



## Earth's thermal evolution with multiple convection modes: A Monte-Carlo approach



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### ABSTRACT

We present a thermal evolution model, based on the results of recent numerical simulations, in which we consider that different sized oceanic plates are associated with different modes of surface motion (mobile-lid and sluggish-lid tectonics). These different modes are, in turn, associated with different heat loss scalings. Varying initial conditions and system parameters systematically we run several thousand thermal models that we compare with constraints on present-day mantle temperature, present-day Urey ratio and overall minimum core heat flow. The dual heat loss mode approach readily satisfies the Urey ratio constraint that is unexplained by classic thermal evolution models.

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### 1. Introduction

To date, there is no broadly accepted model for the evolution of Earth's mantle temperature in response to changing rates of internal heat production and surface heat loss. Whereas the evolution of radiogenic heat production is governed by the approximately chondritic composition of the bulk silicate Earth (McDonough and Sun, 1995; Lyubetskaya and Korenaga, 2007), different parametrizations of surface heat loss exist in the literature leading to distinct thermal evolution scenarios (e.g., Schubert et al., 1980; Christensen, 1984; Conrad and Hager, 2001; Korenaga, 2008). The applicability of any given scenario to the thermal evolution of the Earth can be evaluated with constraints, which typically include the present day interior temperature and the present day Urey ratio, which is the ratio of radiogenic heat production to total surface heat loss. In a summary of present day thermal constraints, Jaupart et al. (2007) estimate the present day Urey ratio to be 0.33, with an allowable uncertainty range of 0.21–0.49. Recently, Lenardic et al. (2011) have argued that continents play a key role in Earth's thermal history. The insulating effect of continents leads to increased mantle temperatures compared to an Earth without continents. Increased mantle temperatures lead to reduced viscosities, which in turn lead to increased convective overturn and oceanic heat flux. Lenardic et al. (2011) estimate that for today's continental coverage the oceanic heat flux is about the same as for an Earth without insulating continents in which convective

overturn would be reduced. However, the mantle in a continent-less Earth would have significantly increased heat production. This suggests that Earth without continents would have a higher Urey ratio than an Earth with continents. Their adjusted Urey ratio is 0.51, with an allowable uncertainty range of 0.33–0.76.

Classic thermal evolution models typically arrive at present-day Urey ratios larger than this value (e.g., Davies, 1980; Schubert et al., 1980) to avoid so called “thermal catastrophes”, where integrating the surface heat flux back in time causes the mantle to melt usually within about 1 Ga in response to an exponential increase in surface heat flux with mantle temperature (e.g., Christensen, 1984; Korenaga, 2008). This “classical” picture assumes that surface heat flux scales with a subduction rate governed by the interior mantle viscosity alone. It also assumes that the same plate tectonic regime persists over all of Earth's history. One solution to the thermal catastrophe problem is, thus, to include the additional dissipation related to deforming plates (e.g. Christensen, 1984; Conrad and Hager, 2001; Korenaga, 2008) such that the dependence of subduction rate on mantle temperature is less. An alternative solution is to relax the assumption of a single style of plate tectonics and heat loss, and investigate whether the dynamics driving plate motions have changed over Earth history.

Recent numerical simulations bring the assumption of a single style of plate tectonics into question Höink et al. (2011). The simulations suggest that mantle heat loss through the seafloor may be associated with mantle stirring by two forces: classical slab-pull and “asthenosphere-drive”, which is the viscous drag force related to a Poiseuille-like flow driven as a result of lateral temperature variations in the asthenosphere, depending on oceanic plate size. Slab-pull is the dominant plate driving force for large plates and

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is characterized by mobile-lid convection (Fig. 1a). In contrast, asthenosphere-drive is the dominating plate-driving force for smaller plates and is associated with sluggish-lid convection (Fig. 1b).

For the case of asthenosphere-drive, the scaling of mantle heat loss is qualitatively similar to recently suggested thermal history models (e.g. Conrad and Hager, 1999; Korenaga, 2006) in that it predicts a less efficient mode of heat loss compared to flow in the slab-pull regime. If the average size or size distribution of oceanic plates has varied over Earth’s history, there are consequently at least two convective heat loss modes operating together to cool the Earth. In this paper, we exploit this possibility and develop a thermal history model based on this dual mode potential. Considering the two limiting modes of mantle convection our Monte-Carlo approach can identify those thermal history models that are rigorously permitted by available observations. The dual-mode model is not overly sensitive to uncertainties in initial thermal conditions.

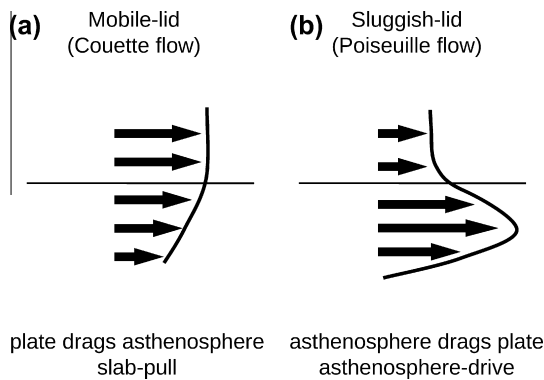
**2. Thermal evolution with two convection modes**

In typical thermal history calculations, the rate of change of mantle temperature is governed by the surface heat loss and the rate of internal radioactive heat production (e.g., Turcotte et al., 2001):

$$\frac{dT}{dt} = \frac{1}{C} [H(t) - Q(T)] \tag{1}$$

Here,  $T$  is the temperature,  $t$  time,  $C$  a constant ( $7 \times 10^{27}$  J/K) and  $H(t)$  the radiogenic heat production within the mantle. We model the internal heat production from radioactive decay using the abundances and half-lives of  $^{238}\text{U}$ ,  $^{235}\text{U}$ ,  $^{232}\text{Th}$  and  $^{40}\text{K}$  following Turcotte and Schubert (2002) (p. 137), and take the present day value to be 13 TW (Jaupart et al., 2007). We do not explicitly model heat production in the continents, and we include no effect of continental extraction over time. From the final (present day) values of  $H$  and  $Q$  we compute the present day Urey ratio. A successful thermal evolution case in terms of the present day Urey ratio constraint will then have a ratio in the range of 0.33–0.76 (Lenardic et al., 2011).

The surface heat loss parametrization  $Q(T)$  is at the heart of any thermal evolution model. The classic scaling, which assumes that the Earth is wholly in a mobile lid regime (e.g. Christensen, 1985), is given by



**Fig. 1.** Convective mantle heat loss through the seafloor is considered to be associated with two leading plate driving forces operating in tandem, slab-pull and asthenosphere-drive. (a) Slab-pull is the dominant plate driving force for large plates and is associated with mobile-lid convection and Couette flow in the asthenosphere, whereas (b) asthenosphere-drive dominates for smaller plates and is associated with sluggish-lid convection and Poiseuille flow in the asthenosphere.

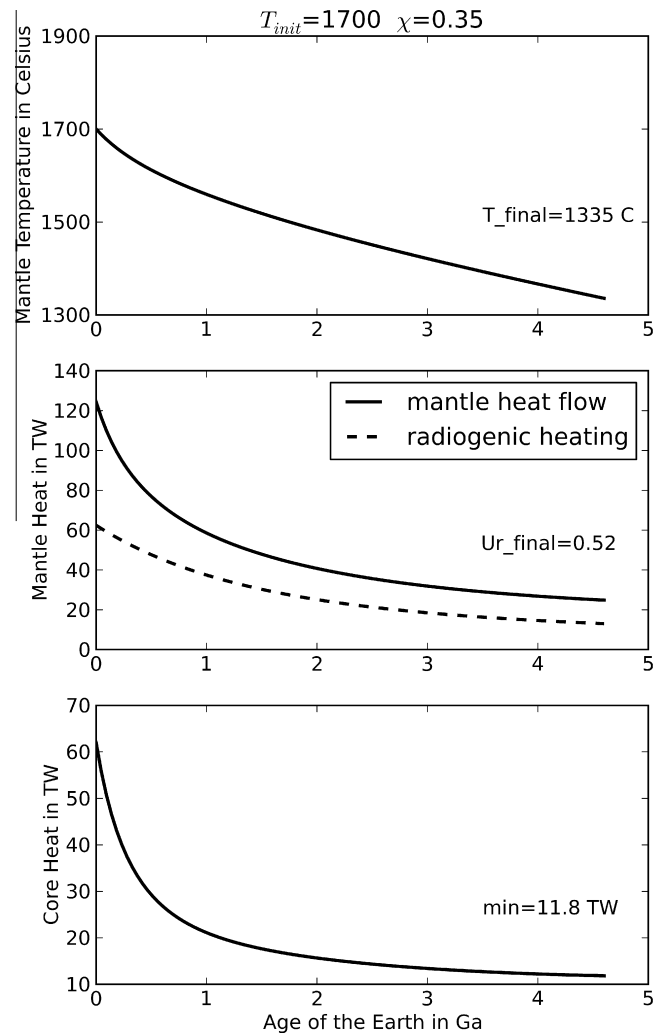
$$Q_{\text{classic}}(T) = Q_0 \left( \frac{T}{T_0} \right)^m \tag{2}$$

where  $Q_0$  is  $3.7 \times 10^{13}$  W,  $T_0 = (1350 + 273.15)$  K = 1623 K, and  $m = 12$ . In this regime, plate buoyancy is the dominant driving force and the bulk internal viscosity of the mantle provides the main resisting force.

Recent work has demonstrated that some plates, especially small plates that are not attached to descending slabs, might be predominantly driven by viscous coupling to a fast-flowing asthenosphere (Höink et al., 2011). These cases are more appropriately described by a sluggish-lid model. Numerical models show that this mode of convection is associated with a different scaling between surface heat loss and convective vigor (Höink and Lenardic, 2010). We adopt their numerically obtained heat loss scaling for the sluggish-lid mode. A linear interpolation through their results is

$$Q_{\text{slug}}(T) = Q_0 \left( m \frac{T}{T_0} + c \right) \tag{3}$$

with  $m = -1.49$  and  $c = 2.18$ .



**Fig. 2.** Thermal evolution case with dual mode convection in which the mobile-lid mode and the sluggish-lid mode contribute with 35% and 65%, respectively, to the total surface heat flow ( $\chi = 0.35$ ). The initial temperature for this case is 1700 Celsius. Plotted as a function of time are (a) mantle temperature, (b) mantle heat loss (solid line) and internal heat generation (dashed line), (c) heat flow from the core. Final mantle temperatures, final Urey ratio and minimum core heat flux are used to constrain plausible thermal evolutions.

We assume that each of Earth's plates operates in either the sluggish-lid or the mobile-lid mode. We also take into consideration the relative contribution of the modes to the total surface heat loss. The total surface heat loss is then

$$Q(T) = \chi Q_{\text{classic}}(T) + (1 - \chi) Q_{\text{slug}}(T) \quad (4)$$

where  $\chi$  denotes the fraction of the total heat loss that is associated with the classic scaling of the mobile-lid regime.

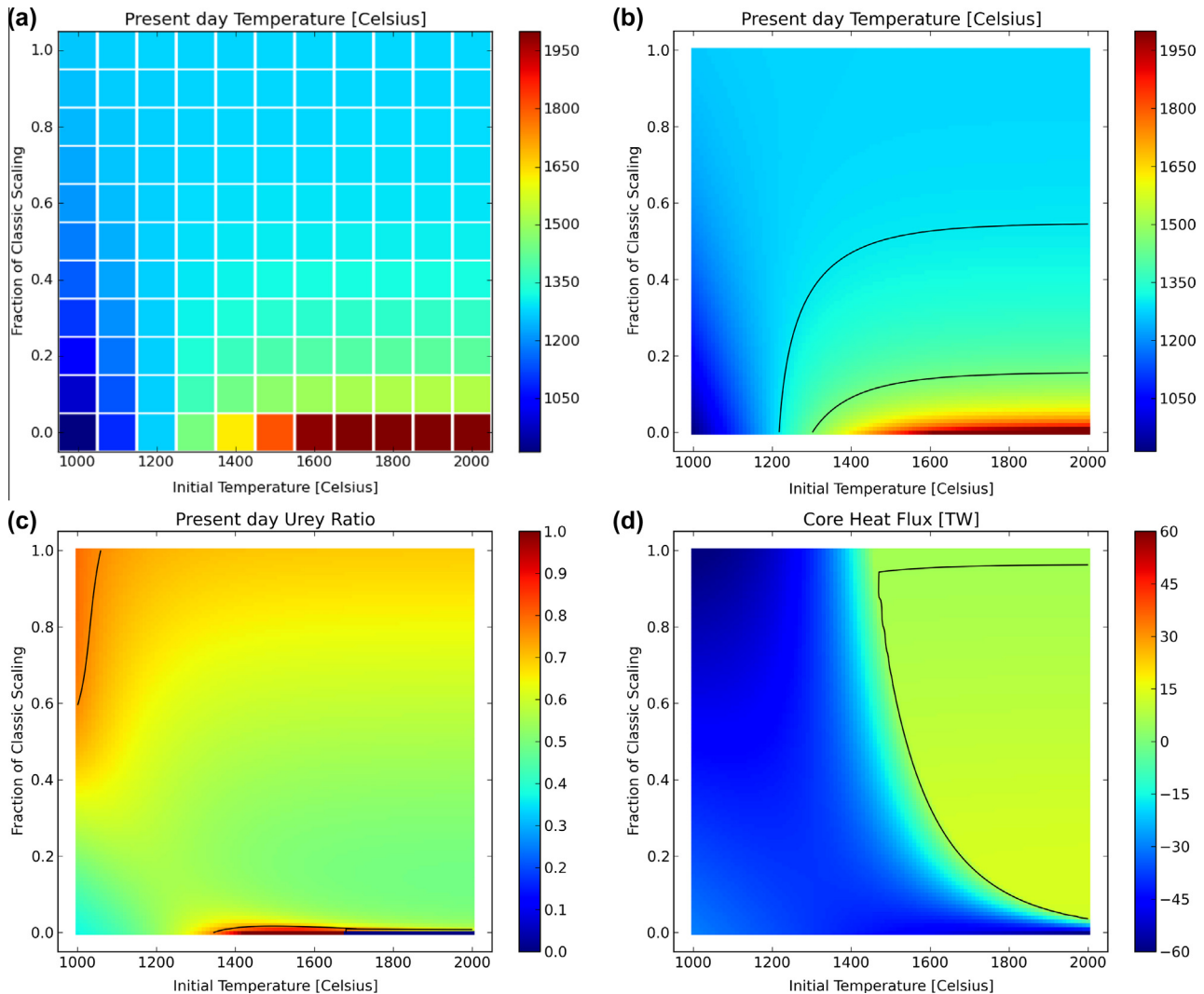
### 3. Results

Eq. 1 can be integrated in time starting with an initial temperature,  $T_{\text{init}}$ , which is not known and is thus considered a free parameter in this study. The other free parameter is  $\chi$ . For each combination of  $T_{\text{init}}$  and  $\chi$  we integrate Eq. 1 in time for 4.6 Ga. Fig. 2a shows the evolution of the interior temperature of such a thermal evolution with  $T_{\text{init}} = 1700$  C and  $\chi = 0.35$ . Fig. 2b shows the evolution of radiogenic heating and mantle heat flow, and Fig. 2c shows the evolution of the core heat flow. These quantities

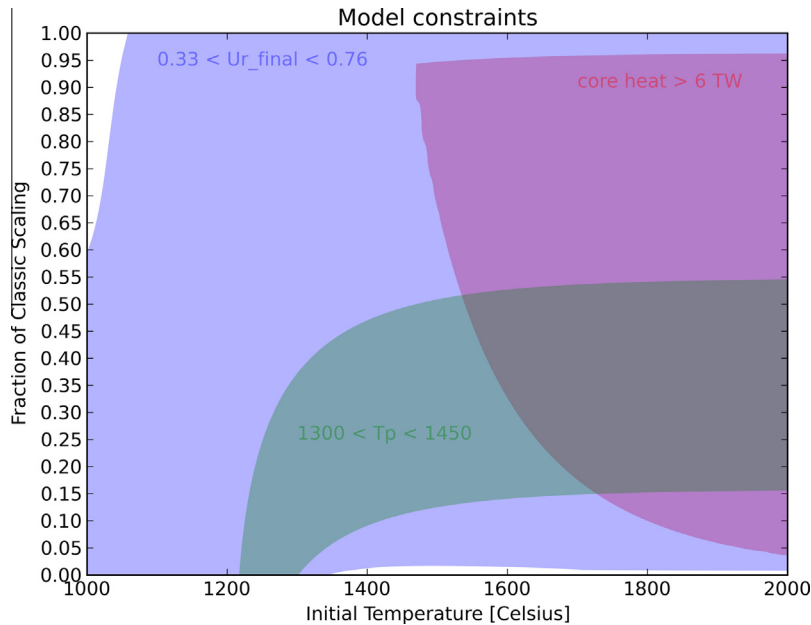
are computed during the integration and subsequently used to evaluate the constraints.

Fig. 3a shows the present day interior temperature results of a first sweep with  $11 \times 11$  model runs. Classic thermal histories are given by the top most row of scenarios ( $\chi = 1$ ). Note that for  $\chi < 1$ , i.e., when the less efficient heat loss scaling of the sluggish mode is included, the planet retains more heat, leading to reduced heat loss and higher interior temperatures at present day than the classic model would predict.

Our modeling strategy is to use a large number of thermal evolution models to perform a systematic, high-resolution sweep across the parameter space spanned by possible values of  $T_{\text{init}}$  and  $\chi$ , and to select those models that simultaneously satisfy present day Urey ratio and interior temperature. Because the integration for each model takes only a few seconds on a single-core netbook we can easily run several thousands of models. Fig. 3b shows the same result as Fig. 3a but for about 10,000 scenarios, allowing for a much finer resolution in parameter space, and for a clearly contoured region that is consistent with the present day interior temperature constraint (outlined by solid black lines).



**Fig. 3.** (a) Present day mantle temperature for  $11 \times 11$  thermal evolution scenarios with different initial temperatures and different contributions from the convection modes,  $\chi$  (discussed in the text). This type of plot can be used to constrain plausible evolution scenarios. For a more detailed scan of the parameter space we increased the number of thermal evolution scenarios by one order of magnitude in each dimension. (b) Same as (a) but with  $101 \times 101$  thermal evolution scenarios. Contoured is the range of plausible thermal evolution scenarios based on the present day mantle temperature constraint ( $1300 \text{ C} < T_{\text{final}} < 1450 \text{ C}$ ). (c) Present day Urey ratio for same scenarios as in (b). Outlined in contours is the present day Urey ratio constraint ( $0.33 < U_{r_{\text{final}}} < 0.76$ ). (d) Minimum core heat flux for same scenarios as in (b). Outlined in contours is the minimum core heat flux necessary to drive convection in the core ( $Q_{\text{core}} > 6 \text{ TW}$ ).



**Fig. 4.** Overlay of all model constraints based on 10,201 thermal evolution scenarios. Individual constraints are labeled. The darkest region shows the parameter space in which all constraints are satisfied, effectively providing a family of thermal evolution scenarios that are rigorously permitted by the observations. Our analysis predicts that initial temperature must have been larger than about 1600 C and that the contribution of the classic heat loss scaling was in the range 0.15–0.55, which means that the fraction of plates associated with Poiseuille flow was in the range of 45–85%.

The present day Urey ratio results and constraint are shown in Fig. 3c, and the minimum core heat flow result and constraint in Fig. 3d. The minimum core heat flow constraint is based on the notion that at least 6 TW is needed to drive a dynamo in Earth's core (e.g. Buffet, 2002).

Fig. 4 combines these constraints into a single figure. The parameter space allowed by all the three constraints is the darkest region, which is roughly bound by  $0.15 < \chi < 0.55$  and  $T_{\text{int}} > 1600$  C.

#### 4. Discussion

A key difference of this work to previous thermal evolution studies is that we consider two different modes of heat loss. One mode is associated with classic mobile-lid convection driven primarily by slab buoyancy or “slab-pull”, which is an applicable mode of heat loss for the Pacific plate. The other mode is associated with sluggish-lid convection, which is likely the mode of heat loss of the Atlantic plate and governed predominantly by pressure-driven flow in the asthenosphere (Höink et al., 2011).

The notion of two heat loss modes operating simultaneously on present-day Earth motivated us to explore the possibility that two modes might have simultaneously contributed to the total heat loss throughout Earth's history. Constraints of present-day mantle temperature, present-day Urey ratio and overall minimum core heat flow limit the relative contribution of the classic mode to roughly 35% of the total heat loss ( $0.15 < \chi < 0.55$ ). This implies that asthenosphere flow is on average, both geometrically and temporally, driven by about 35% from the overriding plate and by about 65% from lateral pressure gradients. Our suggestion that the oceanic plates on present-day Earth operate in two different modes, and that the asthenosphere may be a driving force for some plates, has been supported by recent predictions that the asthenosphere is leading plates over a large portion of the planet (Ghosh and Holt, 2012).

The second key difference of our paper is the approach to run a large number of thermal evolution models in a Monte-Carlo ap-

proach. From those we identify the family of models that are rigorously permitted by indicated observations. In doing so we can quantify an uncertainty estimate associated with the input parameters. Our approach allows us to be clear in what we can and what we cannot conclude based on our assumptions and constraints.

Our results find qualitative support in recent work by Natarov and Conrad (2012) who use the depth-dependence of azimuthal seismic anisotropy to constrain the present-day flow type in the asthenosphere. Their finding is that flow the asthenosphere is on average about equally divided between shear flow and pressure-driven flow ( $\chi = 0.56$ ). We note that the ratio obtained in our analysis is likely not constant over the intermediate time scales of changing plate configurations and plate sizes. However, averaged over several Wilson or super-continent cycles, it appears plausible, and thus a good first approximation, that the average ratio remains constant over the thermal evolution of the Earth.

Speculating on how the average ratio  $\chi$  may have changed during Earth's thermal evolution, we might expect that a younger, hotter Earth would favor small plates and a sluggish-lid mode of tectonics with a less efficient heat loss scaling. Therefore an earlier period of Earth's thermal history might have experienced significant amounts of less efficient heat loss, whereas later periods might have experienced more efficient cooling from mobile-lid tectonics of large plates. In addition, any excess heat accumulated during Earth's cooling history could be removed by the more efficient mobile-lid contributions over time, which in turn suggests a robustness of our results in that they are not strongly sensitive to variations initial conditions.

Two key results from our analysis are that the mantle had to start out hotter than at present (which may not surprise) and that, on average, about 45–85% of the surface that contributed to Earth's total heat loss was associated with sluggish-lid convection, i.e. Poiseuille flow in the asthenosphere. Because this type of convection is associated with less efficient heat loss it allows for much lower initial temperatures early in Earth's history. It is therefore particularly important in Earth's distant past to avoid the notion of extreme mantle temperatures. Associating this heat flow trend with sluggish-lid convection, in which the asthenosphere drives

the overriding plate, leads to a fundamentally new result and provides an attractively simple physical solution to the Urey ratio problem.

Similar to previous thermal history models, our model can identify which class of models match present day observational constraints, e.g. mantle temperature and Urey ratio. In addition our thermal history model also brings with it a new constraint which has the potential to lend our thermal history added support or to provide a means to refute it. If the preliminary results that support a combination of plate driving forces, e.g., slab-pull and asthenosphere drive (Alvarez, 2010; Höink and Lenardic, 2010; Höink et al., 2011; Natarov and Conrad, 2012) that operate at present and are associated with two different heat loss scalings, do not hold up, then our thermal history model is not applicable. This connection to additional observational constraints makes our thermal history model and its underlying assumptions testable.

In this paper we use the Occam's razor approach by assuming that the ratio of Couette flow in the asthenosphere to Poiseuille flow in the asthenosphere is constant in a given calculation. Given the variability in other parameters, the results from this assumption are similar to those suggested by Natarov and Conrad (2012). As more constraints become available, our approach can easily be used to explore the value of  $\chi$  or its history. Moving past the assumption of constant  $\chi$ , a relative change in the importance the modes of plate tectonics in time could be based on peaks of orogenic activity, which are associated with changes in the physical properties of plates and their velocities (Kranendonk and Kirkland, 2013).

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