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Correlating mantle cooling with tectonic transitions on early Earth

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ABSTRACT

The dominant tectonic mode operating on early Earth (before ca. 2.5 Ga) remains elusive, with an increasing body of evidence suggesting that non-plate tectonic modes were likely more prevalent at that time. Thus, how plate tectonics evolved after that remains contentious. We performed two-dimensional numerical modeling of mantle convection at temperatures appropriate for the Hadean–Archean eons and show that subduction and rift systems may have spontaneously emerged on Earth from an earlier drip-and-rift–dominated tectonic mode in response to the secular cooling of the mantle. This cooling of the mantle was mediated by repeated events of rifting and dripping that likely occurred over a few hundred million years. As the mantle cooled, its effective viscosity and the thickness and strength of the lithosphere increased, which helped establish rigid plates and initiate plate tectonics on Earth.

INTRODUCTION

At present, Earth's interior cools by a mantle-convection mode known as plate tectonics, in which the lithosphere plays a critical role (cf. Lenardic, 2018). It is comprised of a globally linked network of rigid lithospheric plates that are separated by weak plate margins and that participate in rifting, subduction-collision, and transform faulting. However, non-plate tectonic modes, like stagnant or sluggish-lid tectonics, have been suggested to be more dominant on early Earth (e.g., Moore and Webb, 2013; Sizova et al., 2015; Fischer and Gerya, 2016; Rozel et al., 2017; Capitanio et al., 2020; Foley, 2020; Lourenço et al., 2020), albeit alternate views also exist (e.g., Miyazaki and Korenaga, 2022; Hastie et al., 2023). The hypothesis of early non-plate tectonic modes relies on two arguments: (1) mantle temperatures were higher in the Hadean–Archean than today (Herzberg et al., 2010; Condie et al., 2016), and (2) mantle viscosity is strongly dependent on temperature, which affects convective vigor and pattern (Karato and Wu, 1993; Tackley, 1993; Moresi and Solomatov, 1995). These factors would have reduced convective stresses during the Hadean–Archean, likely failing to overcome lithospheric strength (Moresi and Solomatov, 1995; O'Neill et al., 2007; Lenardic, 2018). Geological evidence increasingly favors a non-plate tectonic mode, at least before ca. 3.2–3.0 Ga (e.g., Johnson et al., 2017; Bédard, 2018; Stern, 2018; Brown et al., 2020; Chowdhury et al., 2021; Palin and Santosh, 2021; Cawood et al., 2022). This leads us to one of the highly contentious questions in solid Earth sciences: why and how did the Earth transition from a non-plate tectonic mode to plate tectonics?

Subduction is the primary driver of plate motions on the modern Earth (Forsyth and Uyeda, 1975). Therefore, to understand how plate tectonics emerged, we need to resolve how episodes of subduction can initiate within a non-plate tectonic mode. While models suggest that meteoritic impacts or mantle plumes may cause isolated subduction events (Gerya et al., 2015; O'Neill et al., 2020), it remains unclear as to how subduction can initiate without such external forces. Although subduction may spontaneously result from lithospheric differentiation or gravitational collapse of continents (Rey et al., 2014; Sizova et al., 2015; Capitanio et al., 2020), a general mechanism showing how mantle cooling may initiate subduction and plate tectonics is missing.

We carried out numerical modeling of mantle convection starting from high mantle potential temperatures (T_p) and investigated how lithosphere dynamics spontaneously change through time as T_p decreases. We identify various tectonic stages by observing surface heat flow (Q_s) and horizontal lithospheric velocity (v_x) that show a co-evolution of mantle T_p, mantle viscosity, and the style of lithosphere dynamics. By elucidating this dynamic feedback, we propose a self-consistent mechanism through which Earth progressed from a non-plate tectonic mode to plate tectonics.

NUMERICAL MODELING

We modeled mantle convection in a 1200-km-deep × 4800-km-wide two-dimensional (2-D) Cartesian domain using Underworld2 (https://www.underworldcode.org/intro-to-underworld/; Fig. S1 in the Supplemental Material[1]). We varied the starting mantle T_p in the models between 1500 °C and 1600 °C (Table S1) following the Archean mantle T_p estimates (e.g., Herzberg et al., 2010; Ganne and Feng, 2017). We used suitable temperature-dependent rheology for each rock type and considered the effects of mantle melting and higher radiogenic heat production. Details of the modeling are given in the Supplemental Material.

Figure 1 shows the evolution of our reference model with an initial mantle T_p of 1600 °C. With the establishment of mantle convection, the lithosphere enters into a stagnant-lid mode but undergoes weak internal deformation. The stagnant lid is broken by thermal instabilities intro-

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[1]Supplemental Material. Modeling details, including the initial model setup and additional figures. Please visit https://doi.org/10.1130/GEOL.S.24944901 to access the supplemental material; contact editing@geosociety.org with any questions.

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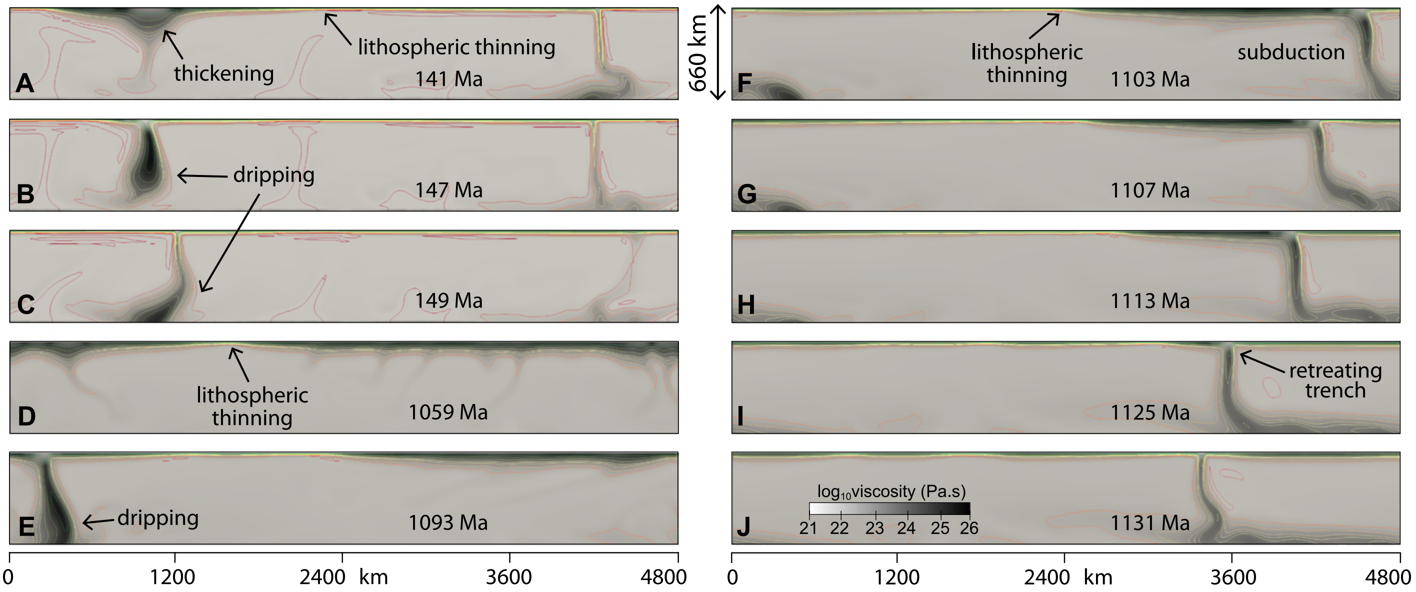

Figure 1. Evolution of the reference model with an initial mantle potential temperature (T_p) of 1600 °C. The model evolves from a stagnant-lid mode to a dripping-and-rifting–dominated mode (A–E) to a subduction-and-rifting–dominated mode (F–J). The drip-and-rift stage shows rifting, local thickening of the lithosphere, and dripping. The subduction-and-rift stage shows the formation of rigid plates and the occurrence of a retreating style of subduction together with rifting.

duced at the lower boundary. Thereafter, the lithosphere undergoes extension to create rift-like settings, while undergoing compression at other places, creating thickened lithospheric segments (plateaus; Fig. 1A). Lithospheric thickening in these plateau regions leads to the formation of denser minerals like garnet within the deep basaltic crust, which in turn triggers Rayleigh-Taylor instabilities and dripping (Figs. 1B–1E). The hotter geotherm of the lithosphere lowers its strength, further facilitating the initiation and growth of drips. While individual dripping events last for <10 m.y., repeated events of lithospheric thickening followed by dripping (and concomitant extension) continue for a few hundred m.y. (Figs. 1A–1E). This tectonic mode of the model is referred to as the “drip-and-rift” mode, which evolves into a “subduction-and-

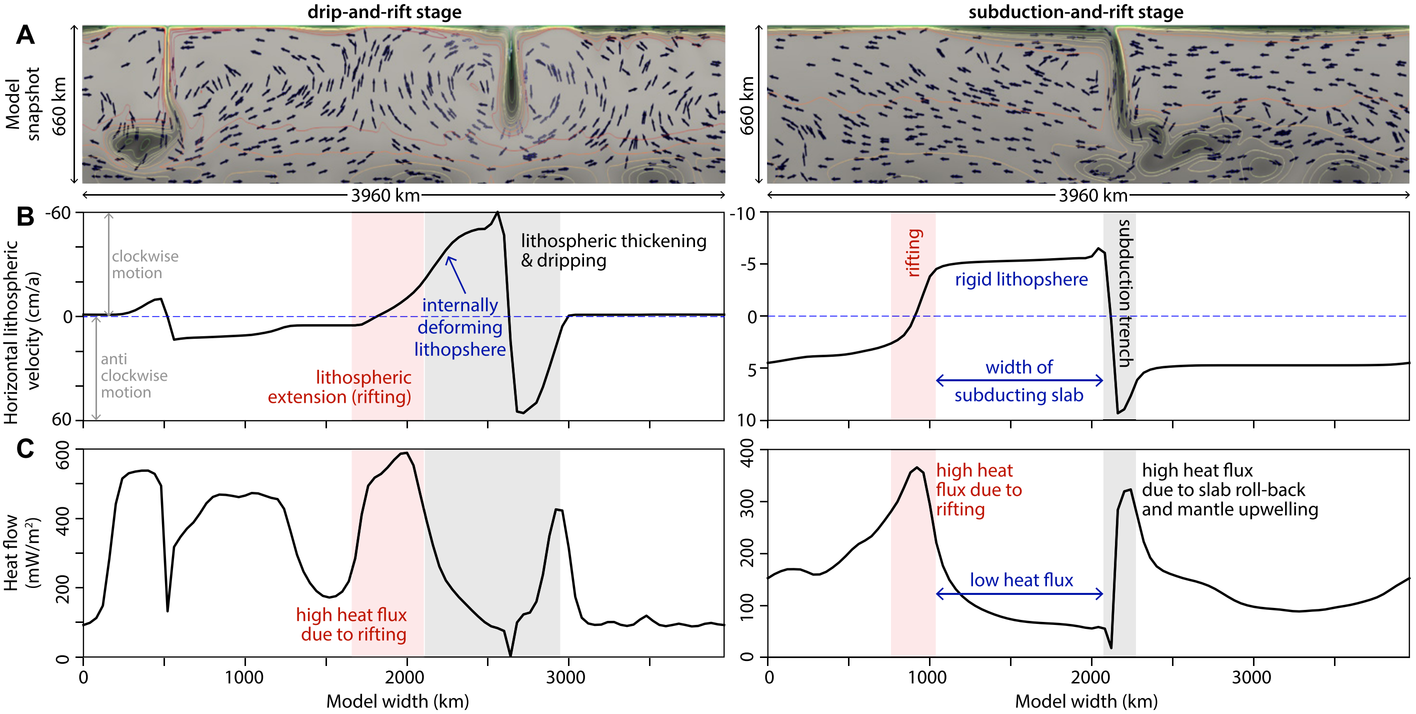

Figure 2. (A) Snapshots of the modeled drip-and-rift and subduction-and-rift stages. (B, C) Plots of the lithosphere’s horizontal velocity (v_x) and heat flow (Q_s) profiles across the model width for these two tectonic stages. The lithosphere shows high lateral mobility around the vicinity of the dripping site, although the v_x profile looks different from that of a subducting lithosphere, which is defined by a constant low velocity. This constant v_x profile reflects the rigidity of subducting lithosphere. The Q_s profile also varies between the two tectonic stages, and that of the subduction-and-rift stage mimics the Q_s profile of a typical, modern-day oceanic lithosphere.

rift” mode with time. This mode starts with the formation of a drip that grows until one side of the lithosphere begins to subduct (Figs. 1F–1I). The subducting lithosphere rolls back, mimicking the convective flow dynamics of a retreating subduction system (Figs. 1F–1I). The subduction terminates via slab break-off, which initiates through lithospheric necking at a shallow depth (<60–70 km; Fig. 1J). At the same time, the zone of rifting migrates toward the subduction zone. The overall duration of the subduction event from initiation to slab break-off is <30 m.y.

Thus, our model shows a spontaneous transition from the drip-and-rift mode to subduction-and-rift mode after ~1100 m.y. of evolution, which is also evident in the Nusselt number versus time plot (shown in Fig. S3). We further quantified v_x and Q_s profiles from the model to better characterize the tectonic modes and measure the plateness of lithospheric segments (Fig. S2; Tackley, 2000). The drip-and-rift mode shows variable lithospheric mobility (Figs. 2A and 2B). v_x is significantly high (~50–60 cm/a) around the dripping location and decreases as one moves away from the drip (Fig. 2B). The strong downward pull exerted by the drip causes this lithospheric mobility. However, the stresses are not uniformly transmitted laterally over large distances (<600 km), as is evident from the declining v_x, reflecting the lithosphere’s non-rigid nature. In contrast, the subduction-and-rift mode displays the v_x profile of a rigid lithosphere undergoing subduction. The subducting lithosphere shows a constant v_x of ~4–6 cm/a over a length scale of ~1200 km (Figs. 2A and 2B), suggesting that it responds to large horizontal stresses via lateral displacement, and not by internal deformation, as expected by a coherent and rigid plate (Bercovici, 2003; van Hunen and van den Berg, 2008). The subduction trench shows a sharp velocity change in a narrow (<200-km-wide) zone. The overriding plate also shows a constant v_x, suggesting that its mechanical response to stress is similar to that of the subducting plate (Fig. 2B). Such a tectonic setting—wide rigid lithospheres separated by narrow deforming margins—is consistent with plate tectonics.

Furthermore, the lithosphere forms in a rift setting and becomes thicker as it migrates closer to the subduction trench during the subduction-and-rift mode (Fig. 2A). Thus, the corresponding Q_s profile shows progressive decline in conductive heat-loss through the lithosphere as it thickens with increasing distance from the rift axis (Fig. 2C), analogous to modern oceanic lithospheres (cf. Turcotte and Schubert, 2014). The high heat-flow regions are restricted to rifts and overriding lithosphere inboard of the trench where the mantle rises due to slab roll-back, resembling the dynamics of a retreating subduction system. In contrast, the drip-and-rift mode shows high heat-flow regions corresponding to broad regions of thinned lithosphere, whereas the plateau and/or dripping regions are marked by low heat flow (Fig. 2C). Notably, the model evolution suggests that the drip-and-rift mode is more efficient in transmitting heat through the lithosphere over relatively shorter time scales as compared to the subduction-and-rift stage (Fig. 2C). This effect will be more pronounced in natural (three-dimensional) settings, where the radial flux of the lithosphere will feed the drip. Models with different initial mantle T_p values show tectonic evolution similar to the reference model (Figs. S4 and S5). They show the same development of symmetric drips followed

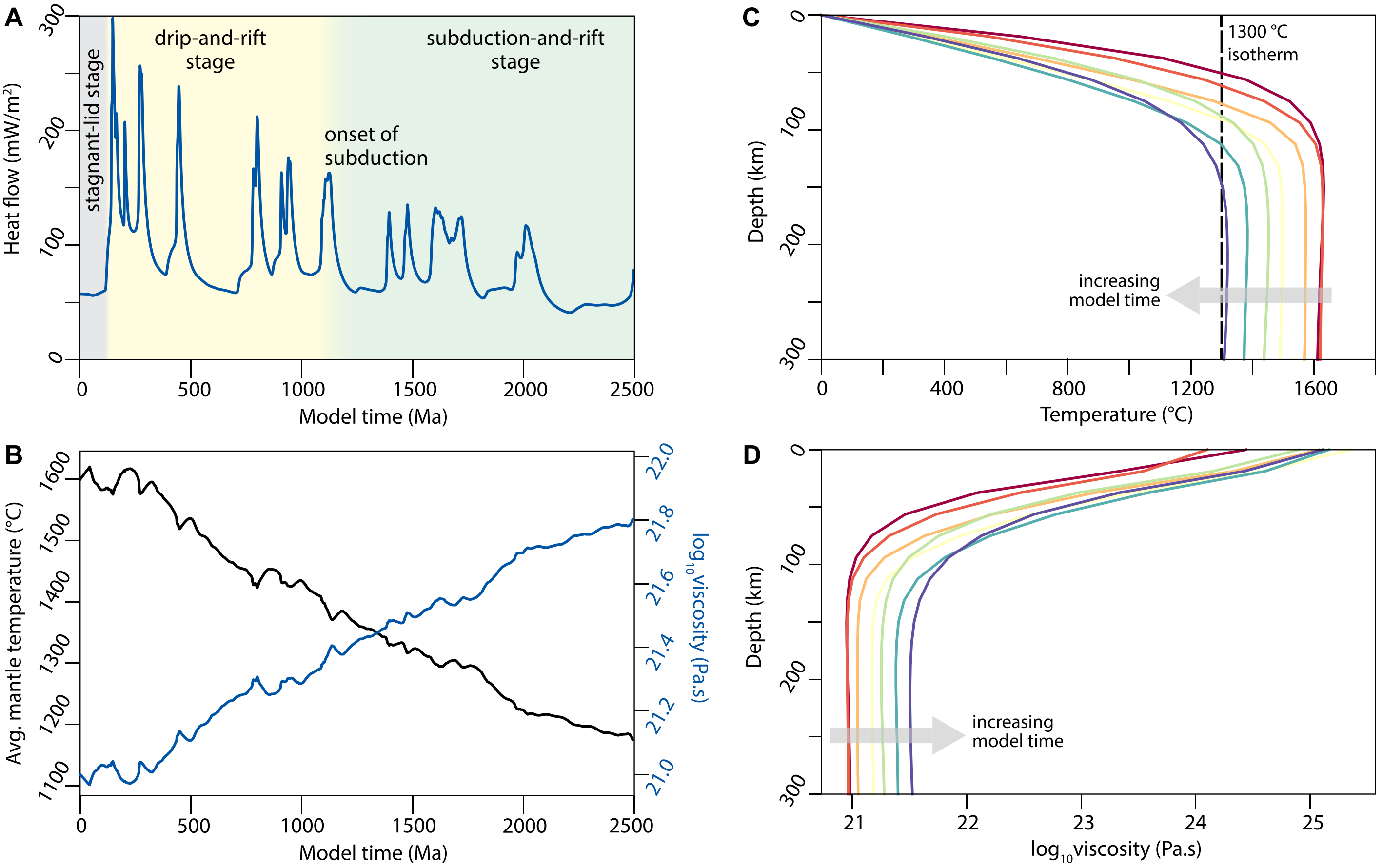

Figure 3. Variation of (A) average heat flow, and (B) average (upper) mantle temperature (black line) and viscosity (blue line) with model time. The average heat flow pattern shows short-lived but frequent episodes of high heat-loss during the drip-and-rift stage. (C, D) Evolution of thermal and viscosity profiles of the upper 300 km in the reference model, averaged over the model width. The color code (from red-yellow-green-blue) represents the model time from the start to ca. 1.0 Ga. The vertical dashed black line in C is the 1300 °C isotherm that defines the lithospheric thermal thickness. As the mantle cools with time, the lithospheric thickness, and thereby strength, increases.

by asymmetric subduction zones as a function of declining mantle temperature (Figs. S6 and S7); however, the mantle thermal condition at which the tectonic transitions occur, and thereby their timing, differ from those observed in the reference model (Fig. S8).

DISCUSSION

Our models illustrate the spontaneous initiation of subduction from a non-plate tectonic mode due to the cooling of mantle, which changes the thermomechanical properties of the lithosphere-mantle system. To illustrate this, we determined how average Q_s and average (upper) mantle temperature and effective viscosity vary with model time (Fig. 3). During the stagnant-lid stage, the average Q_s is at its minimum since the heat loss happens only by conduction (Fig. 3A). Hence, the average mantle temperature remains high, which keeps its effective viscosity low (Fig. 3B). As episodes of dripping and rifting begin, these are associated with rapid heat loss (~200–300 mW/m^2) interspersed with longer intervals of reduced heat loss (~60–100 mW/m^2; Fig. 3A). The high heat loss is due to rifting associated with large-scale mantle upwelling and lithospheric dripping. The cold drips further cool down the mantle. Notably, the magnitude of average Q_s during periods of high heat loss shows a near-exponential decay with time, suggesting that the rate of mantle cooling is a function of the frequency of rifting and dripping. This cooling manifests in the steady decline in average mantle temperature over ~2.5 b.y. (Fig. 3B).

During the subduction-and-rift stage, periods of low heat loss are longer, while periods of high heat loss show a near-constant magnitude of average Q_s (~100–125 mW/m^2) (Fig. 3A). The periods of high heat loss correspond to the episodes of subduction and rifting, where the mantle cools via convective heat loss at rifts, and via mixing with cold lithospheres at subduction zones. Notably, the magnitude of average Q_s during periods of high heat loss is much lower than the corresponding average Q_s during the drip-and-rift stage. The decline in mantle temperature leads to the increase of its effective viscosity with time (Fig. 3B). At this point, the pattern of mantle convection transitions from multiple small-wavelength cells to fewer large-wavelength cells (Fig. 2A). We explain this transition by re-balancing the main forces of plate tectonics: the buoyancy force and the viscous resistance to the mantle flow. Buoyancy declines with decreasing temperature, and viscous resistance increases with decreasing temperature (Fig. 3B). Mantle cooling also leads to cooling and consequent thickening of the lithosphere, which increases lithospheric strength. This is substantiated by the evolution of our models' thermal and viscosity profiles (averaged over model width), which show a drop in lithospheric temperature and a concomitant increase in lithospheric thickness with time (Figs. 3C and 3D).

Thus, our results suggest that efficient mantle cooling during dripping and rifting increases mantle viscosity and lithospheric strength, which helps establish rigid lithospheres (i.e., plates) and plate margin–like processes. The rate of heat loss during the drip-and-rift mode is higher than during the subduction-and-rift mode, implying that repeated occurrences of dripping and rifting may have significantly cooled Earth's interior. However, our models predict that the mantle was still hotter by 130–190 °C than today, when the subduction-and-rifting mode may have begun (Fig. S8). This is why our modeled subduction style (e.g., shorter duration, shallow slab break-off) differs from modern, cold-style subduction, which agrees well with the results of previous modeling studies (e.g., Sizova et al., 2015, Fischer and Gerya, 2016; Gerya et al., 2021). The mantle thermal conditions of our model may have existed during the late Archean to early Proterozoic (Herzberg et al., 2010). We understand that the relation between Earth's mantle T_p and age is debated (e.g., Herzberg et al., 2010; Ganne and Feng, 2017), and our 2-D modeling represents regional, rather than global, tectonics—both of which may affect the timing of tectonic transitions. Nevertheless, the concurrence of a wide range of evidence in the rock record toward a diachronous establishment of plate tectonics across Earth at ca. 3.2–2.2 Ga (cf. Brown et al., 2020; Cawood et al., 2022) supports our inferences and is consistent with how weak plate boundaries may have developed during that time (Bercovici and Ricard, 2014).

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