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Plate Tectonics, Mixed Heating Convection and the Divergence of Mantle and Plume Temperatures

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Abstract

Petrological data indicate that upper mantle and mantle plume temperatures diverged 2.5 billion years ago. This has been interpreted as plate tectonics initiating at 2.5 Ga with Earth operating as a single plate planet before then. We take an Occam's razor view that the continuous operation of plate tectonics can explain the divergence. We validate this hypothesis by comparing petrological data to results from mixed heating mantle convection models in a plate tectonic mode of mantle cooling. The comparison shows that the data are consistent with plate tectonics operating over geologic history.

1 Introduction

The Earth's interior has cooled over time. Petrological data provide constraints on mantle temperatures and, by association, Earth's cooling rate. Condie et al. [2016] broke petrological data into three compositional types representative of different mantle sources: ambient mantle, mantle plume heads, and mantle plume tails. Figure 1a shows the trends from their data. Plume temperatures mildly declined over Earth's history. Ambient mantle tracked the plume trend early in Earth's history before diverging at 2.5 Ga. A succinct measure of thermal divergence is captured in the ratio of ambient mantle to plume tail temperatures (Figure 1b). Condie et al. [2016] argued that the thermal divergence at 2.5 Ga indicates that Earth transitioned from a single plate to a plate tectonic planet.

In the spirit of multiple working hypotheses [Chamberlin, 1897], a tectonic transition should not be considered the only viable hypothesis to explain a thermal divergence. The alternative hypothesis we propose is that plate tectonics operated over geological history and a thermal divergence reflects the mantle being heated by both internal and basal heat sources [Moore, 2008]. The bulk of this

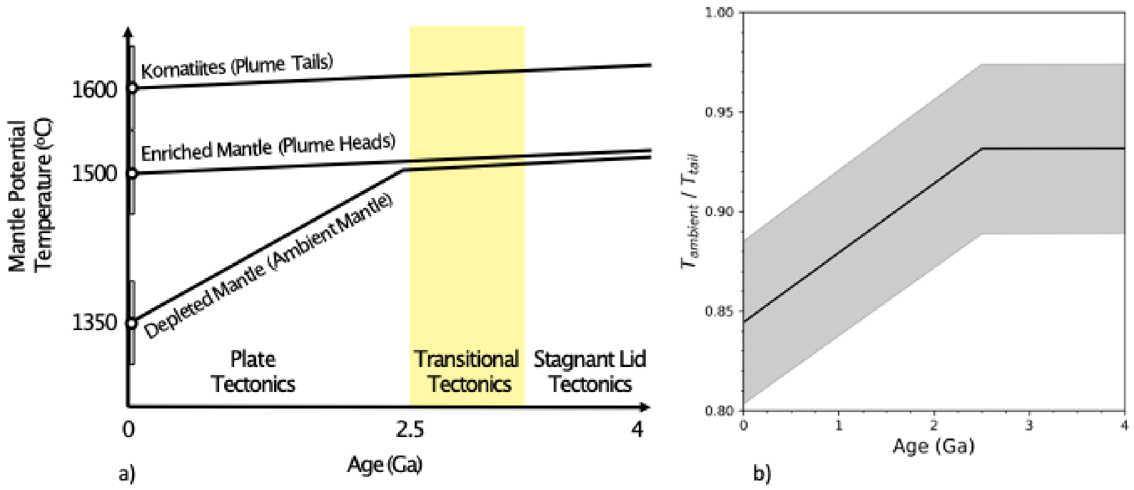


Figure 1: Petrological trends in ambient, plume head and plume tail temperatures indicating a thermal divergence between ambient and plume temperatures (modified from Condie et al. [2016]).

paper will test that hypothesis. A tectonic transition hypothesis adds complexity as it involves not only understanding plate tectonic cooling but also the processes that lead to a tectonic transition. The uncertainties associated with that added complexity will make testing/refuting a tectonic transition hypothesis more difficult [Popper, 1962]. Our choice to present and test the simpler hypothesis is an application of Occam's razor. It also relates to a null hypothesis for the tectonic history of the Earth attributed to Kevin Burke [Harrison, 2020]: "Assume plate tectonics operated until we have evidence that it wasn't." A thermal divergence has been assumed to be that evidence but we will show that the petrological data behind it are compatible with the operation of plate tectonics over geologic time.

2 Conceptual Arguments and Numerical Experiments

The Earth's mantle cools by convective heat transfer. The tectonic expression and cooling efficiency of mantle convection can vary [Lenardic, 2018]. Plate tectonics exemplifies convection in an active lid mode. The entire upper thermal boundary layer, the oceanic lithosphere, participates in convective overturn and mantle cooling. Single plate planets operate in a stagnant lid mode; the coldest portions of the lithosphere do not participate in convective overturn [Moresi and Solomatov, 1998], reducing the cooling rate relative to an active lid mode. Invoking a tectonic transition to explain a thermal divergence [Condie et al., 2016] stems from the idea that a transition from a stagnant to active lid mode could enhance mantle cooling. It also stems from the idea that a single tectonic mode over time cannot lead to divergences.

Mantle cooling scales with the vigor of mantle convection, expressed in terms of a Rayleigh number: a ratio of forces that drive convection to those that resist it [Schubert et al., 2001]. A combination of internal heating and heat flowing from the core into the mantle drive convection. Two heating sources allow two Rayleigh numbers to influence mantle convection. A bottom heated Rayleigh number depends on the temperature drop from the core-mantle boundary to the Earth's surface. An internal heating Rayleigh number depends on the concentration of radiogenic elements within the mantle [Moore, 2008]. If the two Rayleigh numbers can evolve with a level of independence, then plume and ambient mantle temperatures could diverge without a tectonic transition being required.

The range of potential cooling paths in mixed heating convection can be illustrated via numerical experiments/models. Figures 2 and 3 show results from several suites of numerical experiments. The suites follow from the study of Lenardic et al. [2021] (full model equations and solution procedures can be found in that reference). Models are formulated in terms of a basal heating Rayleigh number (Ra) and a ratio of the internal to basal heating Rayleigh numbers (H). The two non-dimensional parameters are defined as:

$$Ra = \frac{\rho g \alpha \Delta T D^3}{\kappa \eta} \tag{1}$$

and

$$H = \frac{\rho H^* D^2}{k \Delta T} \tag{2}$$

where ρ is density, g is the acceleration due to gravity, α is thermal expansivity, ΔT is the driving temperature across the mantle, D is the thickness of the mantle, κ is the thermal diffusivity, η is the mantle viscosity, H^* is the concentration of internal mantle heat production (in units of Wkg^{-1}), and k is the thermal conductivity.

Modeled internal temperatures show that enhanced cooling could occur along different convective pathways. Figure 2 presents geotherms as a function of Ra, H, and convective mode. The geotherms indicate that a transition from stagnant to active lid convection could increase the cooling rate of the ambient mantle; the plate tectonic geotherm associated with an Ra value of 10^6 and an H value of 10 (Figure 2b) was significantly cooler than the equivalent stagnant lid geotherm (Figure 2e). Geotherms also show that declining H in a continuous active lid regime with declining Ra produced increased cooling rates; changes in H lead to greater geotherm divergences at lower values of Ra, indicative of an increased cooling rate with declining H.

Any hypothesis applied to the data of Figure 1a must also account for the existence of mantle plumes

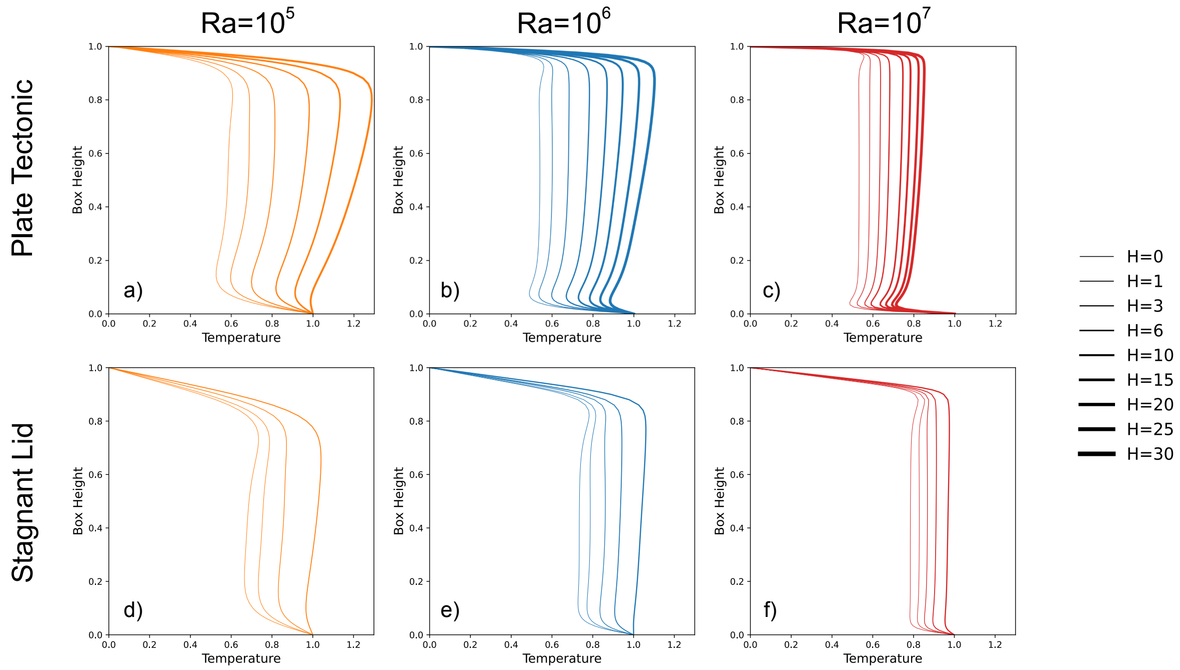


Figure 2: Geotherms for plate tectonic and stagnant lid convection models with different Ra and H values.

and the maintenance of a geodynamo over geologic history. The two are related. Heat flowing from the core into the base of the mantle leads to a lower thermal boundary layer, the source for mantle plumes.

The geotherms in Figure 2 show how internal heating could impact the lower thermal boundary for different convective modes. Increasing H increased the internal temperature and decreased the temperature drop across the lower thermal boundary layer, regardless of Ra or mode. A large enough increase in H eliminated the lower thermal boundary layer. This effect occurred for the lowest Ra suite of plate tectonic models and in every Ra suite of stagnant lid models. The geotherm of the stagnant lid model associated with an Ra value of 10^6 and an H value of 6 demonstrates the tipping point: the geotherm is vertical at its base. This is an insulating boundary. Heat does not enter the base of the mantle. As such, plumes are not generated. These results are consistent with arguments that Earth-like mantle plumes are not likely to exist on single plate planets [Nataf, 1991, Lenardic and Kaula, 1994, Jellinek et al., 2002].

Figure 3 further demonstrates the difficulty with invoking stagnant lid behavior to explain mantle thermal plume trends: small increases in H promoted rapid weakening of plumes, preventing them from reaching the upper mantle. The thermal fields in Figure 3 come from experiments with $H = 6$ and the indicated Ra value. The top row of Figure 3 shows that, in active lid convection, plumes originated at the base of the model and rose through the interior to the upper boundary. This was not the case for all stagnant lid models (bottom row of Figure 3). Increasing H values weakened plumes, initially preventing

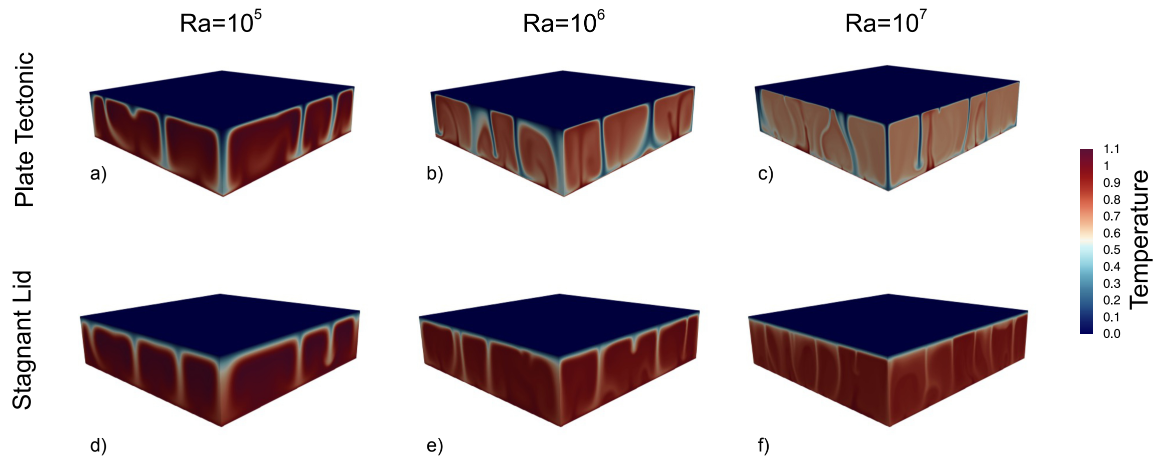


Figure 3: Three-dimensional renderings of the cartesian 4x4x1 convecting models. Figures a-c are plate tectonic and Figures d-f are stagnant lid. All renderings are for the stated Ra value and a value of H=6.

their rise to the mantle surface before suppressing plumes all together when heat flow into the mantle ceased.

Adding complexities to the base level models could potentially allow for plumes in a stagnant lid mode. Our intent is not to argue against that potential, but to hold to the Occam's razor approach and note that the models presented show that maintaining plumes in an active lid mode requires fewer added complexities (fewer free parameters) relative to a stagnant lid mode. Similar considerations hold for matching constraints on core-mantle boundary (CMB) heat flux.

Maintaining a geodynamo requires a minimum CMB heat flux [Buffett, 2002]. The low basal heat flux associated with stagnant lid models (Figure 2) has been argued to be a reason why a long-lived geodynamo is difficult to maintain on a single plate planet [Nimmo, 2002]. Maintaining a minimum core heat flux in the Earth's past, when H values were higher, is less of a problem for active lid convection. For active lid convection, increasing H leads to an increasing subadiabatic thermal gradient in the mantle (Figure 2a-2c), the result of emplacing cold upper thermal boundary layer, an analog for subducting slabs, at the base of the mantle. A subadiabatic gradient maintains a higher core heat flux then would be inferred based solely on the temperature difference between plumes and ambient mantle.

The illustrative examples of this section show that changes in mantle cooling rate can occur without tectonic transitions. They also show that continuous plate tectonics encounters fewer potential problems, relative to a tectonic transition hypothesis, for maintaining plumes and a geodynamo. The next section will quantify the ability of continuous plate tectonics to account for the data or Figure 1 and for CMB heat flux constraints.

3 Quantitative Scaling Analysis

Even with only two-nondimensional parameters, H and Ra, a range of thermal paths are possible over Earth's history. We could run numerical experiments to map the full range of model behavior, but that is unnecessary. Moore [2008] developed theoretical scaling relationships that predict how thermal outputs should vary with H and Ra for mixed heating convection in an active lid mode. The theory has been extensively tested against numerical convection experiments in both 3-D Cartesian [Lenardic et al., 2021] and 3-D Spherical modeling domains [Weller et al., 2016, Weller and Lenardic, 2016]. We can use the theory, calibrated to a spherical geometry in line with Earth mantle dimensions, to test the ability of continuous plate tectonics to account for observational constraints.

The theoretical scalings of Moore [2008] predict ambient mantle temperatures and thermal boundary layer temperature structures. Combining the scaling relationships for upper mantle temperature and basal boundary layer structure leads to a scaling prediction for the ratio (R_{ap}) of ambient mantle ($T_{ambient}$) to plume tail temperature (T_{plume}), assuming that T_{plume} will track the average temperature within the lower thermal boundary layer. The theory also predicts non-dimensional basal heat flux (Nu_b), which can be compared with constraints on core heat flux needed to maintain a geodynamo. The pertinent scaling relations are given by

$$R_{ap} = \frac{T_{abmient}}{T_{plume}} = \frac{0.19 + 1.62\ H^{3/4}\ Ra^{-1/4}}{0.595 - 0.516\ H^{3/4}\ Ra^{-1/4}}. \tag{3}$$

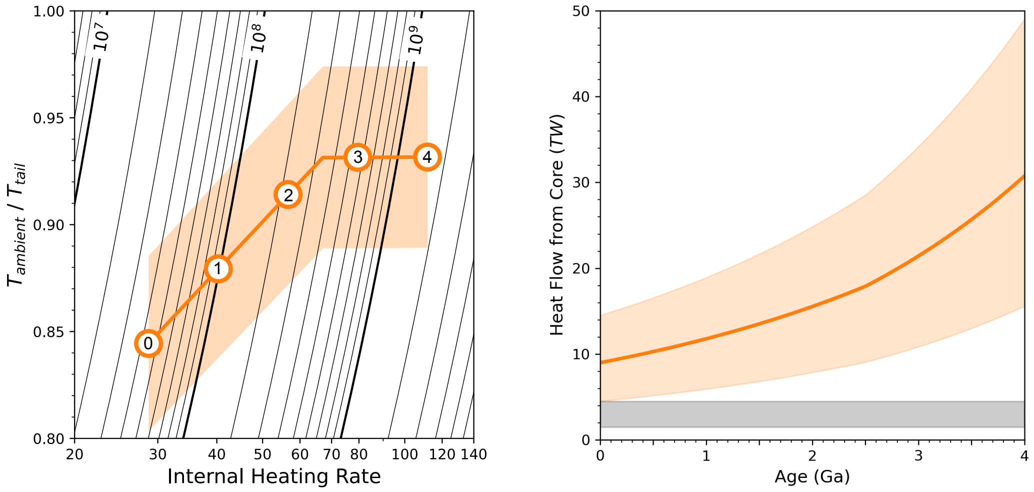
$$Nu_b(Ra, H) = 1 - 0.231H + 0.112(Ra - Ra_c)^{0.354} \tag{4}$$

where Ra_c is the critical Rayleigh number [Schubert et al., 2001]. The scalings explicitly account for a non-adiabatic thermal gradient in the mantle and its increase with increasing H.

Hypothesis testing requires dimensional values. Heat flux can be dimensionalized using estimates of present-day core heat flux into the mantle [Buffett, 2002, Lay et al., 2006]. Added dimensionalization requires constraints on the mantle heat ratio (H) over geologic history. The estimated present day heat production (H_o) within the bulk silicate Earth (BSE) is 7.38 x 10^{-12} Wkg^{-1} [Turcotte and Schubert, 2014]. The amount of heat produced within Earth's interior at any time (H^*) can be treated as

$$H^*(t) = H_o exp(\lambda t) \tag{5}$$

where λ is a decay constant, taken as $3.4\ x\ 10^{-10}\ yr^{-1}$ [Turcotte and Schubert, 2014], and t is the age of Earth in years before present. We assume that plumes originate from a thermal boundary layer just above the CMB. Figure 1a shows that plume tail temperatures have not varied much over Earth's history. Near constant plume tail temperatures can be achieved if the CMB temperature also remains nearly constant. Neglecting adiabatic effects, this suggests a temperature drop across the mantle (ΔT) of 1700 K, the value we use in this initial analysis. The remaining constants in Equation 2 take the values: $\rho = 3300\ kgm^3$, $D = 2900\ km$, and $k = 4.2\ W(mK)^{-1}$. The value of H is found to have dropped from 112 to 29 over the past four billion years. Different estimates for H constraints can be applied for what follows but, as will be shown, uncertainties in the petrological data will allow for a wide range of H history paths that are consistent with the hypothesis that continuous plate tectonics can match thermal divergence constraints.



(a) (b)

Figure 4: The predicted Ra values over Earth's most recent four billion years (a) with numbered circles indicating the age in billions of years ago; (b) the estimated heat flow from the core (orange region) redimensionalized using a present day uncertainty of 5-13 TW and previous constraints on heat flow needed to maintain a geodynamo (gray region).

Figure 4a shows the predicted R_{ap} values in $Ra - H$ space along with a cloud of trajectories that can account for the data of Figure 1. Data consistent trajectories were calculated by constraining Equation 3 to match data ratios (Figure 1b) and estimated H values, producing an estimate of Ra values over the interval of 0 to 4 Ga. A constant CMB temperature does not imply a constant Ra. Changes in Ra are dominated by changes in mantle viscosity. The required decline of Ra between 4 and 2.5 Ga is consistent with increasing viscosity due to mantle cooling. The milder decline of Ra between 2.5 Ga and present day is consistent with models and data constraints on deep-water cycling [Seales and Lenardic, 2020b, Parai and Mukhopadhyay, 2018]. Both indicate a switch from preferential dewatering to rewatering of the mantle at 2.5 Ga. Hydrating the mantle would tend to decrease mantle viscosity [Li et al., 2008]. A net rewatering, then, would offset the tendency of mantle cooling to increase viscosity in the face of decaying radiogenics. Collectively this would lead a milder decline of Ra consistent with the results of Figure 4a. The data consistent $Ra-H$ paths of Figure 4a can be substituted into Equation 4 to calculate a predicted basal heat flux and associated core heat flow (Figure 4b). The estimate always exceeded the minimum threshold, based on Nimmo [2002], needed to maintain a geodynamo (gray band).

A final constraint is that mantle plumes must remain strong enough to rise through the mantle and generate melt. The theory of Moore [2008] did explicitly consider how thermal plumes impinging on the base of the lithosphere affected the scaling of surface heat loss. This was extended by Lenardic et al. [2021] to consider the role of plume impingement on plate velocities. Both studies made predictions for H and Ra values where plume impact on the base of the lithosphere would not have an effect on scalings (see also Lenardic and Moresi [2003] for related results). Those values can be used to determine H and Ra combinations that allow plumes to rise to the base of the lithosphere. The $Ra - H$ trajectories of Figure 4a, consistent with the data of Figure 1, all meet the conditions needed for plumes to rise through the mantle.

4 Conclusions

Numerical experiments and scaling analysis show that changes in mantle cooling rates and thermal divergences, inferred from petrological data, do not require a tectonic transition during Earth geologic history; the continuous operation plate tectonics, in a mixed heating mantle, can satisfy petrological constraints, maintain plumes over geologic history, and satisfy core heat flux constraints.

Although our analysis highlighted difficulties with invoking a single plate early Earth, our intent was not to rule out tectonic transitions. Given uncertainties in observational data, for events/processes that occurred billions of years ago, and uncertainties inherent to thermal-tectonic history models [Seales et al., 2019, Seales and Lenardic, 2020a], it should not be a surprise if multiple hypotheses/models could be consistent with data constraints of the type in Figure 1. This becomes all the more likely for complex models that involve a number of free parameters and/or poorly understood processes; such models are subject to overfitting, making refutation via observational data difficult, if not impossible [O'Neill, 1973, Lever et al., 2016].

This above is not unique to studies of the Earth's deep past. It has motivated the use of Occam's razor – prefer the simpler hypothesis - to discriminate between multiple hypotheses that can match observations. The Occam's razor version of our conclusions is that the operation of a plate tectonic mode of convection, in a mixed-heating mantle, is the simplest hypothesis, to date, that has been shown to be quantitatively consistent with the data of Figure 1. The simplicity is reflected in the fact only two non-dimensional parameters come into play and that an analytic theory allows variable dimensionalization assumptions to be easily explored.

Observations, beyond the data in Figure 1, will likely continue to be used to argue for tectonic transitions. We end with a suggestion, in line with Harrison [2020], that there is, at a minimum, an onus to consider the degree to which the operation of plate tectonics could account for any such data. More ideally, that potential could be validated or refuted using some level of quantitative analysis akin to that of this paper.

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