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What controlled the thickness of continental crust in the Archean?

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ABSTRACT

Exposed continents are one of Earth's major characteristics. Recent studies on ancient ocean volume and exposed landmasses suggest, however, that early Earth was possibly a water world, where any significant landmass was unlikely to have risen above sea level. On modern Earth, the thickness of continental crust seems to be controlled by sea level and the buoyancy of continental crust. Simply applying this concept to the Archean would not explain the absence of exposed continents, and we suggest that a third element that is currently insignificant was important during early Earth: the strength of continental upper crust. Based on the pressure imbalance expected at continent-ocean boundaries, we quantified the conditions under which rock strength controls the thickness of continental crust. With the level of radiogenic heat production expected for early Earth, continents may have been too weak to have maintained their thickness against a deep ocean.

INTRODUCTION

Earth is covered by two different kinds of crust: oceanic and continental crust. The normal oceanic crust is ~7 km thick (White et al., 1992), whereas the continental crust is ~40 km thick on average (Christensen and Mooney, 1995). The thickness of oceanic crust is a simple function of mantle potential temperature beneath mid-ocean ridges (McKenzie and Bickle, 1988); a hotter mantle melts more, resulting in thicker oceanic crust. For the thickness of continental crust, we do not expect such a genetic relationship with the state of the present-day mantle because the formation and evolution of continental crust are more complex, involving a variety of tectonic processes over a time scale of billions of years. Instead, as suggested by Hess (1962), the long-term thickness of continental crust may be regulated by a combination of isostasy and sea level. Because the continental crust is less dense than the oceanic crust, isostasy allows the former to be thicker than the latter. As the continental crust thickens, its surface eventually exceeds the sea level, above which erosion becomes important. In the hypothesis of Hess (1962), therefore, the thickness of continental crust is controlled by the ocean volume, where a deeper ocean allows the existence of thicker continental crust. This effect of ocean volume on continental height is well understood in geology. The mean height of continents with respect to the sea level, known as the continental freeboard (Wise, 1974), has been close to zero at least back to 2 b.y. ago (Korenaga et al., 2017).

Recent geochemical studies exploring the emergence of continents (Bindeman et al., 2018; Johnson and Wing, 2020) have raised the possibility that during most of the Archean, Earth was a water world. A study on the deep-water cycle has also suggested that the Archean ocean could have been more voluminous, with its surface reaching 4–6 km above mid-ocean ridges (Korenaga et al., 2017). If the thickness of continents is regulated only by isostasy and sea level, however, exposed continental crust seems inevitable, even with a deep ocean. This is especially so because the mass of continents is likely to have reached the present-day level on early Earth (Korenaga, 2018). Even with more gradual continental growth, continents can still grow to sea level through thickening by orogeny.

We investigated the possibility that, in addition to sea level and isostasy, the thickness of continental crust is also regulated by the strength of crustal rocks. Although it has already been suggested that the Archean crust was too weak to have supported high mountains (Rey and Coltice, 2008), previous studies have been limited to topographic variations within continents. Here, we considered the integrity of continents at a greater spatial scale; that is, with respect to adjacent ocean basins. Our results suggest that, whereas strength does not seem to be a limiting factor today, ductile flow could have been more important in the Archean.

We first estimated differential stresses applied on the continental crust by performing isostatic calculations. We also estimated temperature in the upper crust by calculating the geotherm for both the modern and Archean Earth. As the concentration of heat-producing elements in the Archean continental crust is still debated, we compared three cases: no secular change in crustal composition (Guo and Korenaga, 2020), 75% less heat production (Condie, 1993), and 50% less heat production (Ptáček et al., 2020). From these stress and temperature conditions, we evaluated the representative deformation rate of continental upper crust at the present and in the Archean. Finally, we investigated how the Archean continental height might have been controlled and what this implies for the early Earth landscape.

MODEL SETTING

The topography of continental crust and its overall thickness are controlled by different mechanisms. The former is supported by variations in crustal thickness, for which the strength of lower crust is important (e.g., Rey and Coltice, 2008). Higher radiogenic heat production and higher mantle temperatures in the Archean could have weakened and even melted the lower crust (Galer and Mezger, 1998), thereby limiting the surface relief. We expect a different mechanism to control the average thickness of continents (cf. England and Molnar, 1997). At the boundary of continental and oceanic domains, the horizontal flow of continental lower crust would be limited by the surrounding oceanic lithosphere, leaving the continental upper crust to control the average crustal thickness (Fig. 1). As the top portion of continental crust is bounded only by ocean water, its ability to support its own weight should determine the continental height. The strength of continental upper crust is also better constrained by geological observations. The strength of continental lower crust depends on its water content, lithology, and the depth

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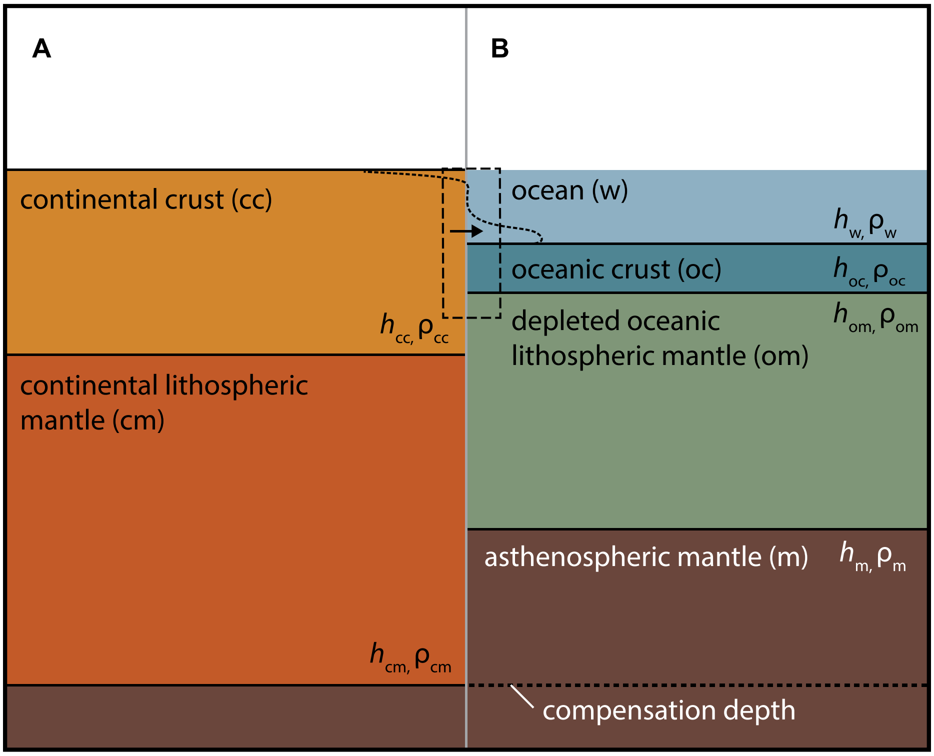

Figure 1. Schematic drawings of the compositional stratifications in the top few hundred kilometers of Earth in the continental domain (A) and oceanic domain (B). Different layers have different thicknesses (*h*) and densities (ρ) as indicated. (These layers are not drawn to scale.) Dotted lines indicate expected crustal flow based on horizontal pressure imbalance and rock rheology. Dashed rectangle denotes the main focus of our modeling (Fig. 2).

distribution of radiogenic heating (Burov and Diament, 1995), all of which are poorly constrained in deep time. In contrast, the silica content of the continental upper crust is likely to have stayed relatively constant through Earth history (Keller and Harrison, 2020). Crustal thickness may also be regulated by delamination, as thickened crust could stabilize garnet in the lower crust, but delamination is not dynamically feasible under most conditions (Mondal and Korenaga, 2018).

In our model, the pressure difference at the continent-ocean interface drives crustal flow, the rate of which is controlled by the rheology of continental upper crust. A temperature profile through the continental crust is calculated using the secular evolution of radiogenic heat production and mantle potential temperature (see the Supplemental Material[1] for details). The flow law for the upper crust is based on our reanalysis of published deformation experiments on quartz aggregates. When discussing the strength of crust or mantle, it is customary to calculate yield stress for an assumed strain rate. In our model setting, however, the stress driving deformation is predetermined by the aforementioned pressure difference, so instead of yield stress, we calculate strain rates corresponding to the pressure difference.

Pressure Difference between Continental and Oceanic Domains

Because the continental upper crust is denser than the surrounding seawater, the pressure difference at the continent-ocean boundary drives the horizontal flow of continental crust into the ocean (Fig. 1); this pressure difference exists at both passive and active margins. As the oceanic lithosphere is denser than the continental crust, the pressure difference is reversed at greater depths, and the continental lower crust is supported by the surrounding oceanic lithosphere. Therefore, the overall thickness of continental crust is contingent on the free-flowing continental upper crust. In our model, the compensation depth was taken to be the base of continental lithospheric mantle (Fig. 1), and the corresponding isostatic balance is given by

$$h_{cc}\rho_{cc} + h_{cm}\rho_{cm} = h_{w}\rho_{w} + h_{oc}\rho_{oc} + h_{om}\rho_{om} + h_{m}\rho_{m}, \quad (1)$$

where h and ρ denote thickness and density, respectively, and subscripts "cc," "cm," "w," "oc," "om," and "m" refer to continental crust, continental lithospheric mantle, water, oceanic crust, oceanic lithospheric mantle, and asthenospheric mantle, respectively. Here, the continental structure is compared with the oceanic structure at a mid-ocean ridge to provide a minimum ocean depth at the continent-ocean boundary. More realistic cases with older seafloor are considered in the discussion section. Our isostasy model was built on the continental freeboard model of Korenaga et al. (2017), in which the thicknesses and densities of different layers and their temporal evolution are estimated from a range of geological and geophysical observations as well as theoretical considerations (see the Supplemental Material for a summary of key model parameters). In this study, we varied the thickness of continental crust as a free parameter, and to provide a conservative estimate on pressure difference, the top of continental crust was assumed to be at or below sea level (Fig. 1).

Strength of Upper Continental Crust

The rheology of continental upper crust is usually considered to be controlled by the rheology of wet quartz aggregates (Kohlstedt et al., 1995; Bürgmann and Dresen, 2008). However, several different flow laws have been published (e.g., Luan and Paterson, 1992; Gleason and Tullis, 1995; Rutter and Brodie, 2004a, 2004b; Fukuda et al., 2018), and predicted crustal strength varies substantially with the choice of quartz flow law. Because crustal strength played a central role in our analysis, we critically examined major deformation data on quartz aggregates using the nonlinear inversion method developed by Korenaga and Karato (2008) and amended by Mullet et al. (2015) (see the Supplemental Material for details). We focused on ductile deformation because the available pressure difference at the continent-ocean boundary does not exceed the brittle strength of rocks, assuming a friction coefficient of 0.8 (Byerlee, 1978).

Our reanalysis showed that, as opposed to the suggestion made by Fukuda et al. (2018), there is little experimental support for grain boundary sliding being the dominant deformation mechanism of quartz aggregates. A combination of diffusion and dislocation creep is shown to be sufficient to explain the published quartz deformation data, with dislocation creep being most relevant under geological conditions. Our reanalysis further suggested that the deformation data of Gleason and Tullis (1995) provide statistically the most reliable flow law. In this study, therefore, we used the flow law derived from their data using our inversion.

RESULTS

Strain-rate profiles expected at the edges of continental crust were calculated for crustal thicknesses between 35 and 60 km under present-day and Archean conditions. Representative calculations are shown in Figure 2 for a

[1]Supplemental Material. Reanalysis of the deformation data of quartz aggregates and the details of strain rate modeling. Please visit https://doi.org/10.1130/GEOL.S.20044190 to access the supplemental material, and contact editing@geosociety.org with any questions.

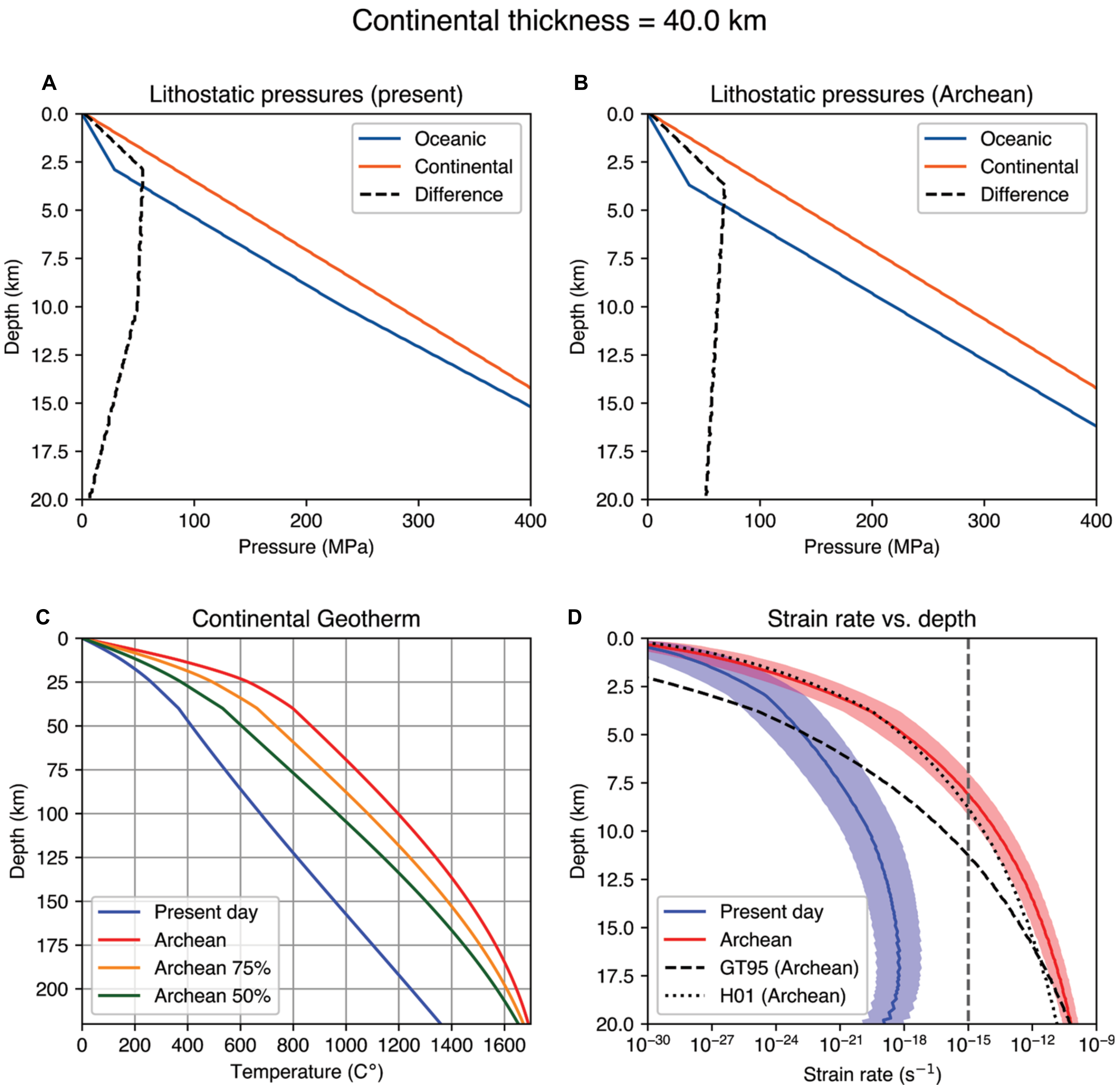

Figure 2. Modeling of strain-rate profiles for present-day and Archean crust with a thickness of 40 km. (A,B) Predicted pressure difference as a function of depth for the present-day and Archean Earth, respectively. (C) Present-day (blue) and Archean (red) geotherms. (D) Corresponding strain-rate profile (shading indicates interquartile range corresponding to the uncertainty of the quartz flow law). Vertical gray dashed line corresponds to the geological deformation rate (10^{-15} s^{-1}). For comparison, Archean geotherms with 75% (orange) and 50% (green) heat production are shown in C, and Archean strain-rate predictions according to the original flow law of Gleason and Tullis (1995, black dashed [GT95]) and the field-based flow law of Hirth et al. (2001, black dotted [H01]) (see the Supplemental Material [see footnote 1] for uncertainty) are shown in D.

thickness of 40 km. The present-day strain rate did not exceed the geological deformation rate of 10^{-15} s^{-1} (corresponding to a deformation time scale of ~30 m.y. for 100% strain), even at greater depths. In contrast, the Archean crust reached the geological deformation rate at relatively shallow depths, suggesting that the continental upper crust was capable of significant flow in the Archean, possibly limiting the continental height.

We focused on the strain rate at the base of the ocean (Fig. 3) because it is the highest strain rate achievable in the upper crust adjacent to the ocean. The strain rate continues to increase below the base of the ocean, but it is unlikely to be realized because the crust is bounded by oceanic lithosphere at those depths. The strain rate calculated under present-day conditions was much smaller than the geological strain rate of 10^{-15} s^{-1} for almost the entire range of crustal thickness considered. For the early Archean, on the other hand, the relative buoyancy between the continental and oceanic domains would place mid-ocean ridges at ~6 km below sea

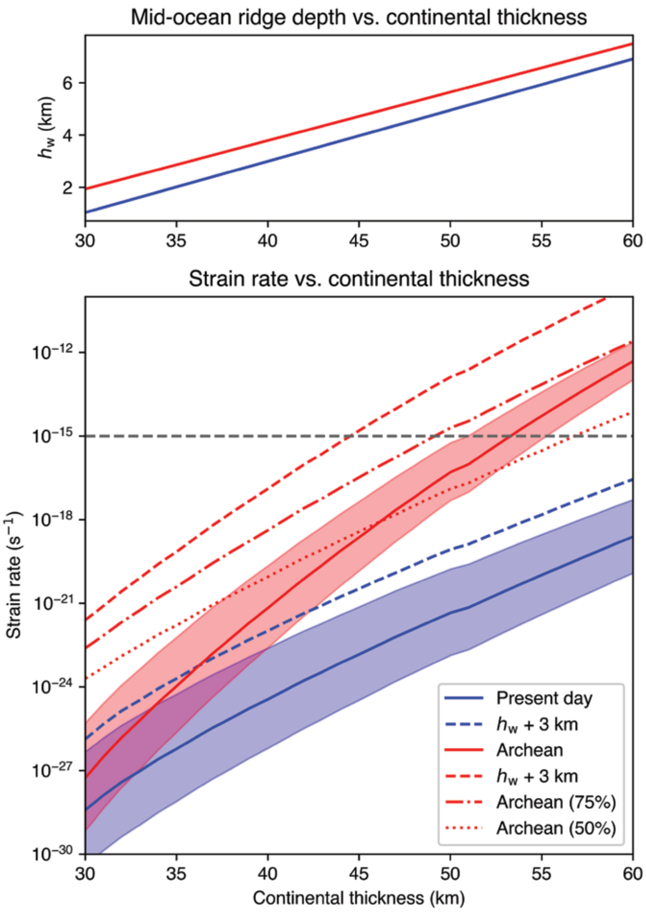

Figure 3. (Top) Depth of mid-ocean ridges (h_w) corresponding to continental thicknesses, according to the freeboard model of Korenaga et al. (2017). (Bottom) Crustal strain rate at the base of the ocean (e.g., at ~2.5 km depth at present in Fig. 2D) as a function of continental thicknesses: present-day (blue) and Archean (red), with shading for interquartile range. Median strain rates at a depth of 3 km below the ridge depth are shown with dashed lines. Also shown are two more Archean predictions, at a depth of 3 km below ridge depth, with 75% (red dot-dashed) and 50% (red dotted) heat production.

level (Korenaga et al., 2017; Rosas and Korenaga, 2021), for which the continental crust would have to be >50 km thick to reach sea level (Fig. 3). Such crustal thickness would be sufficient to produce a geologically significant strain rate. This secular change in crustal strength arises partly because the crustal geotherm was hotter in the past due to higher radiogenic heat production and higher mantle temperature (Fig. 2) and partly because a slightly deeper part of the upper crust becomes relevant for a deeper ocean in the past (Fig. 3).

DISCUSSION

We generally focused on crustal strain rates expected at the depth of mid-ocean ridges. However, the depth of ocean basins at the continent-ocean interface can be greater than at mid-ocean ridges because of seafloor subsidence. Thus, at realistic continent-ocean boundaries where old seafloor is adjacent to continents, we can expect higher crustal strain rates because strain rates generally increase with depth (Fig. 2). For comparison, the strain rate expected in the case of seafloor subsidence of 3 km, which is observed for present-day seafloor older than ca. 100 Ma, is also shown in Figure 3 (dashed lines). Even with this consideration, crustal strain rates are much lower than the geological deformation rate (10^{-15} s^{-1}) under present-day conditions. Thus, it is reasonable to conclude that crustal strength does not play any role in controlling continental thickness at present. Under Archean conditions, on the other hand, the geological deformation rate is reached when crustal thickness is greater than ~45 km, and this suggests a difficulty of growing continents to reach sea level when the oceans is deeper than ~5 km at mid-ocean ridges (Fig. 3). The stability of the Archean continental crust can be increased by lowering crustal heat production, and with only 50% heat production, the crust may be able to grow up to ~55 km (Fig. 3), allowing it to emerge above sea level even when the mid-ocean ridge is ~6 km deep.

A real continent-ocean boundary would not be as sharp as that depicted in Figure 1, and a more gradual transition would reduce the pressure difference. With the pressure difference halved, for example, the predicted strain rate would be lowered by around one order of magnitude given the stress dependence of crustal rheology. This difference is smaller than the uncertainties associated with flow-law predictions, seafloor subsidence, or crustal heat production (Fig. 3). Another realistic complication not captured by our model is the effect of a cold skin layer of the continental crust adjacent to the ocean. Such a cold layer would deform in a brittle regime, with the yield strength being ~56% of lithostatic pressure, assuming a friction coefficient of 0.8 and hydrostatic pore-fluid pressure. As our model geometry conforms to the homogeneous stress condition, for which the Reuss average is appropriate (Karato, 2008), upper-crustal flow would still be controlled primarily by the ductile strength of a weaker interior as long as the cold skin layer remained relatively thin (see the Supplemental Material).

CONCLUSIONS

When aiming to understand the early Earth landscape, the importance of a theoretical approach becomes apparent because relevant geological data are scarce. Given the available experimental constraints on the strength of continental upper crust, it seems unlikely for continents to have emerged from the deep ocean expected for the early Archean, unless the crust was depleted in heat-producing elements. At the same time, our results also suggest that continental crust could easily have thickened up to ~40 km, even in the Archean (Fig. 3), so exposed continents would have been possible if the ocean was not so deep. Because the history of ocean volume is unlikely to have remained monotonic (Miyazaki and Korenaga, 2022), the possibility of exposed land, which plays an essential role in some major hypotheses for the origin of life (e.g., Deamer, 2019), could have depended critically on a subtle balance between the growth of oceans and continents (Korenaga, 2021). Given an ocean depth, our model can predict the maximum possible crustal thickness, and this capability will be vital in estimating the extent of exposed land on early Earth.

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