

Time variability in Cenozoic reconstructions of mantle heat flow: Plate tectonic cycles and implications for Earth's thermal evolution

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The thermal evolution of Earth is governed by the rate of secular cooling and the amount of radiogenic heating. If mantle heat sources are known, surface heat flow at different times may be used to deduce the efficiency of convective cooling and ultimately the temporal character of plate tectonics. We estimate global heat flow from 65 Ma to the present using seafloor age reconstructions and a modified half-space cooling model, and we find that heat flow has decreased by ~0.15% every million years during the Cenozoic. By examining geometric trends in plate reconstructions since 120 Ma, we show that the reduction in heat flow is due to a decrease in the area of ridge-proximal oceanic crust. Even accounting for uncertainties in plate reconstructions, the rate of heat flow decrease is an order of magnitude faster than estimates based on smooth, parameterized cooling models. This implies that heat flow experiences short-term fluctuations associated with plate tectonic cyclicity. Continental separation does not appear to directly control convective wavelengths, but rather indirectly affects how oceanic plate systems adjust to accommodate global heat transport. Given that today's heat flow may be unusually low, secular cooling rates estimated from present-day values will tend to underestimate the average cooling rate. Thus, a mechanism that causes less efficient tectonic heat transport at higher temperatures may be required to prevent an unreasonably hot mantle in the recent past.

global heat flow | mantle convection | plate reconstructions | seafloor spreading

Earth's heat loss is fueled by two dominant sources: (i) decay of radioactive elements within the planet's interior and (ii) secular cooling of the mantle (see reviews in refs. 1 and 2). Approximately 70% of Earth's total heat loss of ~46 TW occurs through oceanic lithosphere (ref. 2, referred to hereafter as J07) because it is the only part of the surface that actively participates in mantle convection. This component is also subject to the tectonic evolution of the ocean basins: the geometry of these basins and the organization of the plates within them change over the course of the Wilson cycle (e.g., refs. 3 and 4). If oceanic heat flow is sensitive to these changes, then global heat flow might have been different in the recent past. Temporal variations in Earth's heat flow have important implications for mantle dynamics and can influence parameterized models of Earth's thermal evolution (e.g., ref. 5, referred to hereafter as G05). New tectonic reconstructions of seafloor age (e.g., ref. 6, referred to hereafter as X06; see also refs. 7 and 8) present an opportunity to constrain the time variability of mantle heat flow directly and so provide new insights into the relationship between plate tectonics and Earth's thermal evolution.

Global heat flow is dominated by young oceanic crust, with minor contributions from older oceanic crust, plume activity, and continental radiation (see, e.g., discussion in J07). Recently erupted mid-ocean ridge basalt conducts heat into the oceans at rates that can exceed 475–510 mW/m² (e.g., refs. 2 and 9). As the seafloor spreads away from ridges, oceanic crust is continuously cooled, resulting in a decrease in heat flow away from the ridge.

Half-space cooling models relate heat flow to the age of oceanic crust, and young oceanic crust (<80 Ma) has been found to transport heat proportional to the inverse square root of its age (10, 11). For reasons that are still debated, old oceanic crust departs from half-space cooling at ~80 Ma and emits a relatively constant heat flow of ~48 mW/m² (e.g., refs. 9 and 12–14). Assuming these features hold for the past, we can use models of reconstructed seafloor age to estimate past oceanic heat loss and hence infer the history of heat transport efficiency.

Secular cooling histories for the Earth can be estimated by parameterized convection models (e.g., refs. 15–17). In these models, heat flow is calculated by using scaling relationships from boundary layer analysis in the form of $Q = C(L) Ra^\beta$ (e.g., refs. 15 and 16). Q is total convective surface heat flow, and $C(L)$ is a factor that is often assumed constant but may depend on convective wavelength L (5). Ra is the Rayleigh number for convection in the mantle, and β determines the sensitivity of surface heat flow to changes in convective vigor; $\beta = 1/3$ for thermal or plate convection (see, e.g., review in ref. 18, referred to hereafter as K06). We can characterize secular cooling via the Urey ratio, $\gamma(0) = H(0)/Q(0)$, where $H(0)$ is the radioactive heat production in the convecting mantle at present time ($t = 0$) divided by the total convective heat flow $Q(0)$. Using proposed cosmochemical abundances of radioactive elements in the Earth yields $\gamma(0) \sim 0.3$ (e.g., refs. 18–20). Here the radiogenic heat produced in the crust (~8 TW; J07) is not taken into account because it is not part of convective heat transport. These estimates of the Urey ratio suggest that ~70% of present-day heat loss represents secular cooling. This cooling rate is too fast to be consistent with other constraints on Earth's thermal history: for example, $\gamma(0) \sim 0.3$ coupled with $\beta = 1/3$ produces very hot mantle temperatures (the "thermal catastrophe") at ~2 Ga if present-day mantle temperatures are to be matched (16, 17, 21). Several lines of evidence imply that the Earth was not in an entirely molten state and that temperatures were not more than ~40% higher than today back to ~4 Ga (e.g., ref. 22). To push the thermal catastrophe back to the first billion years of Earth's lifetime, Christensen (17) found that a Urey number of 0.85 is required: only 15% of Earth's current heat flow can represent secular cooling if $\beta = 1/3$.

Many authors have proposed reduced or temperature-dependent values for β to solve this problem (e.g., ref. 17). For example, viscous bending at subduction zones (23) or other rheological limits (24) may restrict the efficiency of convective heat transfer and decrease the value of β to below 1/3 (23).

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Abbreviation: Myr, million years.

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Petrological effects in a hotter Earth may further limit efficiency, leading to a negative β (25). Alternatively, the abundance of heat-producing elements in the mantle could be larger than suggested by cosmochemical studies and direct measurements of mid-ocean ridge basalts. If an additional reservoir of heat-producing elements is buried in the lower mantle, either in a deep abyssal layer (26) or within “blobs” that do not mix with the rest of the mantle (27), then the Urey number would be greater than $\gamma(0) \sim 0.3$, which could prevent thermal catastrophe in the recent past. Recent work by Lyuetskaya and Korenaga (28, 29) and Zhong (30) demonstrates that many aspects of the radiogenic budget are still debated. Other constraints on mantle cooling, e.g., from petrology, are also nonunique and have recently been revised downward so that typical estimates for cooling are now thought to be approximately ≤ 100 K/Gyr (e.g., ref. 22).

Assuming that heat sources, and thus low values for the present-day $\gamma(0)$, are relatively well constrained, and if the “ $\beta = 1/3$ ” type of plate tectonic heat transport efficiency holds, another way to avoid the thermal catastrophe is to invoke time-variable heat flow (5). The dominating factor controlling heat flow variations may be changes in the convective wavelength associated with supercontinental assembly and dispersal (5, 31, 32). G05 shows that Earth’s thermal history can be explained if the present-day heat flow is relatively high compared with the mean heat flow over long periods of time because such a situation could lead to an underestimate of the present-day Urey number. We evaluate this possibility using available plate tectonic reconstructions for the Cenozoic. Our approach utilizes information about past spreading rates and plate configurations to infer changes in surface patterns of convection, which control the time dependence of heat flow. This is an alternative to the model by Labrosse and Jaupart (31), who assume that present-day seafloor age distributions hold for past configurations of plate tectonics.

Time Variability of Heat Flow

By applying the modified half-space cooling model of J07 to the seafloor age reconstructions of X06, we estimate patterns of mantle heat flow as a function of time (Fig. 1). Using our model, we estimate total heat flow of ~ 27 TW in the oceanic regions and ~ 41 TW for the globe at present. These values are slightly smaller than the estimates of J07 and could be fine-tuned by adjusting integration parameters. However, such fine-tuning is unnecessary because we are only interested in relative changes. Fig. 1 shows results back in time based on both the Gordon and Jurdy (33) and Hall (34) reconstructions. It is apparent that the largest variations in heat flow are associated with young seafloor and changes in the distribution of ridges and primarily result from changes in the configuration of plates in the Pacific basin. Furthermore, the differences between the two plate reconstructions have a major effect on heat flow estimates (Fig. 1). This uncertainty in the age reconstruction can be expected to dominate other uncertainties, such as the choice of cooling model. Errors based on plate reconstructions will be even more severe for times earlier than 65 Ma (6).

Because the oceanic contribution dominates the change in global heat flow, we will focus on oceanic plates. Fig. 2 shows the relative change of total oceanic heat flow versus time as computed from the reconstructions of Fig. 1. Although estimates of absolute heat flow are clearly uncertain, both plate reconstructions predict a decrease in heat flow since 65 Ma, with some second-order variations that are likely to be insignificant. We note that a reduction in oceanic heat flow is observed despite an increase in total oceanic area during the Cenozoic of $\sim 8\%$ (6); the recognized decrease in continental area is a result of the Alpine–Himalayan collision.

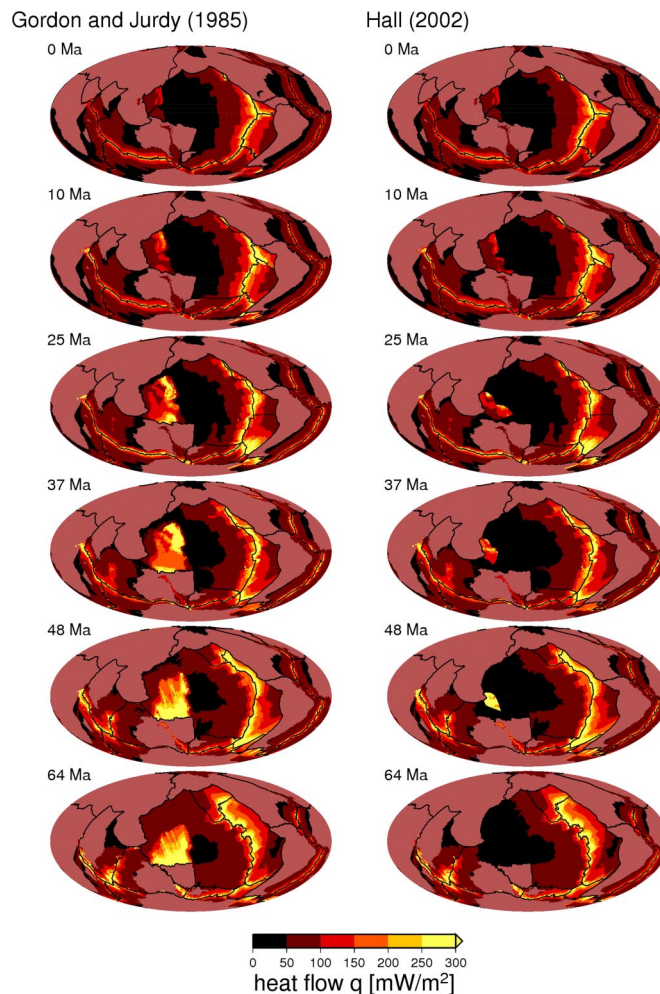


Fig. 1. Global estimates of surface heat flow at different times based on Xu *et al.* (6) age reconstructions and a modified half-space cooling model (2). (Left) Based on Gordon and Jurdy (33) plate reconstructions. (Right) Based on Hall (34) plate reconstructions. The uniform pale red color indicates the assignment of a constant heat flow of 65 mW/m^2 in the continents.

The solid and dashed lines in Fig. 2 are linear regression fits and correspond to average rate of heat flow change, d , since 65 Ma of $d = -0.14\%$ every million years (Myr) and $d = -0.43\%$ every Myr for the Hall (34) and Gordon and Jurdy (33) based reconstructions, respectively (Fig. 2). Substituting the GDH1 model from Stein and Stein (9) produces negligible differences in d , and the individual uncertainties of the best-fit d values are smaller than the systematic difference between the plate reconstructions. The heat loss calculations are clearly affected by uncertainties in the X06 reconstructions (cf. X06 for a detailed discussion of the error associated with this type of reconstruction). However, assuming that the more recent plate reconstructions based on the regional refinement of Hall (34) yield a better representation of the true seafloor age distribution in the past, we infer a change in heat flow of approximately -0.15% per Ma. We note that all of our estimates are based on the assumption that seafloor age distributions, to which heat flow would be most sensitive, change over time, a hypothesis contested by some (cf. refs. 35 and 36) but supported by others (e.g., refs. 37 and 38).

The absence of published error estimates for plate reconstructions makes a statistical significance analysis beyond Fig. 2 essentially impossible. The general trends seen in Fig. 1 and an analysis of the inferred age distributions point to the Pacific–Farallon ridge,

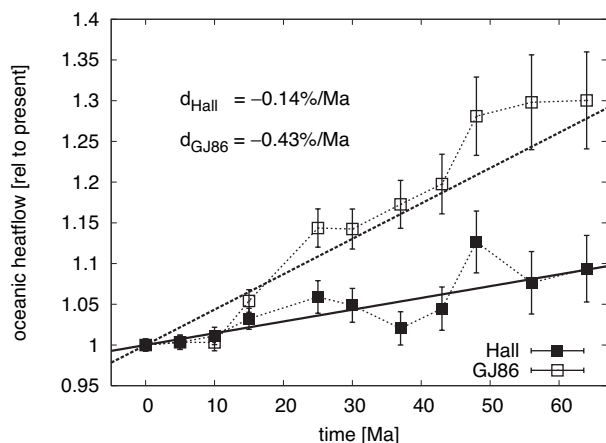


Fig. 2. Temporal variation of the globally integrated heat flow based on the estimates from the two plate tectonic reconstructions as shown in Fig. 1. For regions with half-space cooling-derived heat flow ($q = C_A t^{-1/2}$), we performed an integration over seafloor age by summing over 1-Myr age integrals and multiplying each of these integrals by the area of seafloor within that age interval. Error bars for each heat flow estimate are computed by assuming progressively increasing uncertainty in these area estimates as described below. Filled square symbols (Hall) are for Xu *et al.*'s (6) reconstruction based on Hall (34), and open squares (GJ86) are based on Gordon and Jurdy (33). Solid and dashed lines are best-fit linear trends with rates, d , of relative change in total oceanic heat flow as specified in the key.

which is nearly halved in length through the Cenozoic, as the primary cause of the decrease in heat flow inferred from the Hall (34) reconstruction (Fig. 2). Whereas reconstructions of ridge systems that have been entirely subducted (e.g., Kula–Farallon at 64 Ma) are uncertain (4), the shortening of the Pacific–Farallon ridge system is evident even in present-day seafloor ages (38). To invalidate the null hypothesis of constant heat flow during the Cenozoic, future work should include a comprehensive analysis of the range of age distributions compatible with the constraints from plate reconstructions.

Changes in Tectonic Styles and Length Scales

Seafloor area–age distributions determine the net oceanic heat flow and are products of past spreading rates and plate geometries (e.g., refs. 31 and 35). Moreover, G05 have suggested that changes in the aspect ratio of convective cells reflect variations in heat transport efficiency. Because such variations should emerge from oceanic plate reconstructions, we have measured plate and ridge length scales as a function of time. Although such geometric quantities are more indirect proxies for heat flow, they can be determined with greater certainty than age distributions for times older than 65 Ma. Furthermore, because these measures are not based on the age reconstruction itself, they can provide independent constraints on trends that determine changes in heat flow during the Cenozoic. Because plate reorganizations that are relevant to heat flow changes during the Cenozoic and earlier have mainly occurred within the Pacific basin, we focus our analysis there. These geometrical arguments assume that ridges and trenches are good proxies for convective wavelength, whereas in fact the interplay between plume-like upwellings, slabs, and oceanic seafloor production may be more complicated. Although ridges are passive features, they nonetheless largely control the oceanic heat flow.

We computed maps of the distance to the nearest ridge for the Pacific basin (Fig. 3) using the Cenozoic reconstructions of Gordon and Jurdy (33) and the Mesozoic plate reconstructions of Lithgow-Bertelloni and Richards (39). These maps demonstrate how changes in the geometry of the plates affect the

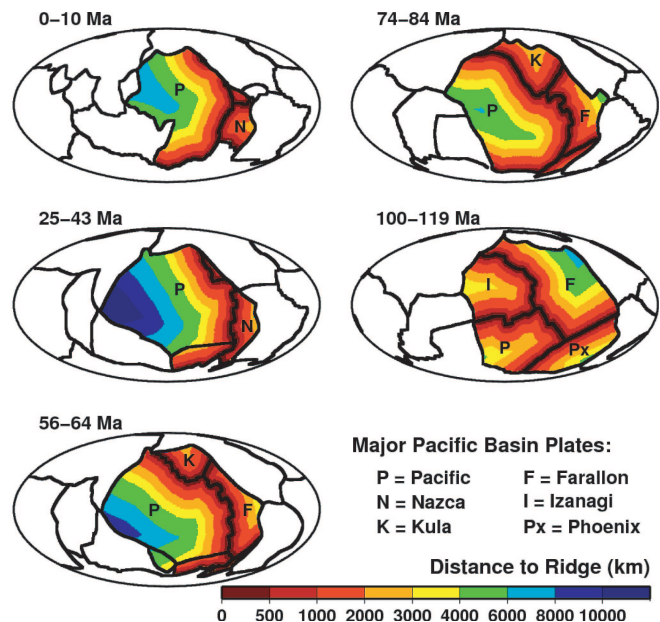


Fig. 3. Cenozoic and Mesozoic evolution of the Pacific basin as characterized by seafloor distance to the nearest mid-ocean ridge. Notice the progression from four relatively small plates to one large plate and compare with Fig. 1. Maps were created after Lithgow-Bertelloni and Richards (39).

seafloor age distribution (cf. Fig. 1). For example, the area-weighted mean and median distance to a ridge (Fig. 4*a*) show an overall increase in Pacific tectonic length scales since 120 Ma. Longer convective wavelengths are less efficient at convective heat transport and thus produce lower heat flow (5). Thus, decreasing Cenozoic heat flow (Fig. 2) could reflect a transition to longer convective wavelengths.

The peak in seafloor-to-ridge distance at ~40 Ma (Fig. 4*a*), however, indicates that the average and median ridge distances do not entirely control total heat flow at any given time. Instead, heat transport is dominated by younger oceanic crust. Fig. 4*b* demonstrates that the area of seafloor close to a ridge in the Pacific has been decreasing with time. Although all intervals show a decrease in seafloor area since 120 Ma associated with the loss of Pacific area to the Atlantic basin, the decrease in area close to a ridge (within, say, 2,000 km from a ridge) has been most rapid. This feature is associated with the general trend toward shortening of the Pacific ridge length (Fig. 3) and a reduction in spreading rates in the Pacific and is consistent with the observed decrease in heat flow with time. Trends of heat flow decrease between 65 and 120 Ma are based entirely on this analysis of tectonic reconstructions and are confined to the Pacific basin. Without global data sets that span back to 120 Ma, constraints for other oceanic basins are difficult to obtain, and uncertainties are unavoidable. However, ocean basins outside of the Pacific are not likely to contribute much to changing heat flow because of the scarcity of subduction zones in these regions (cf. ref. 40). Subduction zones are necessary to produce high heat flow variation because they essentially allow the replacement of old oceanic crust with young, hot oceanic crust. Thus, focusing on the Pacific basin, where the majority of subduction has taken place since 120 Ma, is reasonable when estimating heat flow variability.

Earth's Thermal Evolution

Continuing the trend of reduced heat loss displayed in the Hall-based model (34) of Fig. 2 at a rate of $d \sim -0.15\%$ every Myr would result in zero heat loss in ~700 Myr; it is thus

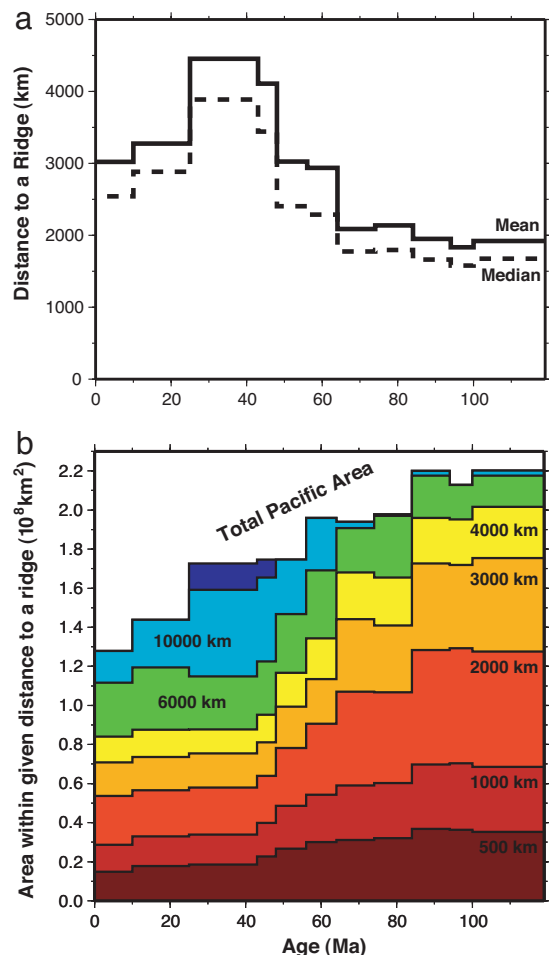


Fig. 4. Distribution of seafloor with distance from a mid-ocean ridge showing mean (solid line) and median (dashed line) seafloor distance-to-ridge measurements calculated by using seafloor reconstructions (39) as in Fig. 3 (a) and distribution of Pacific seafloor within a given distance from a mid-ocean ridge through time (b). The reduction in “ridge-proximal” oceanic crust since 120 Ma is consistent with the reduction in heat loss shown in Fig. 2.

implausible that this change represents a smooth trend. To quantitatively compare our d rates, we conducted several parameterized convection experiments inspired by the work of G05. We assume for simplicity that models of time-averaged oceanic plate behavior are meaningful tools for understanding heat transport in the mantle while acknowledging that effects such as variable continental cover (e.g., refs. 5 and 41) or subduction complexities (e.g., ref. 24) may modify convection. We are not attempting to construct the “ultimate” evolution model for Earth based on heat flow variations over the last 65 Ma but merely wish to put the rates of change into a general context.

We follow K06 in choosing parameters relevant to the temporal evolution of internal heating, temperature-dependent viscosity, and neglect of the core. We start the numerical integration at a present-day asthenospheric temperature, T , of 1,350°C and evaluate the volume-averaged energy equation backward in time to 4.5 Ga. The ratio of heat generation by internal heating compared with the surface heat flow is then explored by testing different present-day Urey ratios, $\gamma(0)$.

Fig. 5 shows the evolution of T and Q for four models with different assumptions about plate tectonic efficiency and $\gamma(0)$. “Thermal convection” uses the canonical $\beta = 1/3$; the choice of

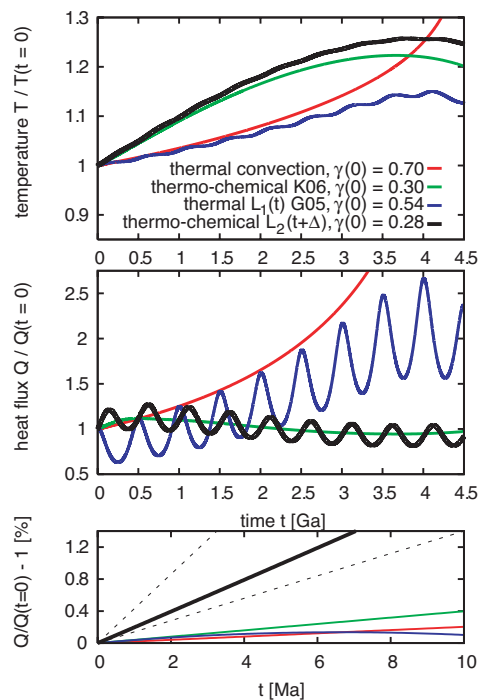


Fig. 5. Thermal mantle evolution for different parameterized convection experiments. *Top* and *Middle* show mantle temperature, T , and total surface heat flow, Q , normalized by the present-day values, respectively. *Bottom* displays zoomed-in relative variations in normalized heat flow for the most recent 10 Ma along with our upper (GJ86) and lower (Hall) bound estimates heat flow change d from Fig. 2. Thermal evolution models are computed by backward integrating the volume-averaged mantle energy equation from the present day by using the heat-producing elements and the general formulation as in Korenaga (18). The key specifies the models as explained in the text, along with the present-day Urey ratio, $\gamma(0)$.

an unrealistically large Urey number [e.g., $\gamma(0) = 0.7$] is then mandated if T is to remain within 30% of its present-day value for all times (e.g., discussion in ref. 18). “Thermochemical K06” uses the modified heat flow scaling with negative β for high temperatures that was suggested by K06, reproducing that author’s results for $\gamma(0) = 0.3$. Although the peculiar nature of the K06 heat flow scaling leads to larger $|d|$ at the present day than for thermal convection, both models yield $|d| < 0.05\%$ every Myr (Fig. 5 *Bottom*). We experimented with transitions from a stagnant lid to a typical plate tectonic regime at 1 Ga, and even those more rapid cooling trends predict $|d| \leq 0.07\%$ every Myr. This implies that even our lower estimate for the rate of heat flow decrease from our seafloor age reconstructions is unlikely to represent a smooth secular trend.

Next we compare our rates with the 500-Ma periodic supercontinental cycle example from G05 where the regular heat flow scaling with $\beta = 1/3$ is modified by a wavelength, L , dependent factor [“thermal $L_1(t)$ G05”]. The blue curve in Fig. 5 mimics the example with sinusoidal changes in L between 3 and 7 similar to G05’s figure 9, where the authors suggested that present-day Urey ratios may be underestimates of long-term averages. The present-day $L = 3$ in this model leads to relatively more efficient heat transport and larger heat flow at present than in the last 0.5 Ga (blue curve; see Fig. 5 *Middle*). Although the magnitude of the long-term (500-Ma scale) fluctuations of Q in the G05 model matches our estimates of $|d| \sim 0.15\%$ every Myr, they have the opposite sign: G05 suggest that Q has increased ($d > 0$), whereas we find that Q has decreased ($d < 0$) during the Cenozoic. [The nonlinearities involved in solving for heat budgets lead to a

transient, but small, $d < 0$ episode in the 10 Ma short-term for thermal $L_1(t)$ G05.]

Similar magnitudes of heat flow rates of change between G05 and this study confirm G05's general suggestion of fluctuating heat flow. However, our heat flow estimates combined with geometric analyses of the Pacific basin plates imply that the current Earth is in a reduced state of interior heat removal. This indicates that using a present-day Urey ratio of ~ 0.3 is an overestimate rather than an underestimate. Korenaga (31) used variations in sea level as a proxy for changes in heat flow and also determined that the present-day heat loss is in a reduced, rather than an enhanced, state. Because X06 demonstrated a drop in sea level using the same seafloor age reconstructions implemented here, our finding of decreasing heat flow is consistent with Korenaga's study (29) but quantifies the magnitude of the decrease in an alternative fashion.

Discussion

Cyclic heat transport at low Urey ratios implies that a solution to the thermal catastrophe may indeed require a thermochemical or rheological mechanism to reduce heat flow efficiency at higher temperatures. It is clear from the limited nature of our estimates that we cannot constrain the time-dependent nature (period or peak amplitude) of the heat flow signal. Our goal, however, is simply to compare parameterized convection models with heat loss values derived from seafloor age distributions. For completeness, we thus include a "thermochemical $L_2(t + \Delta t)$ " model where we have phase-shifted the G05 cyclic $L_1(t)$ factor, applied a somewhat subdued length scale ($L = 4-6$), and combined it with the K06 heat flow scaling (black lines in Fig. 5). Average heat flow in the last 1 Ga for this model is $\sim 10\%$ larger than the present. Relative to constant heat sources, this implies an effective time-averaged Urey ratio $\gamma'(0) = \gamma(0)/(Q/Q_0)$; i.e., $\gamma'(0) \sim 0.28$ for $\gamma(0) = 0.3$, which is the value we use for "thermochemical $L_2(t + \Delta t)$." This model displays rates of change in Q within the last 65 Ma that are within the d ranges shown in Fig. 2. Thus, our tectonic estimates of d are substantially larger than those expected for smooth, uniformitarian cooling models. We conclude that plate tectonics is operating in a state characterized by pronounced episodicity in heat flow, of the sort displayed by the thermochemical (black curve) fluctuating model in Fig. 5.

As of yet, there are no spherical convection computations that faithfully incorporate both lithospheric rheology and the thermomechanical effect of the continental crust on the convective planform. However, existing computations can provide clues on the Earth's behavior. Variations in heat flow with $d \sim 0.1\%$ every Myr are typical of mobile lid convection (42), and dramatic plate reorganizations may lead to values that exceed 0.1% every Myr (43, 44). Our results are therefore consistent with theoretical expectations of convective fluctuations in heat flow.

How do convective and plate length scales control heat flow and lead to these variations? In the simplest sense, convective wavelength can be calculated by measuring the distance between surface expressions of this process: specifically, the distance between mid-ocean ridges and their corresponding subduction zones (Fig. 4a). We note that this spacing does not directly depend on continental separation. In fact, continental separation was largest during Pangean times and has since been decreasing, which would to first order suggest a reduction in convective wavelength since then (cf. ref. 5), inconsistent with our analysis. This mismatch is apparently caused by the oceanic system's indirect response to continental separation (cf. refs. 41 and 44). Pacific oceanic plate length scales have been increasing through time since 120 Ma (Fig. 4a). Continental dispersion may provide estimates of an upper bounding wavelength, but more information is necessary to recognize how multiple plates organize within a single ocean basin. The oceanic plate system

appears to respond to the boundary conditions set by the continents, although it is not clear at this point which controls the latter and how the two systems interact, e.g., by means of global subduction mass transport or the dynamic controls of tectospheric keels.

Conclusion

We show that heat flow reduction may have occurred at a rate of $\sim 0.15\%$ every Myr since at least 65 Ma. In addition, our geometric analysis (Fig. 4) indicates that a similar decrease in heat flow and change of length scale has likely been operating in the Pacific for a longer time span, since at least 120 Ma. If the Pacific basin continues on its evolutionary trajectory, then the rest of the Farallon system and the East Pacific Rise eventually may be subducted underneath the Americas. This implies that we are not at a minimum in heat loss today and that decreasing heat flow may persist for some time into the future, continuing the interplay between oceanic plate organization and supercontinental cycles.

This ongoing decrease in heat flow may be only the most recent manifestation of cyclic, or episodic, variations in plate tectonic heat flow that overprint the secular cooling of the Earth. A decreasing amount of total heat flow suggests that current estimates of Urey ratios may be appropriate or too high, implying a need for mechanisms that reduce the efficiency of convective heat transport in the past (e.g., ref. 18) to address the thermal catastrophe. Distance-to-ridge estimates from the present to 120 Ma in the Pacific basin indicate a decrease in the fraction of seafloor covered by ridge-proximal crust and consequently a decrease in heat flow toward the present, which is consistent with the observed Cenozoic trend. Since 120 Ma, oceanic plates in the Pacific basin have undergone a transition from multiple plates of comparable size to one primary plate, producing an increase in the average convective wavelength. This increase is coincident with a reduction in heat flow in the Pacific because longer wavelengths represent a less efficient cooling mode. Thus, continental separation itself is only an upper bound on the convective length scale because oceanic plates self-organize to control heat flow variation.

Methods

The age of the present-day seafloor is well determined nearly everywhere in the oceans (e.g., ref. 45). Additional regional-specific seafloor age reconstructions have been developed by Heine *et al.* (7) and Brown *et al.* (8). For the past, seafloor age must be determined by rotating the present-day age map backward in time by using tectonic reconstructions. For ridge-dominated basins such as the Atlantic, this procedure is straightforward (e.g., ref. 40). For subduction-dominated basins such as the Pacific, however, reconstruction of seafloor ages is difficult because information about the past seafloor has been destroyed by subduction. X06 estimated ages for subducted seafloor by extrapolating from nearby seafloor of known age using age gradients determined from estimates of the spreading rate at the time of seafloor formation that are based on tectonic reconstructions. Using this method, X06 reconstructed the seafloor for nine stages during the Cenozoic. For the early Cenozoic, these reconstructions require a significant fraction of the Pacific seafloor to be exhumed in the western Pacific where there is significant uncertainty in tectonic reconstructions. In this area, X06 compiled two seafloor age reconstructions that differ in their treatment of the Philippine plate. The Gordon and Jurdy (33) reconstruction assumes that the Philippine plate area was fused to the Pacific plate before ~ 10 Ma, whereas the more recent Hall (34) reconstruction of the western Pacific treats the Philippine plate as a rotating microplate present in the Pacific basin since ~ 55 Ma. The age reconstructions from these two

