling mantle and plume–lithosphere interactions.
2. During a Mesoarchean–Neoarchean transition, as secular cooling overwhelmed heat production, plate tectonics emerged, possibly in part via plume-initiated retreating subduction cells that generated proto-continents.
3. The rise of proto-continents and enhanced erosion to provide sediments at their edges may have enabled initiation of subduction under the proto-continents by spreading of continental margins over oceanic lithosphere. This process could have stabilized subduction and promoted the spread of plate tectonics globally, as recorded by the

widespread appearance of high and intermediate T/P metamorphism in the Neoarchean. The formation and breakup of the supercratons, and the formation of the first supercontinent Columbia, demonstrate that plate tectonics was fully developed by the early Paleoproterozoic.

FUTURE ISSUES

1. Geochemical criteria need to be identified to distinguish impact-induced from plume-induced melt products, so that we may determine the contribution of each process to the formation of the Hadean and Eoarchean tonalite-trondhjemite-granodiorite crust.
2. To evaluate hypotheses regarding the tectonics of early Earth, it is necessary to increase the number of metamorphic pressure, temperature, and age data from exposures of ancient (older than 2.8 Ga) continental crust worldwide. Retrieval of such data should be a priority of metamorphic studies.
3. To understand secular change in tectonics on Earth requires a better knowledge of the thermal evolution of Earth and mantle potential temperature and further research to resolve the contentious issue of the amount and temporal evolution of water in the mantle.
4. To understand the evolution of life on Earth, it is necessary to assess linkages between secular change in tectonic mode and the evolution of Earth's atmosphere, oceans, and landscape, since these control nutrient supply and environment.

DISCLOSURE STATEMENT

The authors are not aware of any affiliations, memberships, funding, or financial holdings that might be perceived as affecting the objectivity of this review.

ACKNOWLEDGMENTS

By necessity, in attempting to cover such a broad and (currently) popular topic, we have been able to cite only a small proportion of the relevant published literature. In most instances we have cited recent contributions, such that the interested reader may more easily follow the historical trail of ideas pertaining to Archean tectonics. T.J. acknowledges support from the State Key Laboratory for Geological Processes and Mineral Resources, China University of Geosciences, Wuhan (Open Funds GPMR201704 and GPMR201903). N.J.G. acknowledges Australian Research Council grant FL160100168 for financial support. We thank Dr. Marzieh Baes of the Helmholtz Centre Potsdam for provision of vector files that we modified in producing **Figures 5** and **6**. We are grateful to P. Cawood, C. Hawkesworth, and R. Rudnick for their comments that undoubtedly improved the published version of the paper. Any remaining errors or misconceptions are ours.

LITERATURE CITED

Abbott D, Menke W. 1990. Length of the global plate boundary at 2.4 Ga. *Geology* 18:58–61

Abbott D, Mooney WD, VanTongeren JA. 2013. The character of the Moho and lower crust within Archean cratons and the tectonic implications. *Tectonophysics* 609:690–705

Aulbach S, Arndt NT. 2019. Eclogites as palaeodynamic archives: evidence for warm (not hot) and depleted (but heterogeneous) Archaean ambient mantle. *Earth Planet. Sci. Lett.* 505:162–72

Bédard JH. 2018. Stagnant lids and mantle overturns: implications for Archaean tectonics, magmagenesis, crustal growth, mantle evolution, and the start of plate tectonics. *Geosci. Front.* 9:19–49

Bédard JH, Harris LB, Thurston PC. 2013. The hunting of the snArc. *Precambrian Res.* 229:20–48

Bercovici D, Ricard Y. 2014. Plate tectonics, damage and inheritance. *Nature* 508:513–16

Bercovici D, Tackley P, Ricard Y. 2015. The generation of plate tectonics from mantle dynamics. In *Treatise on Geophysics*, Vol. 7, ed. D Bercovici, G Schubert, pp. 271–318. New York: Elsevier

Bindeman IN, Zakharov DO, Palandri J, Greber ND, Dauphas N, et al. 2018. Rapid emergence of subaerial landmasses and onset of a modern hydrologic cycle 2.5 billion years ago. *Nature* 557:545–48

Bleeker W. 2003. The late Archean record: a puzzle in ca. 35 pieces. *Lithos* 71:99–134

Bleeker W, Ernst RE. 2006. Short-lived mantle generated magmatic events and their dyke swarms: the key unlocking Earth's paleogeographic record back to 2.6 Ga. In *Dyke Swarms—Time Markers of Crustal Evolution*, ed. E Hanski, S Mertanen, T Rämö, J Vuollo, pp. 3–26. London: Taylor & Francis

Bradley DC. 2008. Passive margins through Earth history. *Earth-Sci. Rev.* 91:1–26

Brown M. 2006. Duality of thermal regimes is the distinctive characteristic of plate tectonics since the Neoarchean. *Geology* 34:961–64

Brown M, Johnson T. 2018. Secular change in metamorphism and the onset of global plate tectonics. *Am. Mineral.* 103:181–96

Brown M, Johnson T. 2019a. The 51st Hallimond Lecture—Time's arrow, time's cycle: granulite metamorphism and geodynamics. *Mineral. Mag.* 83:323–38

Brown M, Johnson T. 2019b. Global age, temperature and pressure data for secular change in metamorphism. *EarthChem Libr.* 2019. **https://doi.org/10.1594/IEDA/111316**

Brown M, Johnson T. 2019c. MSA Presidential Address: metamorphism and the evolution of subduction on Earth. *Am. Mineral.* 104:1065–82

Capitanio FA, Nebel O, Cawood PA, Weinberg RF, Clos F. 2019. Lithosphere differentiation in the early Earth controls Archean tectonics. *Earth Planet. Sci. Lett.* 525:115755

Carlson RW, Garnero E, Harrison TM, Li J, Manga M, et al. 2014. How did early Earth become our modern world? *Annu. Rev. Earth Planet. Sci.* 42:151–78

Cawood PA, Hawkesworth CJ, Pisarevsky SA, Dhuime B, Capitanio FA, Nebel O. 2018. Geological archive of the onset of plate tectonics. *Philos. Trans. R. Soc. A* 376:20170405

Cawood PA, Kröner A, Collins WJ, Kusky TM, Mooney WD, Windley BF. 2009. Accretionary orogens through Earth history. *Geol. Soc. Lond. Spec. Publ.* 318:1–36

Cawood PA, Kröner A, Pisarevsky S. 2006. Precambrian plate tectonics: criteria and evidence. *GSA Today* 16:4–11

Chen K, Rudnick RL, Wang Z, Tang M, Gaschnig RM, et al. 2019. How mafic was the Archean upper continental crust? Insights from Cu and Ag in ancient glacial diamictites. *Geochim. Cosmochim. Acta.* In press. **https://doi.org/10.1016/j.gca.2019.08.002**

Chowdhury P, Gerya T, Chakraborty S. 2017. Emergence of silicic continents as the lower crust peels off on a hot plate-tectonic Earth. *Nat. Geosci.* 10:698–703

Condie KC. 1993. Chemical composition and evolution of the upper continental crust: contrasting results from surface samples and shales. *Chem. Geol.* 104:1–37

Condie KC. 2005. TTGs and adakites: Are they both slab melts? *Lithos* 80:33–44

Condie KC. 2018. A planet in transition: the onset of plate tectonics on Earth between 3 and 2 Ga? *Geosci. Front.* 9:51–60

Condie KC, Aster RC, van Hunen J. 2016. A great thermal divergence in the mantle beginning 2.5 Ga: geochemical constraints from greenstone basalts and komatiites. *Geosci. Front.* 7:543–53

Condie KC, Puetz SJ, Davaille A. 2018. Episodic crustal production before 2.7 Ga. *Precambrian Res.* 312:16–22

Crameri F, Tackley PJ. 2016. Subduction initiation from a stagnant lid and global overturn: new insights from numerical models with a free surface. *Prog. Earth Planet. Sci.* 3:30

Davaille A, Smrekar SE, Tomlinson S. 2017. Experimental and observational evidence for plume-induced subduction on Venus. *Nat. Geosci.* 10:349–55

Dhuime B, Hawkesworth CJ, Cawood PA, Storey CD. 2012. A change in the geodynamics of continental growth 3 billion years ago. *Science* 335:1334–36

Dhuime B, Hawkesworth CJ, Delavault H, Cawood PA. 2018. Rates of generation and destruction of the continental crust: implications for continental growth. *Philos. Trans. R. Soc. A* 376:20170403

Dhuime B, Wuestefeld A, Hawkesworth CJ. 2015. Emergence of modern continental crust about 3 billion years ago. *Nat. Geosci.* 8:552–55

Djomani YH, O'Reilly SY, Griffin WL, Morgan P. 2001. The density structure of subcontinental lithosphere through time. *Earth Planet. Sci. Lett.* 184:605–21

Dziggel A, Diener JFA, Kolb J, Kokfelt TF. 2014. Metamorphic record of accretionary processes during the Neoarchaean: the Nuuk region, southern West Greenland. *Precambrian Res.* 242:22–38

Ernst RE, Bleeker W, Söderlund U, Kerr AC. 2013. Large igneous provinces and supercontinents: toward completing the plate tectonic revolution. *Lithos* 174:1–14

Fischer R, Gerya T. 2016a. Early Earth plume-lid tectonics: a high-resolution 3D numerical modelling approach. *J. Geodyn.* 100:198–214

Fischer R, Gerya T. 2016b. Regimes of subduction and lithospheric dynamics in the Precambrian: 3D thermomechanical modelling. *Gondwana Res.* 37:53–70

Flament N, Coltice N, Rey PF. 2008. A case for late-Archaean continental emergence from thermal evolution models and hypsometry. *Earth Planet. Sci. Lett.* 275:326–36

Foley BJ. 2018. The dependence of planetary tectonics on mantle thermal state: applications to early Earth evolution. *Philos. Trans. R. Soc. A* 376:20170409

Friend CRL, Nutman AP. 2019. Tectono-stratigraphic terranes in Archaean gneiss complexes as evidence for plate tectonics: the Nuuk region, southern West Greenland. *Gondwana Res.* 72:213–37

Ganne J, Feng X. 2017. Primary magmas and mantle temperatures through time. *Geochem. Geophys. Geosyst.* 18:872–88

Gapais D, Cagnard F, Gueydan F, Barbey P, Ballèvre M. 2009. Mountain building and exhumation processes through time: inferences from nature and models. *Terra Nova* 21:188–94

Gardiner NJ, Hickman AH, Kirkland CL, Lu YJ, Johnson TE, Zhao JX. 2017. Processes of crust formation in the early Earth imaged through Hf isotopes from the East Pilbara Terrane. *Precambrian Res.* 297:56–76

Gardiner NJ, Johnson TE, Kirkland CL, Szilas K. 2019a. Modelling the hafnium-neodymium evolution of early Earth: a study from West Greenland. *J. Petrol.* 60:117–97

Gardiner NJ, Kirkland CL, Hollis J, Szilas K, Steenfelt A, et al. 2019b. Building Mesoarchaean crust upon Eoarchaean roots: the Akia Terrane, West Greenland. *Contrib. Mineral. Petrol.* 174:20

Gardiner NJ, Wacey D, Kirkland CL, Johnson TE, Jeon H. 2019c. Zircon U-Pb, Lu-Hf and O isotopes from the 3414 Ma Strelley Pool Formation, East Pilbara Terrane, and the Palaeoarchaean emergence of a cryptic cratonic core. *Precambrian Res.* 321:64–84

Gerya TV. 2014. Precambrian geodynamics: concepts and models. *Gondwana Res.* 25:442–63

Gerya TV. 2019. Geodynamics of the early Earth: quest for the missing paradigm. *Geology* 47:1006–7

Gerya TV, Stern RJ, Baes M, Sobolev SV, Whattam SA. 2015. Plate tectonics on the Earth triggered by plume-induced subduction initiation. *Nature* 527:221–25

Giles D, Betts PG, Lister GS. 2004. 1.8–1.5-Ga links between the north and south Australian cratons and the early-middle Proterozoic configuration of Australia. *Tectonophysics* 380:27–41

Greber ND, Dauphas N. 2019. The chemistry of fine-grained terrigenous sediments reveals a chemically evolved Paleoarchean emerged crust. *Geochim. Cosmochim. Acta* 255:247–64

Greber ND, Dauphas N, Bekker A, Ptàcek MP, Bindeman IN, Hofmann A. 2017. Titanium isotopic evidence for felsic crust and plate tectonics 3.5 billion years ago. *Science* 357:1271–74

Griffin WL, O'Reilly SY. 2019. The earliest subcontinental lithospheric mantle. In *Earth's Oldest Rocks*, ed. MJ Van Kranendonk, V Bennett, E Hoffmann, pp. 81–102. Amsterdam: Elsevier. 2nd ed.

Griffin WL, O'Reilly SY, Afonso JC, Begg GC. 2008. The composition and evolution of lithospheric mantle: a re-evaluation and its tectonic implications. *J. Petrol.* 50:1185–204

GSWA (Geol. Surv. West. Aust). 2019. *GeoChem Extract*. Geochemistry Database, Department of Mines and Petroleum, East Perth, Western Australia. **http://geochem.dmp.wa.gov.au/geochem/**

Hall R. 2019. The subduction initiation stage of the Wilson cycle. *Geol. Soc. Lond. Spec. Publ.* 470:415–37

Harrison TM. 2009. The Hadean crust: evidence from >4 Ga zircons. *Annu. Rev. Earth Planet. Sci.* 37:479–505

Hawkesworth CJ, Brown M. 2018. Earth dynamics and the development of plate tectonics. *Philos. Trans. R. Soc. A* 376:20180228

Hawkesworth CJ, Cawood PA, Dhuime B. 2016. Tectonics and crustal evolution. *GSA Today* 26:4–11

Hawkesworth CJ, Cawood PA, Dhuime B. 2019. Rates of generation and growth of the continental crust. *Geosci. Front.* 10:165–173

Hawkesworth CJ, Cawood PA, Dhuime B, Kemp AI. 2017. Earth's continental lithosphere through time. *Annu. Rev. Earth Planet. Sci.* 45:169–98

Herzberg C, Asimow PD, Arndt N, Niu Y, Lesher CM, et al. 2007. Temperatures in ambient mantle and plumes: constraints from basalts, picrites and komatiites. *Geochem. Geophys. Geosyst.* 8:Q02006

Herzberg C, Condie K, Korenaga J. 2010. Thermal history of the Earth and its petrological expression. *Earth Planet. Sci. Lett.* 292:79–88

Hickman AH. 2004. Two contrasting granite–greenstone terranes in the Pilbara Craton, Australia: evidence for vertical and horizontal tectonic regimes prior to 2900 Ma. *Precambrian Res.* 131:153–72

Hoffmann JE, Münker C, Polat A, König S, Mezger K, Rosing MT. 2010. Highly depleted Hadean mantle reservoirs in the sources of early Archean arc-like rocks, Isua supracrustal belt, southern West Greenland. *Geochim. Cosmochim. Acta* 74:7236–60

Hoffmann JE, Münker C, Polat A, Rosing MT, Schulz T. 2011. The origin of decoupled Hf-Nd isotope compositions in Eoarchean rocks from southern West Greenland. *Geochim. Cosmochim. Acta* 75:6610–28

Hoffmann JE, Nagel TJ, Münker C, Næraa T, Rosing MT. 2014. Constraining the process of Eoarchean TTG formation in the Itsaq Gneiss Complex, southern West Greenland. *Earth Planet. Sci. Lett.* 388:374–86

Hoffmann JE, Zhang C, Moyen J-F, Nagel TJ. 2019. The formation of tonalites-trondhjemite-granodiorites in early continental crust. In *Earth's Oldest Rocks*, ed. MJ Van Kranendonk, V Bennett, E Hoffmann, pp. 133–68. Amsterdam: Elsevier. 2nd ed.

Hoink T, Lenardic A, Jellinek AM. 2013. Earth's thermal evolution with multiple convection modes: a Monte-Carlo approach. *Phys. Earth Planet. Int.* 221:22–26

Holder RM, Viete DR, Brown M, Johnson TE. 2019. Metamorphism and the evolution of plate tectonics. *Nature* 572:378–81

Jenner FE, Bennett VC, Nutman AP, Friend CRL, Norman M, Yaxley G. 2009. Evidence for subduction at 3.8 Ga: geochemistry of arc-like metabasalts from the southern edge of the Isua Supracrustal Belt. *Chem. Geol.* 261:83–98

Johnson TE, Brown M, Gardiner NJ, Kirkland CL, Smithies RH. 2017. Earth's first stable continents did not form by subduction. *Nature* 543:239–42

Johnson TE, Brown M, Goodenough KM, Clark C, Kinny PD, White RW. 2016. Subduction or sagduction? Ambiguity in constraining the origin of ultramafic-mafic bodies in the Archean crust of NW Scotland. *Precambrian Res.* 283:89–105

Johnson TE, Brown M, Kaus B, VanTongeren JA. 2014. Delamination and recycling of Archaean crust caused by gravitational instabilities. *Nat. Geosci.* 7:47–52

Johnson TE, Gardiner NJ, Miljković K, Spencer CJ, Kirkland CL, et al. 2018. An impact melt origin for Earth's oldest known evolved rocks. *Nat. Geosci.* 11:795–99

Johnson TE, Kirkland CL, Gardiner NJ, Brown M, Smithies RH, Santosh M. 2019. Secular change in TTG compositions: implications for the evolution of Archaean geodynamics. *Earth Planet. Sci. Lett.* 505:65–75

Kamber BS, Tomlinson EL. 2019. Petrological, mineralogical and geochemical peculiarities of Archaean cratons. *Chem. Geol.* 511:123–51

Kamo SL, Davis DW. 1994. Reassessment of Archean crustal development in the Barberton Mountain Land, South Africa, based on U-Pb dating. *Tectonics* 13:167–92

Karlstrom KE, Åhäll K-I, Harlan SS, Williams ML, McLelland J, Geissman JW. 2001. Long-lived (1.8–1.0 Ga) convergent orogen in southern Laurentia, its extensions to Australia and Baltica, and implications for refining Rodinia. *Precambrian Res.* 111:5–30

Keller B, Schoene B. 2018. Plate tectonics and continental basaltic geochemistry throughout Earth history. *Earth Planet. Sci. Lett.* 481:290–304

Kemp AIS, Whitehouse MJ, Vervoort JD. 2019. Deciphering the zircon Hf isotope systematics of Eoarchean gneisses from Greenland: implications for ancient crust-mantle differentiation and Pb isotope controversies. *Geochim. Cosmochim. Acta* 250:76–97

Kisters AFM, Belcher RW, Poujol M, Dziggel A. 2010. Continental growth and convergence-related arc plutonism in the Mesoarchaean: evidence from the Barberton granitoid-greenstone terrain, South Africa. *Precambrian Res.* 178:15–26

Koeberl C. 2006. Impact processes on the early Earth. *Elements* 2:211–16

Korenaga J. 2013. Initiation and evolution of plate tectonics on Earth: theories and observations. *Annu. Rev. Earth Planet. Sci.* 41:117–51

Korenaga J. 2017. Pitfalls in modeling mantle convection with internal heat production. *J. Geophys. Res. Solid Earth* 122:4064–85

Korenaga J. 2018. Crustal evolution and mantle dynamics through Earth history. *Philos. Trans. R. Soc. A* 376:20170408

Kreemer C, Blewitt G, Klein EC. 2014. A geodetic plate motion and Global Strain Rate Model. *Geochem. Geophys. Geosyst.* 15:3849–89

Kusky TM, Windley BF, Polat A. 2018. Geological evidence for the operation of plate tectonics throughout the Archean: records from Archean paleo-plate boundaries. *J. Earth Sci.* 29:1291–303

Labrosse S, Jaupart C. 2007. Thermal evolution of the Earth: secular changes and fluctuations of plate characteristics. *Earth Planet. Sci. Lett.* 260:465–81

Large RR, Mukherjee I, Zhukova I, Corkrey R, Stepanov A, Danyushevsky LV. 2018. Role of upper-most crustal composition in the evolution of the Precambrian ocean-atmosphere system. *Earth Planet. Sci. Lett.* 487:44–53

Lee C-TA. 2003. Compositional variation of density and seismic velocities in natural peridotites at STP conditions: implications for seismic imaging of compositional heterogeneities in the upper mantle. *J. Geophys. Res. Solid Earth* 108(B9):2441

Lee C-TA, Luffi P, Chin EJ. 2011. Building and destroying continental mantle. *Annu. Rev. Earth Planet. Sci.* 39:59–90

Lenardic A. 2017. A supercontinental boost. *Nat. Geosci.* 10:4–5

Lenardic A. 2018. The diversity of tectonic modes and thoughts about transitions between them. *Philos. Trans. R. Soc. A* 376:20170416

Lenardic A, Weller M, Höink T, Seales J. 2019. Toward a boot strap hypothesis of plate tectonics: feedbacks between plates, the asthenosphere, and the wavelength of mantle convection. *Phys. Earth Planet. Int.* 296:106299

Li ZX, Evans DAD, Murphy JB, eds. 2016. *Supercontinent Cycles Through Earth History*. Geol. Soc. Lond. Spec. Publ. 424. Bath, UK: Geol. Soc.

Liou P, Guo J. 2019. Generation of Archaean TTG gneisses through amphibole-dominated fractionation. *J. Geophys. Res. Solid Earth* 124:3605–19

Mallard C, Coltice N, Seton M, Müller D, Tackley PJ. 2016. Subduction controls the distribution and fragmentation of Earth's tectonic plates. *Nature* 535:140–43

Marchi S, Bottke WF, Elkins-Tanton LT, Bierhaus M, Wuennemann K, et al. 2014. Widespread mixing and burial of Earth's Hadean crust by asteroid impacts. *Nature* 511:578–82

Martin H, Moyen JF, Guitreau M, Blichert-Toft J, Le Pennec JL. 2014. Why Archaean TTG cannot be generated by MORB melting in subduction zones. *Lithos* 198:1–13

Martin H, Smithies RH, Rapp R, Moyen JF, Champion D. 2005. An overview of adakite, tonalite-trondhjemite-granodiorite (TTG), and sanukitoid: relationships and some implications for crustal evolution. *Lithos* 79:1–24

McCoy-West AJ, Chowdhury P, Burton KW, Sossi P, Nowell GM, et al. 2019. Extensive crustal extraction in Earth's early history inferred from molybdenum isotopes. *Nat. Geosci.* 12:946–51

McKenzie D, Bickle MJ. 1988. The volume and composition of melt generated by extension of the lithosphere. *J. Petrol.* 29:625–79

Meert JG, Santosh M. 2017. The Columbia supercontinent revisited. *Gondwana Res.* 50:67–83

Mitchell RN, Bleeker W, van Breemen O, Lecheminant TN, Peng P, et al. 2014. Plate tectonics before 2.0 Ga: evidence from paleomagnetism of cratons within supercontinent Nuna. *Am. J. Sci.* 314:878–94

Moyen J-F. 2011. The composite Archaean grey gneisses: petrological significance, and evidence for a non-unique tectonic setting for Archaean crustal growth. *Lithos* 123:21–36

Moyen J-F, Laurent O. 2018. Archaean tectonic systems: a view from igneous rocks. *Lithos* 302–303:99–125

Moyen J-F, Stevens G. 2006. Experimental constraints on TTG petrogenesis: implications for Archean geodynamics. In *Archean Geodynamics and Environments*, ed. K Benn, J-C Mareschal, KC Condie, pp. 149–75. Washington, DC: Am. Geophys. Union

Moyen J-F, Stevens G, Kisters AFM, Belcher RW, Lemirre B. 2019. TTG plutons of the barberton granitoid-greenstone terrain, South Africa. In *Earth's Oldest Rocks*, ed. MJ Van Kranendonk, VC Bennett, JE Hoffmann, pp. 615–54. Amsterdam: Elsevier. 2nd ed.

Moyen J-F, van Hunen J. 2012. Short-term episodicity of Archaean plate tectonics. *Geology* 40:451–54

Næraa T, Scherstén A, Kemp AIS, Rosing TM, Hoffmann JE, et al. 2012. Hafnium isotope evidence for a transition in the dynamics of continental growth 3.2 Ga ago. *Nature* 485:627–30

Nance RD, Murphy JB, Santosh M. 2014. The supercontinent cycle: a retrospective essay. *Gondwana Res.* 25:4–29

Nebel O, Capitanio FA, Moyen J-F, Weinberg RF, Clos F, et al. 2018. When crust comes of age: on the chemical evolution of Archaean, felsic continental crust by crustal drip tectonics. *Philos. Trans. R. Soc. A* 376:20180103

Nebel-Jacobsen Y, Nebel O, Wille M, Cawood PA. 2018. A non-zircon Hf isotope record in Archean black shales from the Pilbara Craton confirms changing crustal dynamics ca. 3 Ga ago. *Sci. Rep.* 8:922

Nutman AP, Bennett VC. 2019. The 3.9–3.6 Ga Itsaq gneiss complex of Greenland: quasi-uniformitarian geodynamics towards the end of Earth's first billion years. In *Earth's Oldest Rocks*, ed. MJ Van Kranendonk, VC Bennett, JE Hoffmann, pp. 375–400. Amsterdam: Elsevier. 2nd ed.

Nutman AP, Bennett VC, Friend CRL, Hidaka H, Yi K, et al. 2013. The Itsaq gneiss complex of Greenland: episodic 3900 to 3660 Ma juvenile crust formation and recycling in the 3660 to 3600 Ma Isukasian orogeny. *Am. J. Sci.* 313:877–911

O'Neill C, Lenardic A, Weller M, Moresi L, Quenette S, Zhang S. 2016. A window for plate tectonics in terrestrial planet evolution? *Phys. Earth Planet. Int.* 255:80–92

O'Neill C, Marchi S, Bottke W, Fu R. 2019. The role of impacts on Archaean tectonics. *Geology* 48:174–78

O'Neill C, Marchi S, Zhang S, Bottke W. 2017. Impact-driven subduction on the Hadean Earth. *Nat. Geosci.* 10:793–97

O'Neill C, Turner S, Rushmer T. 2018. The inception of plate tectonics: a record of failure. *Philos. Trans. R. Soc. A* 376:20170414

Oreskes N. 2002. *Plate Tectonics: An Insider's History of the Modern Theory of the Earth*. Boulder, CO: Westview

Pearce JA. 2008. Geochemical fingerprinting of oceanic basalts with applications to ophiolite classification and the search for Archean oceanic crust. *Lithos* 100:14–48

Pearce JA. 2014. Geochemical fingerprinting of the Earth's oldest rocks. *Geology* 42:175–76

Pearce JA, Reagan MK. 2019. Identification, classification, and interpretation of boninites from Anthropocene to Eoarchean using Si-Mg-Ti systematics. *Geosphere* 15:1008–37

Pearson DG, Wittig N. 2008. Formation of Archaean continental lithosphere and its diamonds: the root of the problem. *J. Geol. Soc. Lond.* 165:895–914

Pearson DG, Wittig N. 2014. The formation and evolution of cratonic mantle lithosphere—evidence from mantle xenoliths. In *Treatise on Geochemistry*, ed. KK Turekian, HD Holland, pp. 255–92. San Diego, CA: Elsevier. 2nd ed.

Pehrsson SJ, Berman RG, Eglington B, Rainbird R. 2013. Two Neoarchean supercontinents revisited: the case for a Rae family of cratons. *Precambrian Res.* 232:27–43

Pehrsson SJ, Eglington B, Evans DAD, Huston D, Reddy SM. 2016. Metallogeny and its link to orogenic style during the Nuna supercontinent cycle. *Geol. Soc. Lond. Spec. Publ.* 424:83–94

Perchuk AL, Zakharov VS, Gerya TV, Brown M. 2019. Hotter mantle but colder subduction in the Precambrian: What are the implications? *Precambrian Res.* 330:20–34

Percival JA, Skulski T, Sanborn-Barrie M, Stott GM, Leclair AD, et al. 2012. Geology and tectonic evolution of the Superior Province, Canada. In *Tectonic Styles in Canada: The Lithoprobe Perspective*, ed. JA Percival, FA Cook, RM Clowes, pp. 321–78. St. Johns, Newfoundland, Ca.: Geol. Assoc. Can.

Polat A, Hofmann AW. 2003. Alteration and geochemical patterns in the 3.7–3.8 Ga Isua greenstone belt, West Greenland. *Precambrian Res.* 126:197–218

Polat A, Hofmann AW, Rosing MT. 2002. Boninite-like volcanic rocks in the 3.7–3.8 Ga Isua greenstone belt, West Greenland: geochemical evidence for intra-oceanic subduction zone processes in the early Earth. *Chem. Geol.* 184:231–54

Polat A, Wang L, Appel PWU. 2015. A review of structural patterns and melting processes in the Archean craton of West Greenland: evidence for crustal growth at convergent plate margins as opposed to non-uniformitarian models. *Tectonophysics* 662:67–94

Putirka K. 2016. Rates and styles of planetary cooling on Earth, Moon, Mars, and Vesta, using new models for oxygen fugacity, ferric-ferrous ratios, olivine-liquid Fe-Mg exchange, and mantle potential temperature. *Am. Mineral.* 101:819–40

Ravindran A, Mezger K, Balakrishnan S, Kooijman E, Schmitt M, Berndt J. 2020. Initial $^{87}Sr/^{86}Sr$ as a sensitive tracer of Archaean crust-mantle evolution: constraints from igneous and sedimentary rocks in the western Dharwar Craton, India. *Precambrian Res.* 337:105523

Reimink JR, Chacko T, Stern RA, Heaman LM. 2016. The birth of a cratonic nucleus: lithogeochemical evolution of the 4.02–2.94 Ga Acasta gneiss complex. *Precambrian Res.* 281:453–72

Rey PF, Coltice N. 2008. Neoarchean lithospheric strengthening and the coupling of Earth's geochemical reservoirs. *Geology* 36:635–38

Rey PF, Coltice N, Flament N. 2014. Spreading continents kick-started plate tectonics. *Nature* 513:405–8

Roberts NMW, Slagstad T. 2015. Continental growth and reworking on the edge of the Columbia and Rodinia supercontinents; 1.86–0.9 Ga accretionary orogeny in southwest Fennoscandia. *Int. Geol. Rev.* 57:1582–606

Roberts NMW, Spencer CJ. 2015. The zircon archive of continent formation through time. *Geol. Soc. Lond. Spec. Pub.* 389:197–225

Roman A, Arndt N. 2019. Differentiated Archean oceanic crust: its thermal structure, mechanical stability and a test of the sagduction hypothesis. *Geochim. Cosmochim. Acta.* In press. **https://doi.org/10.1016/j.gca.2019.07.009**

Rozel AB, Golabek GJ, Jain C, Tackley PJ, Gerya T. 2017. Continental crust formation on early Earth controlled by intrusive magmatism. *Nature* 545:332–35

Rudnick RL. 1995. Making continental crust. *Nature* 378:571–78

Rudnick RL, Gao S. 2014. Composition of the continental crust. In *Treatise on Geochemistry*, ed. KK Turekian, HD Holland, pp. 1–51. San Diego, CA: Elsevier. 2nd ed.

Schneider KP, Hoffmann JE, Münker C, Patyniak M, Sprung P, et al. 2019. Petrogenetic evolution of metabasalts and metakomatiites of the lower Onverwacht Group, Barberton Greenstone Belt (South Africa). *Chem. Geol.* 511:152–77

Shirey SB, Richardson SH. 2011. Start of the Wilson cycle at 3 Ga shown by diamonds from subcontinental mantle. *Science* 333:434–36

Silver PG, Behn MD. 2008. Intermittent plate tectonics? *Science* 319:85–88

Sizova E, Gerya T, Brown M. 2014. Contrasting styles of Phanerozoic and Precambrian continental collision. *Gondwana Res.* 25:522–45

Sizova E, Gerya T, Brown M, Perchuk LL. 2010. Subduction styles in the Precambrian: insight from numerical experiments. *Lithos* 116:209–29

Sizova E, Gerya T, Stüwe K, Brown M. 2015. Generation of felsic crust in the Archean: a geodynamic modeling perspective. *Precambrian Res.* 27:198–224

Smithies RH. 2000. The Archaean tonalite-trondhjemite-granodiorite (TTG) series is not an analogue of Cenozoic adakite. *Earth. Planet. Sci. Lett.* 182:115–25

Smithies RH, Champion DC, Cassidy KF. 2003. Formation of Earth's early Archaean continental crust. *Precambrian Res.* 127:89–101

Smithies RH, Champion DC, Sun SS. 2004. The case for Archaean boninites. *Contrib. Mineral. Petrol.* 147:705–21

Smithies RH, Champion DC, Van Kranendonk MJ. 2009. Formation of Paleoarchean continental crust through infracrustal melting of enriched basalt. *Earth Planet. Sci. Lett.* 281:298–306

Smithies RH, Champion DC, Van Kranendonk MJ, Howard HM, Hickman AH. 2005a. Modern-style subduction processes in the Mesoarchaean: geochemical evidence from the 3.12 Ga Whundo intra-oceanic arc. *Earth Planet. Sci. Lett.* 231:221–37

Smithies RH, Ivanic TJ, Lowrey JR, Morris PA, Barnes SJ, et al. 2018. Two distinct origins for Archean greenstone belts. *Earth Planet. Sci. Lett.* 487:106–16

Smithies RH, Lu Y, Johnson TE, Kirkland CL, Cassidy KF, et al. 2019. No evidence for deep subduction in the generation of Archean continental crust—the link between sanukitoids and 'high-pressure' felsic rocks. *Nat. Commun.* 10:5559

Smithies RH, Van Kranendonk MJ, Champion DC. 2005b. It started with a plume—early Archaean basaltic proto-continental crust. *Earth Planet. Sci. Lett.* 238:284–97

Smithies RH, Van Kranendonk MJ, Champion DC. 2007. The Mesoarchean emergence of modern-style subduction. *Gondwana Res.* 11:50–68

Smrekar SE, Davaille A, Sotin C. 2018. Venus interior structure and dynamics. *Space Sci. Rev.* 214:88

Sobolev SV, Brown M. 2019. Major surface erosion events were a key control on the emergence and evolution of plate tectonics on Earth. *Nature* 570:52–57

Stern RJ. 2018. The evolution of plate tectonics. *Philos. Trans. R. Soc. A* 376:20170406

Sun SS, McDonough WF. 1989. Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes. *Geol. Soc. Lond. Spec. Publ.* 42:313–45

Tang M, Chen K, Rudnick RL. 2016. Archean upper crust transition from mafic to felsic marks the onset of plate tectonics. *Science* 351:372–75

Tang M, Lee C-TA, Rudnick RL, Condie KC. 2019. Rapid mantle convection drove massive crustal thickening in the late Archean. *Geochim. Cosmochim. Acta.* In press. **https://doi.org/10.1016/j.gca.2019.03.039**

Taylor RJM, Johnson TE, Clark C, Harrison RJ. 2020. Persistence of melt-bearing Archean lower crust for >200 m.y.—an example from the Lewisian Complex, northwest Scotland. *Geology* 48:221–25

Taylor SR, McLennan SM. 1985. *The Continental Crust: Its Composition and Evolution*. Oxford, UK: Blackwell

Turner S, Rushmer T, Reagan M, Moyen J-F. 2014. Heading down early on? Start of subduction on Earth. *Geology* 42:139–42

van Hunen J, Moyen J-F. 2012. Archean subduction: fact or fiction? *Annu. Rev. Earth Planet. Sci.* 40:195–219

van Hunen J, van den Berg AP. 2008. Plate tectonics on the early Earth: limitations imposed by strength and buoyancy of subducted lithosphere. *Lithos* 103:217–35

Van Kranendonk MJ, Smithies RH, Griffin WL, Huston DL, Hickman AH, et al. 2015. Making it thick: a volcanic plateau origin of Paleoarchean continental lithosphere of the Pilbara and Kaapvaal cratons. *Geol. Soc. Lond. Spec. Publ.* 389:83–111

Van Kranendonk MJ, Smithies RH, Hickman AH, Champion DC. 2007. Review: secular tectonic evolution of Archean continental crust: interplay between horizontal and vertical processes in the formation of the Pilbara Craton, Australia. *Terra Nova* 19:1–38

Van Kranendonk MJ, Smithies RH, Hickman AH, Wingate MTD, Bodorkos S. 2010. Evidence for Mesoarchean (∼3.2 Ga) rifting of the Pilbara Craton: the missing link in an early Precambrian Wilson cycle. *Precambrian Res.* 177:145–61

Vanderhaeghe O, Guergouz C, Fabre C, Duchêne S, Baratoux D. 2019. Secular cooling and crystallization of partially molten Archaean continental crust over 1 Ga. *C. R. Geosci.* 351:562–73

Wang H, van Hunen J, Pearson DG. 2018. Making Archean cratonic roots by lateral compression: a two-stage thickening and stabilization model. *Tectonophysics* 746:562–571

Webb A, Müller T, Zuo J, Haproff P, Ramírez-Salazar A. 2020. A non-plate tectonic model for the Eoarchean Isua supracrustal belt. *Lithosphere* 12:166–79

Weller OM, Copley A, Miller WGR, Palin RM, Dyck B. 2019. The relationship between mantle potential temperature and oceanic lithosphere buoyancy. *Earth Planet. Sci. Lett.* 518:86–99

Weller OM, St-Onge MR. 2017. Record of modern-style plate tectonics in the Palaeoproterozoic Trans-Hudson orogen. *Nat. Geosci.* 10:305–11

Windley BF, Garde AA. 2009. Arc-generated blocks with crustal sections in the North Atlantic craton of West Greenland: crustal growth in the Archean with modern analogues. *Earth-Sci. Rev.* 93:1–30

Windley BF, Smith JV. 1976. Archean high-grade complexes and modern continental margins. *Nature* 260:671–75

Young GM, Von Brunn V, Gold DJC, Minter WEL. 1998. Earth's oldest reported glaciation: physical and chemical evidence from the Archean Mozaan Group (∼2.9 Ga) of South Africa. *J. Geol.* 106:523–38

Zeh A, Gerdes A, Barton JM. 2009. Archean accretion and crustal evolution of the Kalahari Craton—the zircon age and Hf isotope record of granitic rocks from Barberton/Swaziland to the Francistown Arc. *J. Petrol.* 50:933–66

Zibra I, Korhonen FJ, Peternell M, Weinberg RF, Romano SS, et al. 2017. On thrusting, regional unconformities and exhumation of high-grade greenstones in Neoarchean orogens. The case of the Waroonga Shear Zone, Yilgarn Craton. *Tectonophysics* 712–713:362–95

Annual Review
of Earth and
Planetary Sciences

Volume 48, 2020

Contents

Errata

An online log of corrections to *Annual Review of Earth and Planetary Sciences* articles may be found at http://www.annualreviews.org/errata/earth