Comment on "Intermittent Plate Tectonics?"

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Silver and Behn (Reports, 4 January 2008, p. 85) proposed that intermittent plate tectonics may resolve a long-standing paradox in Earth's thermal evolution. However, their analysis misses one important term, which subsequently brings their main conclusion into question. In addition, the Phanerozoic eustasy record indicates that the claimed effect of intermittency is probably weak.

By combining several geological and geochemical arguments, Silver and Behn (*1*) proposed that large fluctuations in the efficiency of plate tectonics have occurred over Earth's history, resulting in as much as an order of magnitude reduction in subduction flux. To quantify the effects of such fluctuations on Earth's thermal evolution, the authors proposed the following heat-flow scaling:

$$Q(t) = P(t)Q(T) = aP(t)T^{\beta} \qquad (1)$$

where $Q(t)$ is heat loss, $P(t)$ is the efficiency of plate tectonics, $a = 1.35 \times 10^{-19}$, and $\beta = 6.52$ [see SOM for (*1*)]. The function $P(t)$ can vary from 0 to 1, and with $P = 1$, the above scaling reduces to conventional scaling, which is known to be unable to reconstruct a reasonable thermal history unless Earth's internal heat production is much higher than geochemical constraints suggest (*2*, *3*). Silver and Behn argued that if $P(t)$ fluctuates from 1 to ~0.1 over a billion-year time scale [figure S1 in (*1*)], thermal catastrophe (unreasonably high mantle temperatures) may be avoided even with conventional scaling for $Q(T)$.

Their heat-flow parametrization (Eq. 1), however, appears to be oversimplified. It implies that convective heat flux should become zero ($Q = 0$) when plate tectonics ceases to operate ($P = 0$), but this is unlikely for at least two reasons. As a thought experiment, consider what would happen if plate tectonics is somehow suddenly terminated now. Whether the mantle is convecting or not, surface heat flux from the mantle is determined by the thickness of the top thermal boundary layer. With plate tectonic convection, for example, the thickness of the boundary layer is controlled by the speed of plate motion; faster convection means younger sea floor on average, resulting in higher heat flux. When we stop plate tectonics, on the other hand, new sea floor is no longer produced, and immobile lithosphere would gradually thicken by thermal diffusion as $2\sqrt{\kappa t}$ with surface heat flux of $k\Delta T/\sqrt{\pi\kappa t}$ (*4*), where κ is thermal diffusivity (~10^{-6} m^2 s^{-1}), k is thermal conductivity (~3.2 W m K^{-1}), and ΔT is a temperature contrast between the surface and the interior (~1350 K). Thermal diffusion in the solid Earth is a slow process. The present-day oceanic heat flux of 32 TW (*5*) corresponds to the mean boundary-layer thickness of ~48 km with an equivalent sea-floor age of ~18 million years (My) (not to be confused with the area-weighted average of sea-floor age, which is ~64 My). To reduce heat flux by half (i.e., 16 TW) by doubling layer thickness would take ~54 My, and to reduce heat flux to 8 TW would take ~270 My. A more detailed calculation with the actual two-dimensional distribution of sea-floor age gives essentially the same values as this simple one-dimensional estimate.

This boundary-layer growth would not continue indefinitely, because it is likely to be limited by convective instability (*6*). The physics of stagnant-lid convection becomes relevant, and its heat-flow scaling may be derived based on this convective stability (*7*). At the present-day condition, it is difficult for oceanic lithosphere to become thicker than ~100 km (*8*), so the minimum heat flux at the limit of stagnant-lid convection, which is likely to be a function of mantle temperature, would be ~10 to 15 TW. An order of magnitude reduction in heat flux at ~1 billion years ago (Ga), and at ~4 Ga proposed by (*1*) should be accompanied by an order-of-magnitude increase in the average thickness of top boundary layer (or oceanic lithosphere); lithosphere must become as thick as ~480 km, occupying the entire upper mantle and more. Such a situation is unrealistic given known mantle rheology (*9*, *10*);

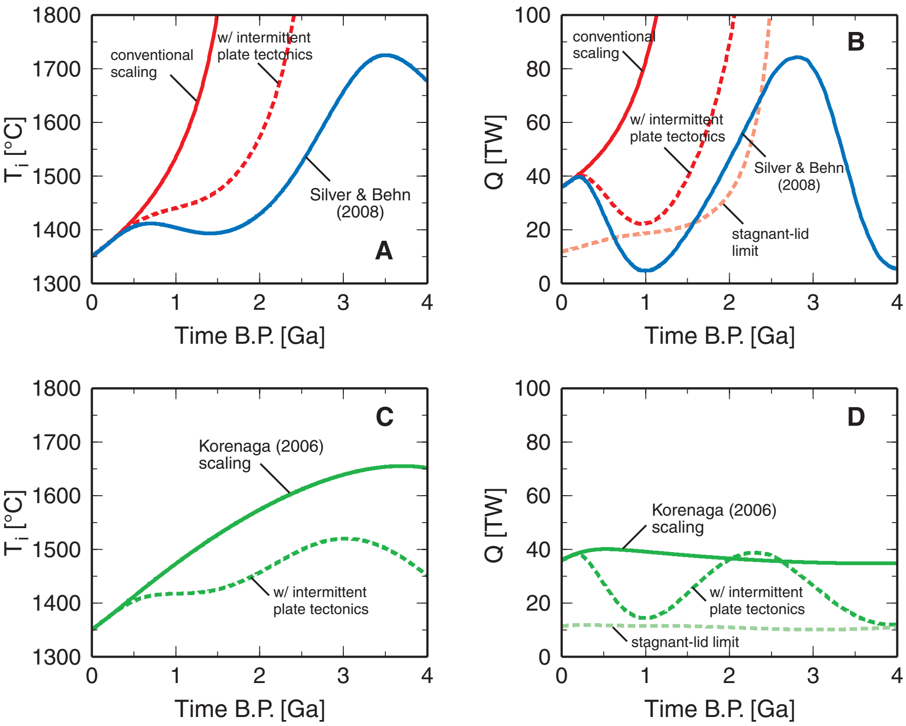

Fig. 1. Illustrative examples of thermal evolution modeling. Internal temperature T_i and surface heat flux Q are plotted as a function of time before the present. (**A** and **B**) Plots using conventional heat-flow scaling [$Q(T) = aT^{\beta}$, with $a = 1.35 \times 10^{-19}$ and $\beta = 6.52$] and the present-day Urey ratio of 0.3 (solid red curve). The effect of intermittent plate tectonics is also shown (dashed curve), using Eq. 2 and the efficiency function $P(t)$ proposed in (*1*). The stagnant-lid limit $Q_{min}(T)$ [dashed pink curve, shown in (B)] is calculated based on maximum plate thickness predicted with temperature-dependent viscosity only [see figure 5 in (*2*)], to be consistent with the assumed heat-flow scaling. The solution proposed in (*1*) (corresponding to Eq. 1) is shown in blue. (**C** and **D**) Plots using the heat-flow scaling of (*2*) with the present-day Urey ratio of 0.3. Maximum plate thickness assumed for the stagnant-lid limit incorporates the effects of mantle melting.

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even old continental lithosphere is not this thick (*11*). Even if the mantle is rigid and allows the indefinite growth of the boundary layer, it would not be instantaneous as indicated by Eq. (1), but would rather take about 2 billion years.

Perhaps a more physically sound parametrization is the following:

$$Q(t) = P(t)Q(T) + [1 - P(t)]Q_{\min}(T) \quad (2)$$

where $Q_{\min}(T)$ is heat flow expected for the stagnant-lid limit. This parametrization ignores the finite diffusion time required to reach the stagnant-lid limit but does provide the lower bound on surface heat flux, which is sufficient for discussion here. Figure 1A compares three cases with conventional heat-flow scaling and the present-day Urey ratio of 0.3. Even with the drastic variation of $P(t)$ as proposed in (*1*), thermal catastrophe still takes place around the beginning of the Proterozoic (dashed red) if modeled with the above parametrization. Large fluctuations in heat flux (and thus unrealistic boundary-layer growth) are prevented by the stagnant-lid limit (Fig. 1B). Silver and Behn's argument on subduction initiation suggests that they are aware of this regulated nature of boundary-layer thickness, but it is not reflected in the quantitative part of their analysis. Intermittent plate tectonics alone does not help to solve the long-standing paradox in Earth's thermal evolution.

Nevertheless, the concept of intermittency is still an interesting complication to be considered when modeling thermal evolution. I thus repeated the exercise with the heat-flow scaling of (*2*), which incorporates the effects of mantle melting beneath mid-ocean ridges. Intermittent plate tectonics does result in a more subdued thermal history (Fig. 1C), but this is accompanied by ~50% reduction in surface heat flux in the past 1 billion years (Fig. 1D). Such dramatic change in heat flux should correspond to a continuous fall in global sea level on the order of a few hundred meters (*12*), which contradicts available geological records for the Phanerozoic eustasy (*13*, *14*). Although the relation between sea level and oceanic heat flux can be complicated by several factors (*12*), the most important complication is usually dynamic topography associated with subduction (*15*). The reduced subduction flux assumed in (*1*) implies a minor role of such dynamic topography, so this discrepancy between model predictions and geological records may not be dismissed easily. Silver and Behn's claim for large fluctuations in the efficiency of plate tectonics is based primarily on the lack of geological records for the continuous operation of plate tectonics (because sea-floor records are all younger than 180 Ma) and indirect geochemical proxies, the interpretation of which is not unique. Plate tectonics does not have to be intermittent, and even if it were, the temporal variation of surface heat flux should be something physically realizable.

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