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ORIGINAL ARTICLE

A model of crust–mantle differentiation for the early Earth

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Abstract The Archean continents, primarily composed of the felsic tonalite–trondhjemite–granodiorite (TTG) suite, were formed or conserved since ~ 3.8 Ga, with significant growth of the continental crust since ~ 2.7 Ga. The difficulty in direct differentiation of the felsic crustal components from Earth's mantle peridotite leads to a requirement for the presence of a large amount of hydrated mafic precursor of TTG in Earth's proto-crust, the origin of which, however, remains elusive. The mafic proto-crust may have formed as early as ~ 4.4 Ga ago as reflected by the Hf and Nd isotopic signals from Earth's oldest geological records. Such a significant time lag between the formation of the mafic proto-crust and the occurrence of felsic continental crust is not reconciled with a single-stage scenario of Earth's early differentiation. Here, inspired by the volcanism-dominated heat-pipe tectonics witnessed on Jupiter's moon Io and the resemblances of the intensive internal heating and active magmatism between the early Earth and the present-day Io, we present a conceptual model of Earth's early crust-mantle differentiation, which involves an Io-like scenario of efficient extraction of a mafic proto-crust from the early mantle, followed by an intrusion-dominating regime that could account for the subsequent formation of the felsic continents as Earth cools. The model thus allows an early formation of the pre-TTG proto-crust and the generation of TTG in the continent by providing the favorable conditions for its subsequent melting. This model is consistent with the observed early fractionation of the Earth and the late but rapid formation and/or accumulation of the felsic components in the Archean continents, thus sheds new light on the early Earth's differentiation and tectonic evolution.

Keywords Crust–mantle differentiation · Heat-pipe tectonics · Plutonic squishy lid tectonics · Proto-crust · TTG · Io

1 Introduction

Earth is the only terrestrial body with thick felsic continents in the solar system. The oldest components of continental crust are preserved in the Archean terrains and are dominantly composed of the felsic tonalite-trondhjemite-granodiorite (TTG) suite associated with ultramafic–mafic greenstones. Despite the ages of the oldest rock relics of the crust roughly confines to the Hadean-Eoarchean boundary, the formation of Earth's pristine crust may start much earlier (Hawkesworth et al. 2017; Jahn et al. 1981; Moyen and Martin 2012). Petrological and geochemical investigations of the rare crustal remnants of the Hadean-Eoarchean Earth have provided a crucial clue that the crustal reservoir must have been separated from the primitive mantle soon after Earth's formation. Hf and Nd isotope data from the 4.4 Ga-old Jack Hills detrital zircons, the oldest mineral relics of the Earth, suggest their hosting

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protolith were felsic rocks derived from reworking of an even older mafic crust extracted from the early mantle (Boyet et al. 2003; Boyet and Carlson 2005; Caro et al. 2003; Kemp et al. 2010). (We herein refer to the pre-TTG crust composed mainly of the mafic compositions in the Hadean as the "proto-crust", which is extracted from Earth's primordial mantle after solidification of the last magma ocean) The $\sim$ 3.8 Ga Nuvvuagittuq Greenstone Belt (NGB) in NE Canada has been viewed as a possible remnant of the Eoarchean proto-crust (Cates and Mojzsis 2007; Cates et al. 2013; David et al. 2009), and the zircon Hf model age of $\sim$ 4.4 Ga and high ^{176}Lu/^{177}Hf ratio of the 3.66–3.35 Ga-old TTG surrounding the NGB greenstone imply that they were derived from a mafic precursor similar to the greenstone in the Hadean (Fig. 1) (O'Neil et al. 2008; O'Neil et al. 2012; ONeil et al. 2013), and the deficits in ^{142}Nd of the NGB rocks relative to terrestrial Nd standard also indicate differentiation of this pre-TTG mafic rocks from the early mantle before 4.4 Ga (O'Neil et al. 2016). Similarly, for old rocks found in the $\sim$ 4.02–3.4 Ga Acasta Gneiss Complex (AGC) in NW Canada and the $\sim$ 3.8 to 3.7 Ga Isua Supracrustal Belt (ISB) in SW Greenland possibly representing another two relics of early crust, the Nd and Hf isotope and ^{142}Nd anomalies suggest their derivation from ultramafic or mafic precursory components in the Hadean proto-crust (Boyet and Carlson, 2006; Caro et al., 2006; Reimink et al., 2014, 2016; Rizo et al., 2011; Stern and Bleeker, 1998).

Despite the early crust-mantle differentiation that may have extracted the mafic proto-crust from the primordial mantle possibly as early as $\sim$ 4.4 Ga, the large-scale formation and/or conservation of the felsic compositions in the crust seems begin late. The continental growth surged until the Neoarchean as evidenced by the clustering of the crystallization ages of detrital zircons at $\sim$2.7 Ga, which possibly presents an outburst of felsic continental crust in Earth's history (Fig. 2) and is a milestone of Earth's crust-mantle differentiation (Condie, 2000; Hawkesworth et al., 2019, 2010) since it is estimated that at least $\sim$ 60% of the continental crust had formed before 2.5 Ga (Belousova et al., 2010). Therefore, geological records through Earth's early history seem compatible with a rapid formation of the mafic proto-crust early in the Hadean followed by the subsequent outburst of felsic continental crust in the late Archean. There is a $>$ 1.5 Ga-long lag of time between the formation of the pre-TTG mafic proto-crust and the large formation of the felsic continent.

From a petrological perspective, the TTG-like felsic components cannot be extracted directly from the ultramafic mantle through partial melting on a large scale. Nevertheless, they could be generated by multi-staged partial melting of the mafic components (favorably the hydrated mafic rocks, as will be discussed in this paper). A long-lasting intermediate stage of crust-mantle differentiation may thus exist and allows repeated intracrustal reworking of the old mafic components in the proto-crust and eventually evolved to the TTG-like felsic components in the Archean continental crust. From the point of geodynamics, however, both the extraction of the mafic components in the proto-crust from the mantle and its subsequent evolution into the continental crust requires melting of their precursory components or/and fractionation of the resultant melt/magma as it leaves the source

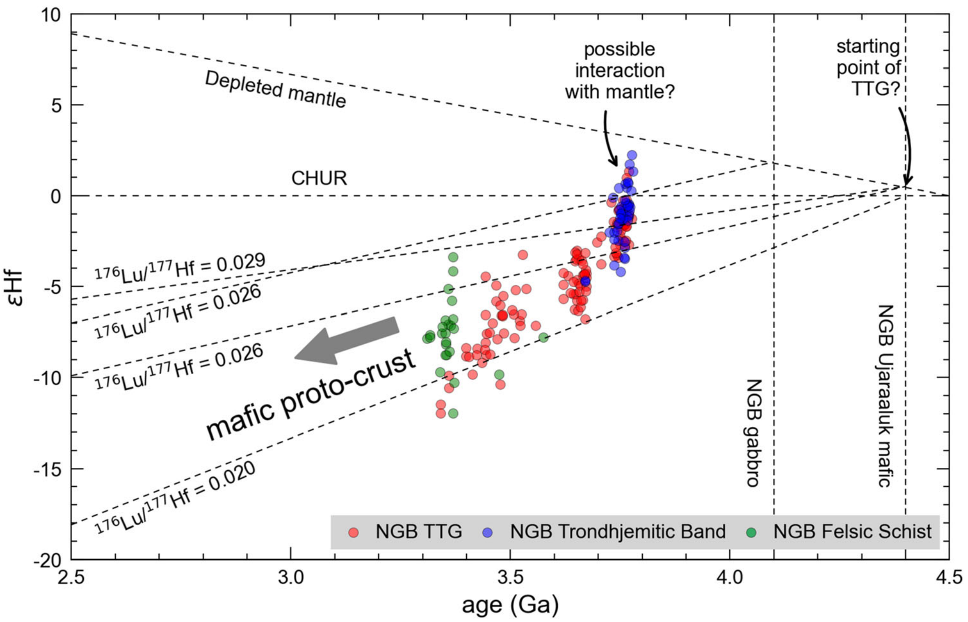

Fig. 1 Evolution of the εHf of zircons from the felsic rocks surrounding the mafic Ujaraaluk unit in the Nuvvuagittuq Greenstone Belt (NGB). The high ^{176}Lu/^{177}Hf ratio and model ages of the felsic rocks are indicative of their derivation from a Hadean mafic crust similar to the Ujaraaluk unit or the intrusive rocks in NGB. Modified after ONeil et al. (2013)

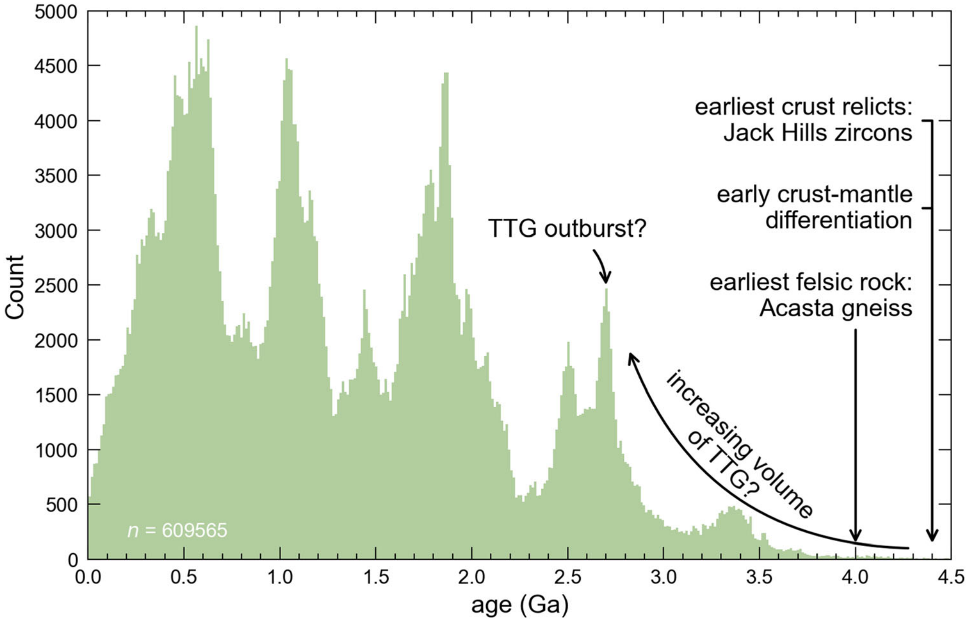

Fig. 2 Histogram of U–Pb ages of global detrital zircons. Data Source: Puetz and Condie (2019)

regions. This could be possible in tectonic regimes that are favorable to the formation of the pre-TTG mafic crust as well as its subsequent reworking. Little is known for the nature of early tectonics due to the lack of geological records.

In this paper, we argue that the tectonic regimes accounting for extraction of the proto-crust and formation of the continental crust should be distinct from plate tectonics due to its likely absence on the energetic and hot Hadean Earth. Instead, we introduced heat-pipe tectonics, an ongoing regime found based on intense tectono-magmatic activities on Jupiter's moon Io, to the Hadean-Eoarchean crust-mantle differentiation of Earth. We presented a model that can account for efficient extraction of the proto-crust from the early mantle followed by subsequent rapid formation of the TTG-like felsic components in the Archean continents, which benefits from the presence of a huge amount of hydrated mafic protolith in the thick proto-crust (on a scale of tens of kilometers thick). The model can explain the key observations and meet requirements for the formation of both the hydrated mafic proto-crust and the felsic continental crust on the early Earth.

2 Magmatism, tectonic regime, and Earth's early crust-mantle differentiation

The clues of early extraction of the crustal reservoir from the primitive mantle raise two fundamental questions: what is the nature of the earliest crust and how did it evolve into the TTG-rich continental crust? The questions are closely associated with the tectonic regime at the time of crust-mantle differentiation early in Earth's history. Although little is known for the nature of the tectonic regime(s), two speculations can be made from knowledge of Earth's geology and geodynamics.

First, there is a need for the formation of a large amount of the pre-TTG mafic proto-crust from the mantle early in its history, and it is likely that the large-scale differentiation may have come with extensive magmatic activities and there must be a tectonic regime allowing or facilitating the magmatism at that time. In principle, the differentiation of crust from the mantle is primarily carried out through magmatism, which involves partial melting of the mantle and generation of magma, followed by its segregation, ascent, fractional crystallization, eruption to the surface, or intrusion into the crust. The processes enable the separation of the incompatible components into the crust with the compatible components left as the residue in the source regions. However, little is known about the nature of the proto-crust-forming tectonic regime(s), and how the resultant pristine mafic components in the proto-crust evolve into felsic rocks in the continental crust remains highly ambiguous. What's less uncertain is that the regime(s) should be compatible with the differentiation of the mantle in the proto-crust-forming stage as early as ~ 4.4 Ga and the growth of the felsic crust in the TTG-forming stage since ~ 3.8 Ga on the early Earth.

Secondly, the formation of Earth's mafic proto-crust early in the Hadean is at odds with the much later prevalence of plate tectonics, which could account for the crust-mantle differentiation of the Earth for a considerable period of its history. The melting of the mantle and growth of the felsic crust on modern-day Earth primarily occur at the plate margins at least since ~ 1.0 Ga ago (Stern et al., 2016), but the feasibility of the plate tectonics on the early

Earth requires evaluation with care. The dominating tectonic regime of most of the terrestrial bodies in the solar system is the stagnant-lid regime, with the occurrence of the plate tectonics unique to the Earth possibly since ∼ 3.0 Ga ago. The plate tectonics features the participation of the lithosphere in mantle convection, thus requires (1) presence of a low-viscosity, convecting mantle, which is made possible by the presence of the volatile-rich and partially melting asthenosphere for the Earth; (2) negative buoyancy and gravitational instability of the lithosphere due to composition and thermal contrast between the asthenosphere and the slabs; (3) the breaking mechanisms of the rigid lithosphere. Among others, the presence of the driving force (i.e., the slab-pull and the ridge push) is the most crucial condition for the operation and persistence of modern plate tectonics. It is believed that these conditions seem to be implausible for the early Earth. The petrological records show that the ambient mantle before ∼ 2.5 Ga ago is much hotter than the present-day one, with a potential temperature ∼ 200 K higher than the latter (Herzberg et al., 2010). Under such circumstances, the temperature-sensitive rheology and composition of Earth's materials may, as numerical studies demonstrated, impose serious limitations on the operation of the plate tectonics on the early Earth: (1) the hot ambient mantle tends to create an oceanic plate, if any, at the mid-ocean ridge with a thicker oceanic crust than that of the modern-day, which is more buoyant and more difficult to subduct; (2) the subducting slabs (the subducted part of an oceanic plate) are rheologically weaker and thus easier to break off if the ambient mantle is hot (Fischer and Gerya, 2016; Sizova et al., 2010; van Hunen and Moyen, 2012; van Hunen and van den Berg, 2008). Consequently, a subduction-related mechanism of the early differentiation seems implausible to account for the formation of the mafic proto-crust.

3 Tectono-magmatic activities and the heat-pipe tectonics on Io

Near four decades of successive observations reveal that Io is a unique terrestrial body with violent volcanism on a global scale. Io is characterized by the existence of abnormally high heat flux and active geology at its surface in response to intense volcanism (de Kleer et al., 2019a; Geissler et al., 2004; Johnson et al., 1988; McEwen, 2002; Morabito et al., 1979). The high heat flux results from the radiation of the recently erupted volcanic deposits as they are exposed to Io's thin atmosphere and cools (Johnson et al., 1988; Kargel et al., 2003; Morabito et al., 1979; Spencer et al., 2007; Strom et al., 1981). Further estimation of the conditions capable of sustaining such a magnitude of volcanism indicates that Io's asthenosphere must be much hotter than ordinary terrestrial bodies and is massively melting to feed the observed violent tectono-magmatic activities. The melting is so extensive that a present-day "magma ocean" is possibly existing in its upper mantle (Khurana et al., 2011; McEwen et al., 1998; Peale et al., 1979). To maintain such a hot and extensively melting state, a supply of enormous heat in Io's interior is required. This is accomplished by the presence of the intense tidal heating within Io, which acquires heat through frequent deformation of Io on a global scale and the internal friction of Io's mantle materials in response to the orbital resonance among Jupiter, Io, Europa, and Ganymede (de Kleer et al., 2019b; Peale et al., 1979).

It is estimated that massively melting of Io's interior could account for the observed violent tectono-magmatic activities and result in a global-scale circulation of mass and rapid transport of heat via a unique tectonic regime known as "heat-pipe tectonics" (Moore and Webb, 2013; O'Reilly and Davies, 1981). This regime distinguishes itself from others (e.g., the plate tectonics and the stagnant-lid tectonics) by its uniqueness, including (1) the vertical circulation of mass and transport of heat between Io's interior and surface through volcanism are so rapid that the

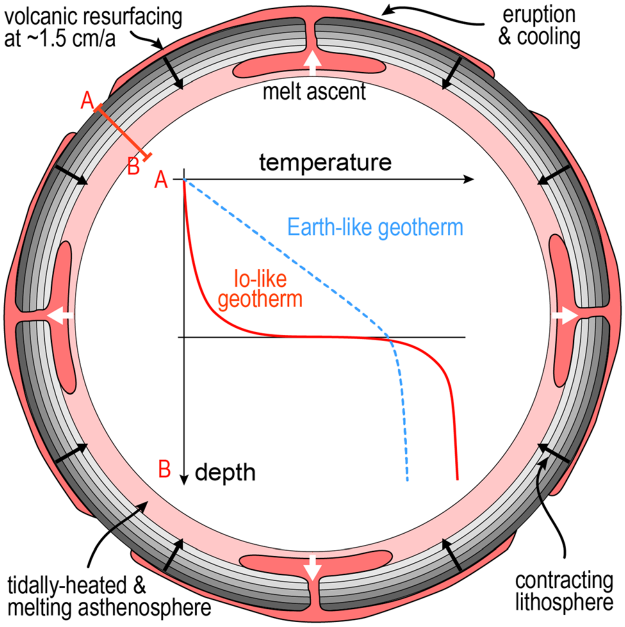

Fig. 3 Schematic illustration of the Io's volcanism-dominating heat-pipe tectonics and the resultant geotherm of Io's upper mantle (inserted, modified after Zhang and Liu, 2020). Rapid volcanic resurfacing of Io leads to a large-scale vertical mass exchange between Io's surface and interior, and downward advection of Io's crust (equivalent to the lithosphere) is successively formed at the surface of Io and destroyed from beneath by the tidally heating asthenosphere. Peculiarly, the rapid mass transport in such a heat-pipe scenario of Io tends to form a cold, rigid, and contracting outer shell (i.e., the lithosphere) atop a hot and extensively melting asthenosphere

latter dominates Io's global tectonics and way of cooling) (Fig. 3a); (2) large-scale volcanism leads to formation of a thick and cold crust atop a hot asthenosphere, since maintaining the high-temperature state is inherently required for the extensive melting of the asthenosphere and the violent volcanism observed, while the crust tends to be cold since it is primarily composed of the fully cooled volcanic deposits and its rapid downward advection is significant enough to suppress its being heated by the hot asthenosphere, thus forming a unique geotherm in Io's upper mantle remarkably distinct from any other terrestrial bodies in the solar system (Fig. 3b); (3) in a heat-pipe scenario of mass transport, the thick crust is equivalent to its lithosphere since the rigid outer shell of Io is its cold crust lies directly atop the asthenosphere from which it derived, and the rapid downward advection of the shell presents the formation of a lithosphere, which is typically formed as a result of cooling of the uppermost mantle (Keszthelyi et al., 2004; Moore et al., 2007); (4) the rapid coverage and subsidence of the volcanic deposits at Io's surface may inevitably lead to an inward contract and concentration of stress within its lithosphere on a global scale, which is evidenced by the active mountain building on Io (Bland and McKinnon, 2016; Schenk et al., 2001).

4 An Io-like mechanism for the formation of the Hadean proto-crust

The poor knowledge of the nature and origin of Earth's pre-TTG proto-crust has been an issue due to the scarcity of Hadean geological records of Earth itself. This dilemma cannot be easily overcome since the geoscience community has heavily relied on the geochemical and petrological analyses of Earth's geological remnants to uncover the evolution of the early differentiation of the Earth. Fortunately, Io's exotic observations provide new insights into the thermal and compositional evolution of the early terrestrial bodies in the solar system. As demonstrated on Io, intense volcanism may have a significant impact not only on the global tectonics of the early Earth but also the way of its crust-mantle differentiation.

4.1 Rapid crust-mantle differentiation

The differentiation of the terrestrial bodies is primarily achieved through magmatism, which makes possible the extraction of the fusible and incompatible components from the mantle as it melts partially. One of the obvious consequences of the intense volcanism on a terrestrial body is the efficient extraction of the crust from the mantle via its extensively melting followed by rapid transport of the melt/magma from its interior to the surface in an Io-like scenario (Keszthelyi et al., 2007; Keszthelyi and McEwen, 1997). The magmatism on the present-day Io is abnormally active, which involves the generation and segregation of magma during partial melting of the upper mantle and its subsequent ascent and eruption. It can be easily estimated from the surface heat flux, which is one of Io's most easily obtained and repeatedly verified observations, that the total gross rate of melt generation of Io is as high as ~ 600 km^3/a (see Appendix for details). This is in sharp contrast to that of the present Earth (< 50 km^3/a) and the Moon, which is geologically dead without any present-day or recently active magmatism. Considering Io is a much smaller terrestrial body with radius, mass, and volume closing to the Moon, and that not all of the melts/magma has erupted to the surface after extracting from the mantle, the prominently high rate of melt generation of Io suggests the presence of an extensive melting upper mantle is required to feed the observed activeness of volcanism. It is estimated that Io could be completely melted every 100 Ma at the current rate of melt generation, which is equivalent to completely melting for ~ 40 times or partial melting (10%) for ~ 400 times in the past 4.0 Ga (Keszthelyi and McEwen, 1997).

The correlation between the intense tectono-magmatic activities and efficient internal differentiation of Io is inspiring for Earth's early evolution. What makes the Io-like heat-pipe regime particularly appealing is that it is more favorable for the formation of the Earth's proto-crust than others. Considering the differentiation of a terrestrial body is primarily accomplished by partial melting of the mantle peridotite, and that large-scale magmatism may prevail in Earth's early history, the conspicuous capability of the volcanism-dominating heat-pipe regime could be an efficient mechanism to account for Earth's initial crust-mantle differentiation (Moore et al., 2017; Moore and Webb, 2013). Particularly, as demonstrated on Io, this regime can favorably form the mafic components in the proto-crust of the Earth through extensive melting of mantle and extraction of the fusible components into its early mafic crust. These mafic components could serve as the crucial intermediates required in the ultramafic-to-felsic evolution path of Earth's crust and give rise to the subsequent formation of continental crust.

4.2 Easy transport of water into the deep crust

Another consequence of the global-scale eruption, bury, and recycling of volcanic deposits of the Io-like tectonics is that it enables easy transport of the surface materials deep into the crust, which is crucial for the subsequent reworking of the mafic proto-crust. For Io, the spectral data of its fresh volcanic products suggest that they badly lack water but are rich in sulfur and sulfide (Johnson et al., 1979;

Smythe et al., 1979; Spencer et al., 2000). These fusible and light components may also facilitate the rapid ascent and eruption of the mantle-derived magma through the crust by lowering the magma density and providing constant positive buoyancy after the recycling of the sulfur and sulfide into the deep crust (Battaglia et al., 2014; Jessup et al., 2007; Leone and Wilson, 2001; Leone et al., 2011). Similarly, an Io-like tectonic regime can efficiently convey the hydrated mafic materials into the deep crust after being exposed in the ancient hydrosphere, if any, via downward advection of the entire lithosphere in this regime. As another appealing aspect of the heat-pipe tectonics on the formation of felsic crust, this increases the water content of mafic components in the crust, thus facilitating its subsequent anataxis and formation of the felsic melts. It should be noted that the hydration of the mafic crust in an Io-like scenario is based on an assumption that there is an early hydrosphere as the mafic crust forms. This is supported by the increased $\delta^{18}O$ of the Hadean Jack Hills zircons and other old rocks, which is indicative of their possible derivation from older and hydrothermally altered mafic precursor exposed to the water (i.e., the early hydrosphere) in the Hadean (Eiler, 2001; Reimink et al., 2021; Smithies et al., 2021; Valley et al., 2005, 2002; Wilde et al., 2001). The recycling of the hydrated mafic crust into the deep mantle in a heat-pipe scenario may occur widespread since the subsidence and downward transport of the hydrated crust does not confine to local regions at Earth's surface (e.g., the subduction zones where oceanic plates absorb water at the surface and release it into mantle wedge at depth). As will be discussed below, this could lead to a significant accumulation of the hydrated mafic components in the proto-crust and serves as a favorable starting point of their subsequent evolution toward the TTG-rich felsic continental crust.

5 Linking the origins of the mafic proto-crust with the formation of the TTG-rich continent

5.1 Geochemical characteristics and petrogenesis of TTG

The TTG suite in association with the ultramafic–mafic greenstone belts has been primarily found in the Archean terrenes and represents the dominating components in Earth's early continental crust (Jahn et al., 1981). The TTG is silica- ($SiO_2 > 64$ wt%), and Na-rich (3.0–7.0 wt%, $K/Na < 0.5$) but K-poor felsic rocks with strongly fractionated Rare Earth Element (REE) (i.e., a high La/Yb ratio of ~ 50 and $Sr/Y > 40$) and negative Nb-P-Ti anomalies, but without Eu and Sr anomalies (Martin et al., 2005; Moyen and Martin, 2012). By contrast, modern granitoids are more enriched in K and HREE and have negative Eu, Na, Ta, Ti, and Sr anomalies (Condie, 2014). There is a consensus-based on the petrological modeling and experiments that the TTG-like felsic melt with TTG signatures cannot be a result of partial melting of the mantle peridotite but can be produced through partial melting of the hydrated metamafic rocks at ~ 1.0–2.5 GPa (Beard and Lofgren, 1991; Johnson et al., 2014; Laurie and Stevens, 2012; Patiño-Douce and Beard, 1995; Rapp et al., 1991; Wolf and Wyllie, 1994). The presence of the residual minerals (e.g., plagioclase, garnet, and rutile) during melting of the mafic source rocks of TTGs may play crucial roles in shaping their major and trace element signatures and the content of these minerals are strongly dependent on pressure and thus the melting depth of the TTG source rocks. Accordingly, three subgroups of TTG are identified: (1) the low-pressure TTG with high contents of HREE, Na, and Ta with less Sr and can be formed by melting of the plagioclase- or garnet-amphibolite at low pressure (1.0–1.2 GPa), with plagioclase left as a residue; (2) the high-pressure TTG depleted HREE, low Nb, Ta, and high Sr can be formed via melting of rutile-bearing eclogite at pressure > 2.0 GPa with residues of garnet and rutile; (3) the medium-pressure TTG the hybrid type of high- and low-pressure TTG (Moyen, 2011; Wei et al., 2017).

From a petrological perspective, therefore, any tectonic setting allowing dehydration melting of the hydrated mafic protolith (e.g., garnet-bearing amphibole or eclogite) at garnet stability field (at a pressure of 1.0–2.5 GPa for the low-/medium-/high pressure TTG) at variable geotherm can be feasible for the formation of the TTG (Hoffmann et al., 2019; Moyen, 2011; Moyen and Stevens, 2006; Rapp et al., 1991; Wei et al., 2017). Further, the outburst of felsic continental crust in the Mesoarchean requires the preexistence of a huge amount of the hydrated mafic materials in the pre-TTG mafic proto-crust. It is estimated that three parts of the mafic rock are required to form one part of the felsic components (Zhao and Zhang, 2021). This implies that the rapid formation of felsic TTG in the late Archean has to be predated by the presence of their mafic precursor in the proto-crust. Also, a tectonic mechanism for the addition of volatiles into the mafic source rocks before or during its formation is required, since the volatiles (especially the water) plays a crucial role in further differentiation of the pristine mafic compositions into TTG-like felsic components by lowering their solidus and facilitating their partial melting (Campbell and Taylor, 1983).

5.2 Formation of felsic continental crust with the presence of proto-crust

The peaks in the ages spectra of global detrital zircons have been interpreted as pulses of felsic magmatism closely related to the productions of the continental crust (Condie and Aster, 2010). An early form of the mafic crust followed by a late outburst of the TTG possibly in the felsic continental crust can be easily identified (Fig. 2), which cannot be explained by a single-stage mechanism that is capable of accounting for the crust-mantle differentiation through Earth's early history.

On the one hand, an Io-like heat-pipe regime, if feasible, is possibly compatible with the earliest stage of crust-mantle differentiation. First, there is a need for the presence of a large amount of hydrated mafic components in the pre-TTG proto-crust for the outburst of the TTG-rich felsic continental crust. The heat-pipe regime can favorably lead to efficient extraction of the mafic proto-crust from the mantle and is inherently conducive to the transport of volatile deep into the crust. Therefore, it can favorably meet the crucial requirements for the subsequent formation of TTG-rich felsic crust by providing large amounts of hydrate mafic protolith of TTG in the proto-crust. This is consistent with the presence of elevated δ^{18}O signature of felsic rock in the earliest crust, which indicates their derivation from mafic precursors interacted with surface water at the low-temperature conditions (Smithies et al., 2021; Valley et al., 2005; Wilde et al., 2001). Second, the regime tends to recycle the entire proto-crust (with both the mafic and the derived felsic components) back into the mantle and is consistent with the scarcity of the earliest crust (Fig. 2).

On the other hand, the TTG-rich felsic continental crust is likely generated and retained in the crust rapidly at a large scale after 3.8–3.6 Ga (Fig. 2). It cannot be a result of the Io-like heat-pipe regime since the latter tends to form a relatively cold crust (Fig. 3b), while the TTG components can only be formed in the crust with a high geothermal gradient (Ernst, 2009; Zhai, 2019; Zhang and Zhai, 2012). Also, the heat-pipe tectonics tends to impede the further differentiation of the mafic composition toward the felsic components since the presence of the felsic crust contradicts to ascent and eruption of the denser mantle-derived mafic magma. The confined crust-mantle differentiation of a terrestrial body in a heat-pipe regime is supported by observations of a prevalence of mafic-dominating volcanism on Io (Johnson et al., 1988; Keszthelyi et al., 2007). Accordingly, another tectonic regime referred to as the "plutonic squishy lid tectonics" is possibly more compatible with the TTG-forming stage on Earth than the extrusion-dominating heat-pipe regime (Lourenco et al., 2018; Rozel et al., 2017). In this scenario, the crust could be progressively differentiated into a mafic lower part and a felsic upper part (Figs. 4b and 5c). In the lower part of the crust, the mantle-derived mafic magma ascends and intrudes into the mafic crust buoyantly, or underplates and resides at the crust-mantle boundary, the crust thickens and is heated from within, elevating the temperature and geothermal gradient of the crust and making this part of the crust a desirable site for TTG formation. Once the thickness of the crust reaches the depth of eclogitization, the crust becomes negatively buoyant and thins via delamination. Simultaneously, the felsic melt can be continuously formed via the reworking of the crust (i.e., partial melting of the hydrated mafic protolith) and remains in the crust. It should be noted that the cycle of the mantle-derived material is refined to the lower part of the crust ($P < 1.5$ GPa), the felsic material further differentiated from the mafic rock is therefore retained in the upper part of the crust. Further, extra water sourced from the surface via localized vertical tectonics (e.g., sagduction) can bring water into the deep crust, where the meta-mafic protolith is hybridized and melted (Francois et al., 2014; Smithies et al., 2021).

Collectively, given the possibility of formation of the mafic proto-crust in an Io-like heat-pipe regime, and the clear petrological constraints for the formation of the TTG, we, therefore, consider a two-stage conceptual model of crust-mantle differentiation of the early Earth, which is compatible with observations of the early Earth and accounts for the formation of both the mafic proto-crust and the TTG-dominating felsic crust: (1) The volcanism-dominating heat-pipe tectonics witnessed on Jupiter's moon Io could be a plausible tectonic regime accounting for the formation of a thick proto-crust composed primarily of hydrated mafic in the Hadean (Figs. 4a and 5b). The proto-crust can be rapidly extracted from the mantle in response to extensive partial melting of the mantle and subsequent differentiation of the mantle-derived magma. Despite the rapid mantle differentiation capable of forming the mafic compositions in the proto-crust, the Io-like scenario of crust-mantle differentiation is not favorable for the further formation of the TTG-like components in the crust under this regime, since the latter tends to give rise to a relatively low geotherm in response to downward advection of the fully cooled crust (Figs. 3b and 4a). (2) The formation and conservation of the TTG in the felsic crust in the Archean require a massive influx of heat and mafic composition from the hot mantle. This is crucial to form a TTG-forming hot zone in the TTG source region. Also important is the intrusion dominating regime is conducive to the retaining of the newborn felsic components in the crust (Fig. 4b) and is more compatible with an increasing trend of accumulation of the TTG-like felsic components on the early Earth (Fig. 2).

In the model, we emphasize that the evolution of Earth's crustal components toward the felsic TTG components is benefited from the presence of a large amount of the hydrated mafic precursor formed aforehand in the proto-crust since a direct extraction of these felsic compositions

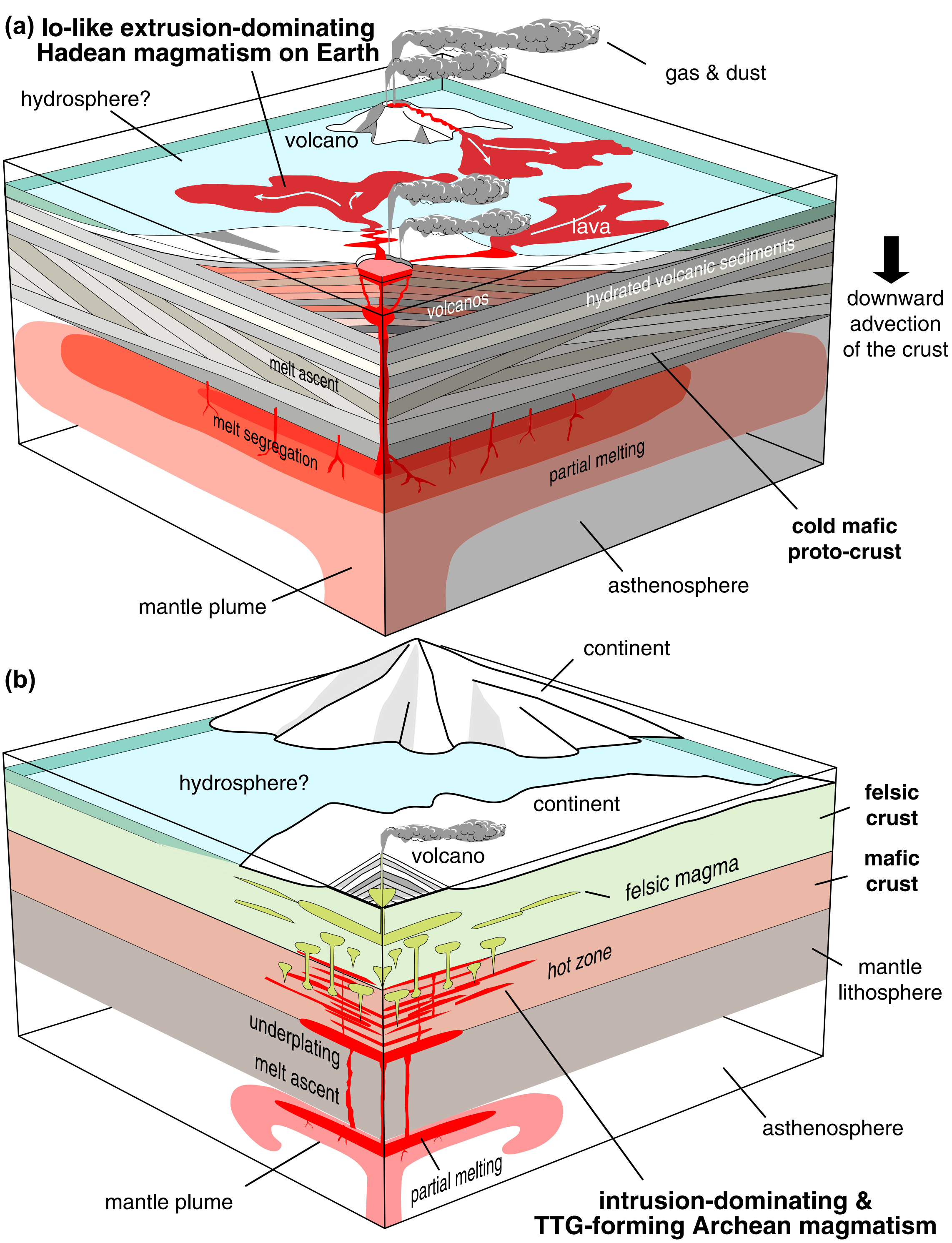

Fig. 4 Sketches of an Io-like, volcanism-dominating tectono-magmatic model of the formation of the Hadean Earth's proto-crust (**a**), and an extrusion-dominating plutonic squishy-lid model favorable for the formation of the felsic components in the Archean continental crust (**b**). We highlight the mantle plume-related mechanism of large-scale melt generation in both stages, which is crucial to provide the mantle-derived melt and feed the shallow magmatic activities. The prevalence of mantle plume activities in the interior of the early Earth since the arrivals of mantle plumes is the most plausible scenario that could cause large-scale mantle melting. Also shown is the likely presence of the hydrosphere as evidenced by the elevated $\delta^{18}O$ (see the text) that can favorably hydrate the mafic components in the proto-crust, which is key to the subsequent formation of TTG-rich components in the felsic continental crust. The sizes of the deep and the surface morphological features are not to scale

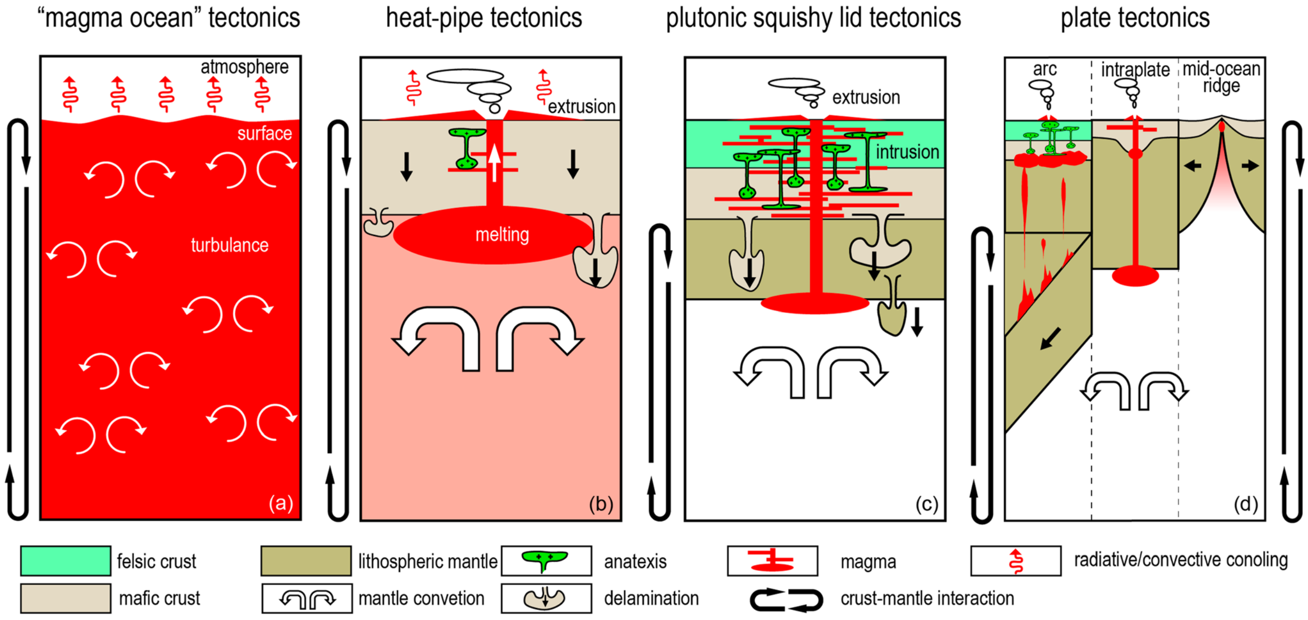

Fig. 5 Cartoon of the possible scenario of early Earth's evolution of the tectonic regimes from the magma-ocean stage (left) and the proto-crust-forming heat-pipe stage in the Hadean toward the TTG-forming squishy-lid stage in the Archean, which is ended by the plate-tectonics stage (right)

from the mantle is difficult. This meets the need for the presence of an early intermediate stage in the evolution path of the Earth's continental crust from its pristine mantle to the TTG-rich felsic crust in the Archean. Accordingly, a transition of tectonic regimes is required from the Io-like extrusion-dominating heat-pipe regime in the Hadean-Eoarchean to an intrusion-dominating regime in the Archean.

6 Discussion

6.1 Similarity of present-day Io and the Hadean Earth

Io's observations provide new insights into the thermal and compositional evolution of the terrestrial bodies in the solar system. The Hadean-Eoarchean Earth is, to some extent, an Io-like terrestrial planet. Particularly, there are possible similarities in their internal dynamics and ways of differentiation.

First, similar to present-day Io, the interior of the Hadean Earth may be energetic. Io is getting enormous tidal heat due to orbit resonance among Jupiter, Io, Europa, and Ganymede (de Kleer et al., 2019b; Hamilton et al., 2013; Moore, 2003; Peale et al., 1979). The mass-circulation in a heat-pipe scenario may be self-sustaining as long as a sufficient amount of heat is supplied. For the Hadean earth soon after its solidification from the magma ocean, the way of maintaining its hot state is the internal heating due to decay of the U, Th, and K ($\sim$ 4–5 times than present-day) (Schubert et al., 2001a) and the presence of the primordial heat accumulated at Earth's early accretion stage. Also, the possible input of heat in response to later exogenic geological processes cannot be ruled out. For example, late accretion in the Hadean-Eoarchean, e.g., the Late Heavy Bombardment (LHB) event in the solar system at $\sim$ 4.1–3.9 Ga (Bottke and Norman, 2017; Norman, 2019), may import a significant amount of kinetic energy along with the impactors, which can eventually be transferred into internal energy and potentially heating the mantle. The interaction between Earth and Moon can also possibly bring extra tidal heat to both of them when the distance between them is much shorter.

Secondly, both Io and the early Earth likely have a hot and extensively melting upper mantle. Io is estimated to have a $\sim$ 50 km-thick and massively melting asthenosphere (with melt fraction $>$ 20%), which is evidenced either from inversion of its magnetic field (Khurana et al., 2011) or from the requirement of a high degree of melting of the upper mantle to feed and maintain the active magmatism. The discovery is of the exceptionally hot and magnesium-rich lava exclusively similar to the komatiitic magma (with a temperature of 1700-2000 K, in contrast to that of the typical terrestrial basaltic lave with a lower temperature of $<$ 1600 K) at a new site of eruption (Kargel et al., 2003; McEwen et al., 1998, 1997) suggest the possible occurrence of ultramafic magmatism on Io, which is diagnostic of high-degree melting of the mantle. Similarly, most of the early terrestrial bodies in the solar system experienced a magma ocean stage in response to energetic early processes (e.g., impacts during accretion or decay of radioactive elements such as ^{26}Al and ^{60}Fe, etc.) during and soon after their formation (Stevenson, 2008). For Earth, the prevalence of komatiitic magmatism is confined to its early history before 2.5 Ga, during which a high-degree melting of the mantle is possible (Barnes and Arndt, 2019).

Finally, the occurrence of intense volcanic activities is pervasive on most of the terrestrial bodies in the solar system, which suggests the volcanism-related tectonics may have been a common and requisite stage of their tectonic evolution (Moore et al., 2017; Turcotte, 1989). Mercury's flood plains filled with massive mafic–ultramafic lava (Head et al., 2011; Marchi et al., 2013; Wilson and Head, 2008) and the presences of landforms as the surface expression of compression of the crust (such as lobate scarps and wrinkles, etc.) formed during its cooling are preserved on Mercury 4.1–3.55 Ga ago (Byrne et al., 2014; Head et al., 2009; Marchi et al., 2013), indicate significant compression and contraction of the lithosphere by loading and subsidence of the volcanic sediments possibly caused by contemporary intense magmatic activity in early Mercury (Charlier et al., 2013; Head et al., 2009; Multhaup, 2009; Watters et al., 1998; Wilson and Head, 2008). Similar early magmatic-tectonic records are retained on the Moon (Head and Wilson, 1992; Hiesinger et al., 2003; Terada et al., 2007). The record of asteroids such as Vesta show that it seems easy for their upper magma to erupt to the surface and the mafic crust was quickly differentiated from its original meteoric materials, in response to extensive internal melting due to intense radiogenic heating through the decay of extinct nuclides (e.g., ^{26}Al) (Clenet et al., 2014; McSween et al., 2019; Wilson and Keil, 2012). These records indicate differentiation of the pristine materials accompanied by active tectono-magmatic activities featured by the eruption of mantle-derived magma and/or contraction and compression of their rigid shells. From the comparative planetary perspective, the Earth may be no exception during its early evolution stage.

Therefore, the present-day Io is a possible analog of the early Earth and other terrestrial bodies in the solar system. Despite the significant differences in the mechanism of internal heating and melting among them, there are similarities in the possible existence of energetic and hot interiors, and active volcanism may be an inherent outcome of their energetic state. It is suggested that the early Earth and other terrestrial bodies may have experienced the heat-pipe stages, which may have facilitated their cooling and internal differentiation in the early evolution (Kankanamge and Moore, 2016; Lourenco et al., 2018; Moore et al., 2017). For Earth, the most favorable period for the prevalence of the heat-pipe regime may start as Earth's magma ocean solidifies (Fig. 5a), and lasts until rapid formation and preservation of TTG-rich components in the felsic continental crust n the early Archean (Fig. 5c). In this period, Earth's interior is still significantly hotter than the present (this is probably the most energetic period in Earth's post-magma ocean history) and is thus prone to high-degree melting of the mantle. Also important is that the period does not overlap the subsequent stage of the outburst of TTG-like components on the Neoarchean Earth, during which the resultant geotherm of Earth in a heat-pipe regime is at odds with TTG-forming conditions as discussed in the previous section.

6.2 The connections with the mantle plume model

Again, it is likely that the extraction of both the proto-crust from the mantle and the TTG-like components from their mafic precursor requires large-scale magmatism. In our model, melting of the mantle and formation of the mantle-derived primitive magma is a crucial starting point of the subsequent crust-mantle differentiation and intracrustal reworking. In general, melting of the post-magma ocean terrestrial bodies in the solar system may come in three ways: melting of rocks due to rising of temperature, or addition/presence of volatiles which lowers the solidus temperature of mantle rocks, or melting due to pressure release of the mantle (i.e., decompression melting) (Gill, 2010a). In our model, we focus on the possible scenarios of crust-mantle differentiation on Earth's upper mantle scale to account for the origin of both the mafic proto-crust and the TTG-rich components in the felsic continental crust. We assume that the dominating mechanism of partial melting of the mantle and generation of the mantle-derived primitive magma is closely related to the mantle plume activates through the frequent arrival of the hot heads of the mantle plumes that are sourced from the deep mantle (Figs. 4 and 5). The presence of the mafic large igneous provinces (LIPs) suggests intense mantle plume activities may have prevailed until even the Phanerozoic eon, let alone the Hadean and the Archean eons, during which the mantle is much hotter. Considering the likely absence of the plate tectonics in which magmatism occurs primarily on the plate boundaries, and that the early mantle is probably much hotter and convects more vigorously, the prevalence of the mantle plume activities plays an indispensable role in providing enormous heat and a huge amount of mantle-derived melts for the formation of the pre-TTG mafic proto-crust, the remelting of the mafic components in the mafic crust as well as the formation of TTG-rich continental crust. A huge amount of primitive magma in this way may be the primary source of magmatism in the heat-pipe stage of Earth. There is consensus between our model and the recent one described by Zhao and Zhang (2021) and Zhu et al. (2021) in that both models emphasize the crucial role of mantle plumes in melting of the hot early mantle, generation of mafic melt, and formation of thick mafic crust (e.g., the "oceanic plateau") in a pre-TTG stage of Erath's crust-mantle differentiation.

6.3 The relationship with the magma ocean-derived crust

The formation of a stable crust on terrestrial bodies requires the extraction of sufficient light components from their interiors through magmatism and the formation of a rigid shell resistant to the tectonics at varied scales (e.g., the convective drag of the underlying mantle). The very first crust of the Earth may have been born at the magma ocean stage, especially during cooling of Earth's last magma ocean possibly formed in response to the Moon-forming impact at $\sim$ 4.47 Ga ago (Bottke et al., 2015; Elkins-Tanton, 2008, 2012). An obvious way that may have formed Earth's earliest "crust" is through cooling, quenching, and hardening of the surface of the magma ocean. This scenario encounters a problem since the quenched "crust" might be compositionally less differentiated and has slight dense contrast concerning the underlying magma. Thus, this layer might be hydromechanically unstable and difficult to survive at the waving surface of the magma ocean (Solomatov, 2015). For the terrestrial magma lakes that filled up with basaltic magma typically with a viscosity of $\sim$ 100–1000 Pa s (Lesher and Spera, 2015), such as the kilometers-scale ones observed on Earth (Helz, 2009; Jellinek and Kerr, 2001) and the hundred-kilometers-scale ones observed on Io (Matson et al., 2006), the chilled outer shells at their surface sink into the magma with lifespans much shorter than what is required by the formation of a thick and rigid crust capable of withstanding the convection drag and gravitational instability. The survival of the chilled crust above a violently convecting ocean of ultramafic magma (with viscosity < 1 Pa s) on the Hadean Earth is undoubtedly much more difficult than above the basaltic magma lakes.

Alternatively, a primordial crust might form as a result of fractional crystallization of the magma ocean, as witnessed on the Moon, and the anorthosite-rich highland crust is a likely product of the lunar magma ocean as it solidifies. However, an anorthosite crust may not form atop a solidifying magma ocean of Earth, since the plagioclase fails to form and accumulate on a large scale in it. Specifically, the aluminum trends to enter the majorite phase, which crystallizes and starts to form cumulates at depth in Earth's magma ocean (at $P > 10$ GPa, in contrast with a much lower pressure of $\sim$ 5 GPa in the lunar magma ocean) with the Al-depleted residue left, from which the aluminum-rich plagioclase is difficult to be extracted (Elkins-Tanton, 2008; Herzberg, 1992). Nevertheless, the composition of the Al-poor residual magma resembles the komatiite (with plagioclase content of $\sim$ 5%), which indicates the possible formation of an ultramafic crust as the solidification of the magma ocean finishes (Elkins-Tanton, 2008, 2012). Similar to the case in which a short-lived quenched shell forms at the surface of a magma ocean, the ultramafic crust might not be stable and could be easily destroyed by the mantle convection (although much less vigorous than the magma ocean) since the composition and dense contrast between the newborn subsolidus mantle and the crust is not significant.

Therefore, the nature of the earliest crust, if there was any, that might be extracted from the magma ocean during its cooling and solidification remains ambiguous so far. It seems that there is little room for crust-mantle differentiation models involving direct extraction of the earliest crust, which is stable and long-lived on a geological time scale, from the magma ocean of the newborn Earth, neither the Moon-like anorthositic nor the ultramafic crust. Nevertheless, this does not stop us from introducing the Io-like mechanism of the early crust-mantle differentiation, since the latter could last long and is not confined to the short-lived stage of the magma ocean of Earth. In this paper, we focused on the mafic crust that emerges from the early subsolidus mantle after the solidification of Earth's last magma ocean due likely to the Moon-forming impact.

7 Conclusions

The occurrence of intense magmatic activities evidenced by the present-day Io is probably an inherent outcome of its high-temperature interior in response to intense internal heating and may have played crucial roles in its chemical and thermal evolution. This shed new light on the early evolution of Earth. Accordingly, a conceptual model of Earth's crust-mantle differentiation is presented, which combines aheat-pipe regime accounting for the formation of the hydrated, mafic proto-crust possibly in the Hadean-Eoarchean with a subsequent TTG-formation scenario of plutonic squishy lidregime that could explain the rapid growth of the felsic crust in the Neoarchean.The -model provides new insight into the early differentiation and tectonic evolution.

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Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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