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# Response to Comment on “Intermittent Plate Tectonics?”

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Korenaga takes issue with our proposal that intermittent plate tectonics provides a solution to the thermal catastrophe paradox, arguing that the heat flux in the absence of plate tectonics is too high. We show that this flux is small enough and changes rapidly enough in response to variations in slab flux to produce a reasonable thermal history back to at least 3 billion years ago.

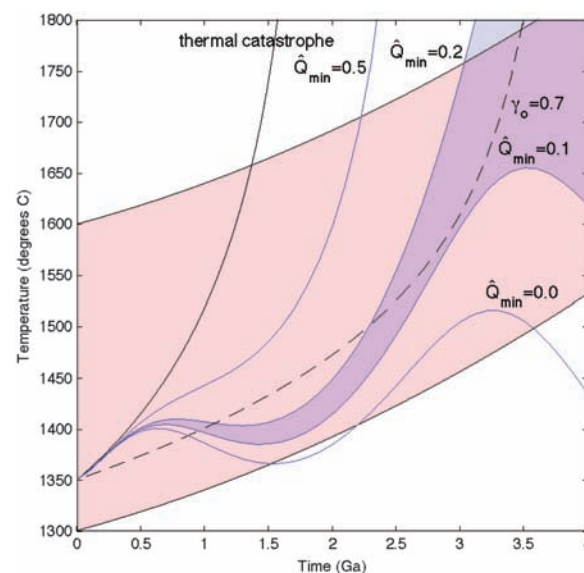
The realization that Earth may have lost heat more slowly in the past than at present has motivated the search for mechanisms to reduce the efficiency of plate tectonics in the past. Several mechanisms have been proposed, such as the resistance to subduction of thick plates (1) produced by deeper melting at higher mantle temperatures (2). We (3) proposed an alternative mechanism, namely subduction termination by continent-continent collision. Our basic argument is that if plate tectonics has worked at roughly half of its modern efficiency, through intermittency, this could explain the reduced loss of heat throughout Earth’s history.

The primary issue raised by Korenaga (4) is that we have underestimated Earth’s heat flux during periods without plate tectonics. Korenaga argues for a modification of our heat-flux parameterization for variable-efficiency plate tectonics [equation 1 in (4)] by introducing a term,  $Q_{min}$ , the heat flux in the absence of plate tectonics [equation 2 in (4)]. In using equation 1, we have implicitly assumed that  $Q_{min}$  is small and can be ignored, and equation 2 reduces to equation 1 in this limit. In contrast, Korenaga (4) argues that  $Q_{min}$  is sufficiently large that intermittent plate tectonics does not prevent “thermal catastrophe.” In this view, plate tectonics is only marginally more efficient than stagnant-lid convection in removing heat. The main issue, therefore, is the magnitude of  $Q_{min}$ . Korenaga suggests that for  $Q_{min}$  to be small (roughly an order of magnitude below present-day heat flux), the thermal boundary layer should be about an order of magnitude larger than its present value. Thus far, we agree with this assessment. He then argues that such an outcome is unlikely for two reasons: (i) there is an upper limit of ~100 km for the thickness of oceanic lithosphere, and (ii) even if lithospheric thickness could become thicker, it would take much longer for  $Q$  to approach  $Q_{min}$  than is assumed by our model. We address both of these points below.

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Our assumption that  $Q_{min}$  is small is based on extensive literature discussing heat flux associated with stagnant-lid convection (5–9). These studies show that for a given internal temperature, the difference in heat flux between plate-tectonic and stagnant-lid modes is greater than an order of magnitude [see figure 4 in (6)]. Indeed, Solomatov and Moresi (5) calculated a reduction by a factor of 5 in heat flux after an instantaneous change from plate tectonics to stagnant-lid tectonics for Venus [see figure 13 in (5)]. Thus, the maximum thickness of the thermal boundary layer is critical in determining the magnitude of heat flux during stagnant-lid convection. To illustrate this point, we show calculations of Earth’s thermal evolution for three cases in which the normalized heat flow during stagnant-lid periods (e.g.,  $\hat{Q}_{min} = Q_{min}/Q_{PT}$ ) is a factor of 0.5, 0.2, and 0.1 of the modern plate tectonic heat flow ( $Q_{PT} \sim 36$  TW) (Fig. 1). These cases correspond to effective boundary-layer thicknesses of ~100 km [the case considered in (4)], 250 km, and 500 km, respectively. We find that although  $\hat{Q}_{min} = 0.5$  results in “thermal catastrophe,” the other two cases are consistent with the available geologic evidence, particularly over the past 3 billion years where the calculated extrapolation from the present is most robust. Indeed, the predicted thermal evolution for  $\hat{Q}_{min} = 0.2$  is similar to that for a large initial Urey ratio (e.g.,  $\gamma_o = 0.7$ ), a model frequently proposed as a means by which “thermal catastrophe” could be avoided [e.g., (9)].



**Fig. 1.** Temperature versus time using equation 2 of Korenaga (4), for  $\hat{Q}_{min} = 0.5, 0.2,$  and  $0.1$  (blue curves), corresponding to effective lid thicknesses of ~100 km, 250 km, and 500 km, respectively. Solid black curve represents full plate tectonics with an initial Urey ratio,  $\gamma_o$ , of 0.3, which leads to thermal catastrophe at ~1.5 Ga. Although  $\hat{Q}_{min} = 0.5$  leads to thermal catastrophe at 2.3 Ga, the smaller values do not, for the interval 0 to 3 Ga, where extrapolation from the present is most accurate. Also shown, full plate tectonics with a high Urey ratio ( $\gamma_o = 0.7$ ), which has frequently been proposed as a means of avoiding a thermal catastrophe. Compared with (3), the plate tectonic efficiency function,  $P(t)$ , has been modified to extend over the full range from 0 to 1, so that the effect of  $\hat{Q}_{min}$  can be isolated. Light shading shows the probable range of mantle temperatures from geological constraints, and dark shading shows the range of probable trajectories for intermittent plate tectonics (i.e., between  $\hat{Q}_{min} = 0.1$  and  $\hat{Q}_{min} = 0.2$ ). Also shown is the curve for  $\hat{Q}_{min} = 0$ .

The question raised by Korenaga (4) is thus whether the thermal boundary-layer thickness in oceanic regions is limited to ~100 km. We contend that there is no strong evidence for this limit. There has been a long-standing controversy as to whether the half-space cooling (HSC) model or a plate model is more appropriate for Earth. Indeed, several studies [e.g., (10, 11)], including one by Korenaga (12), have argued that HSC is preferable. Moreover, even if such a limit currently exists, it is likely produced by plate tectonics itself. The strain-rate dependence of viscosity in the dislocation creep regime implies that as plate tectonics slows and ultimately stops, asthenospheric viscosity would increase and the lid thickness would grow. Indeed, the cratonic roots of continents, which are most removed from plate tectonic activity, approach thicknesses  $\geq 250$  km (13).

The second issue raised in (4) is the time scale over which the thermal boundary layer thickens. Korenaga assumes an instantaneous switch from plate tectonics to stagnant lid. However, our model for intermittent plate tectonics is tied to the long-term history of subduction. Slab flux does not instantaneously drop to zero in the Proterozoic but instead goes from a maximum at 2.5 billion years ago (Ga) to a minimum at 1.0 Ga. During this time, lid thickness should con-

tinually adjust to the lower slab flux as a Pacific-type ocean closes. If the Pacific closes in ~350 million years (My), then the maximum sea-floor age of the Atlantic would be ~550 My. This will result in an average effective boundary-layer thickness of ~130 km even before plate tectonics stops (14). After stoppage, the boundary layer would grow to ~250 km in ~260 My. Thus, the adjustment time for  $\hat{Q}_{\min}$  to decrease below ~0.2 (the likely maximum value for preventing thermal catastrophe) is much shorter than the time scale for variations in subduction flux. Clearly, theoretical work is necessary to more quantitatively constrain Earth's thermal evolution in the presence of time-variable subduction flux. Such calculations will likely require moving beyond the simplified evolution equation [equation 1 in (4)], which requires approximations in both functional form and in parameters such as  $\beta$ .

The final issue raised by Korenaga is the use of sea-level data to test for variations in lithospheric thickness. Although such tests are welcome, given the presently available data (only back to 500 Ma), the limitations on interpretability (i.e., other causes of sea-level change), and the possibly important role of dynamic topography, we do not feel that a definitive test is possible at the present time. Indeed, features such as the African Superswell (15) might be expected in

the internal ocean as the external ocean closes. The diminished contribution from slabs by decreased subduction flux could also produce a counteracting effect. Until such effects are carefully modeled, it will be difficult to make use of this constraint.

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14. Assuming HSC, we define the areally averaged heat flux  $\langle q \rangle$  for a pre-existing ocean basin as  $\int q(\tau(r)) dr / \int dr$ , where  $r$  is the distance from the ridge axis and  $\tau$  is the age of the sea floor at distance  $r$  when plate tectonics stops. For a constant spreading velocity,  $V$ ,  $\tau = r/V$ , and  $\tau$  ranges from 0 to the oldest sea floor,  $\tau_{\max}$ .  $\langle q \rangle$  can then be expressed in terms of  $\tau_{\max}$  and the time,  $t$ , subsequent to the cessation of plate tectonics as
 
$$\langle q \rangle = C \tau_{\max}^{-1} \int_0^{\tau_{\max}} (\tau + t)^{-1/2} d\tau, \text{ where } C = k\Delta T(\pi\kappa)^{-1/2},$$

$$\langle q \rangle = 2C\tau_{\max}^{-1} [(\tau_{\max} + t)^{1/2} - t^{1/2}].$$
 We use this expression in two ways. First, we determine the effective age,  $\tau_e$ , and effective thickness,  $h_e$ , at the time that plate tectonics stops ( $t = 0$ ). Second, we estimate the time,  $t$ , at which  $h_e$  reaches 250 km. Setting  $t = 0$  and writing  $\langle q(0) \rangle = C\tau_e^{-1/2}$  reveals that  $\tau_e = \tau_{\max}/4$  and  $h_e = h_{\max}/2$ . Thus, for  $\tau_{\max} = 550$  my,  $\tau_e = 138$  my and  $h_e = 132$  km. After the cessation of plate tectonics, the time necessary to reach  $h_e = 250$  km, can then be found by solving  $\langle q(t) \rangle / \langle q(0) \rangle = h_e(0)/h_e(t) = 132 \text{ km}/250 \text{ km}$ , which yields  $t \sim 260$  My.
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