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Eustasy, supercontinental insulation, and the temporal variability of terrestrial heat flux

Jun Korenaga *

Department of Geology and Geophysics, Yale University, P.O. Box 208109, New Haven, CT 06520-8109, USA

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Abstract

Heat flux from convection in Earth's mantle has recently been suggested to vary substantially (20–30%) with the Wilson cycle of continental aggregation and dispersal, because of possible changes in the aspect ratio of convective cells, and the present-day heat flux may be at the maximum at such a temporal variation. This possibility of strong temporal fluctuations in heat flux has an important bearing on how we should model the thermal evolution of Earth in general. As most of convective heat flux appears as oceanic heat flux, and changes in oceanic heat flux can cause changes in the global sea-level, the likely amplitude of such a temporal variation can be quantified by long-term eustasy. Though this inference may be complicated by other processes that can affect the global sea level, most of them predict sea-level fall when Pangea was present, allowing to place a likely bound on the temporal variability of heat flux. Given the geologically plausible age–area distribution of seafloor, the present-day oceanic heat flux is likely at the minimum (not the maximum) of a possible temporal fluctuation, and the oceanic heat flux at ~ 200 Ma cannot be lower than today by more than a few percent. I also suggest that mantle warming by supercontinental insulation is probably up to only ~ 20 K, though it still has a nontrivial consequence for the global sea level.

Keywords: sea-level changes; mantle convection; oceanic hypsography; continental flooding

1. Introduction

At the present day, Earth is releasing heat at the rate of around 44 TW [1,2], and how this heat flux is internally supported has long been debated. Heat production by radiogenic elements with long half lives (U, Th, and K) is estimated to be only 20 TW [3] or even lower [4], so a substantial fraction of surface heat flux must be supported by secular cooling. If whole-mantle convection is assumed, such a large degree of secular cooling is usually believed to imply an unrealistically hot Earth in the past [5], and a few different mechanisms have been proposed to avoid this so-called thermal catastrophe scenario (see [6] for review). Some authors still prefer whole-mantle convection by nearly doubling the amount of radiogenic elements (thus entirely neglecting geochemical constraints on them) [7], and others turn to some form of layered-mantle convection [8]. I myself have suggested that plate-tectonic convection on Earth can efficiently retain fossil heat, which could drastically reduce the amount of secular cooling in the past [6,9].

* Tel.: +1 203 432 7381; fax: +1 203 432 3134.
E-mail address: jun.korenaga@yale.edu.

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Recently, Grigné et al. [10] proposed that surface heat flux may fluctuate with the Wilson cycle (i.e., a period of a few hundred million years) and that, if the present-day convective heat flux is higher than its temporal mean by ~25%, this could also resolve the thermal catastrophe problem. They argue that the presence of a supercontinent should result in larger oceanic plates, which yield lower convective heat flux in their numerical models. Though their argument is probably too simplistic (because their calculation of thermal evolution relies on the heat flow scaling law derived from earlier, *isoviscous* convection models [11]), how heat flux might change with plate-tectonic cycles is still a very important issue neglected by most of previous studies. The thermal history of terrestrial planets has usually been studied with parameterized convection models, which is merely an order-of-magnitude analysis. It would be unwise, therefore, to use the present-day surface heat flux if it is substantially different from a more representative, temporal average.

Estimating surface heat flux in the past is difficult. The present-day heat flux is a combination of oceanic heat flow (~32 TW) and continental heat flow (~12 TW). About 60–70% of continental heat flow (~8 TW) is estimated to come from the long-lived radiogenic elements in continental crust, so continental heat flux is not expected to change substantially on the time scale of a few hundred million years. On the other hand, oceanic heat flow is entirely of a convective origin, and it could potentially vary as quickly as surface plate motion changes. Our estimate on the present-day oceanic heat flow is largely based on the age–depth relationship observed for seafloor, which allows us to relate the oceanic heat flow with the area–age distribution of seafloor [1,12]. If seafloor spreading is faster in the past, for example, this should lead to younger seafloor on average, which corresponds to higher oceanic heat flow [13]. Because of subduction, we do not have a complete knowledge of the area–age distribution in the past, and reconstructing it beyond the Cenozoic is subject to large uncertainties [14]. On the other hand, different area–age distributions imply different capacities for the ocean basin, and thus the temporal variation in oceanic heat flux may be reflected in global sea-level changes [15]. Extracting such information from sea-level changes, however, may not be so straightforward as assumed in some previous studies, because long-term sea-level changes could also be influenced by subducted slabs and supercontinental insulation [16]. Because of these complexities, a potential linkage between eustasy and oceanic heat flux appears to have been abandoned or simply forgotten.

In this paper, I will show that long-term sea-level changes are still useful to place *bounds* on possible temporal variations in oceanic heat flux, if various causes are carefully sorted out. Though some previous studies suggest that deep convective phenomena due to subducted slabs could dominate the global sea-level change, it appears that the role of subducted slabs has been overemphasized as far as eustasy over the last 200 My is concerned. I note that discussion throughout this paper is focused on this geological period after the breakup of Pangea, for which we have decent geological constraints on oceanic plate motion and the history of subduction.

As debates over the magnitude of sea-level changes during the Phanerozoic appear to be converging [17], it is important to explore the implication of long-term eustasy for terrestrial heat flux. As I will elaborate in the following, sea-level changes do place a tight constraint on past heat flux. The present-day heat flux is most likely at the temporal minimum, not the maximum, and heat flux when Pangea existed (~200–300 Ma) should not be different from the present-day value by more than a few percent. I begin with a brief review on eustasy.

2. Long-term eustasy

Global sea levels can vary at a vast range of time scales (1–10^8 years) [17,18], and here I focus on its long-term variations, which usually refer to variations over tens to hundreds of million years. Important causes for such long-term eustasy include: (1) changes in the area–age distribution of seafloor by, for example, changes in plate motion or the reorganization of plate tectonics itself, (2) changes in the age–depth relationship of seafloor by sediment thickness variation, crustal thickness variation (e.g., by the formation of oceanic plateaus), or deeper convective processes, (3) changes in the volume and spatial distribution of continental crust, and (4) coherent vertical movements of all (or most of) continents due to sublithospheric convective processes (e.g., supercontinental insulation). Sea-level changes due to changes in ice volume take place at much shorter time scales. The thermal expansion of oceans due to secular variation in ocean temperature has only a minor effect on sea level (<10 m). Given the number of the above listed potential causes, one may doubt if we can extract any useful constraint on past heat flow (i.e., the age–area distribution of seafloor in the past) from sea-level records. Although we will not be able to establish a precise relationship between heat flux variations and sea-level changes, it is still possible to place a reasonable bound on heat flux if we limit ourselves to long-term eustasy. This is because most of those causes would predict sea-level fall when Pangea was present. I will return to this point in the next section.

The overall *pattern* of long-term sea-level changes in the last 200 million years is similar among various estimates (Fig. 1a); sea level was close to the present-day level at 200 Ma, and it reached its maximum at ~100 Ma (Cretaceous transgression), followed by gradual fall to the present-day level. It is the magnitude of this long-term variation that has been controversial. The widely-cited estimate by Vail and others [19], which is based on seismic stratigraphy, has ~ 300 m rise during the Cretaceous, but this amplitude is the result of calibration with Pitman's sea-level curve [20], which in turn is based on his estimate for changes in global spreading rates in the past. Sea-level estimate based on changes in spreading rates requires, however, an accurate knowledge of the age–area distribution of seafloor in the past, which is not available because of subduction as noted earlier. Moreover, even rapid seafloor spreading during the Cretaceous has been under scrutiny [21,22,49], and the sea-level estimates based on backstripping persistently exhibit much reduced amplitude (by about a factor of three) [17,23].

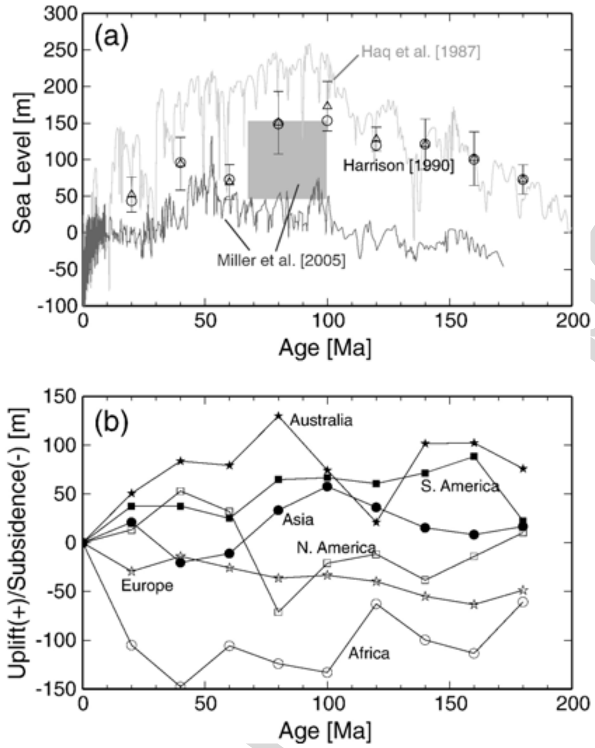

Fig. 1. (a) Estimates of global sea-level changes for the last 200 My, according to Haq et al. [47] (light gray), which is the revised version of the Vail curve [19], Harrison [18] (circles and triangles), and Miller et al. [17] (dark gray). The Miller curve is based on backstripping (0–100 Ma is from their own study on New Jersey coastal plain and the rest is from the work of Sahagian et al. [48] on the Russian platform). Gray box indicates the likely range of sea level during the Late Cretaceous as suggested by Miller et al. [17]. For Harrison's estimates, triangles and error bars denote the continental average and its standard deviation, respectively, and circles denote the global estimate. (b) Uplift and subsidence of individual continents, as derived as a byproduct of the continental average made by Harrison [18].

Continental flooding provides a complementary view on eustasy. The flooded area of one particular continent can be influenced by its own vertical movement irrelevant to global sea-level changes, such as dynamic topography induced by subducting slab [16,24], but it may still possible to extract an eustatic signal by averaging sea-level estimates from different continents. Such an attempt by Harrison [18] is illuminating (Fig. 1). He made two different estimates by: (1) calculating sea-level changes for six individual continents (Africa, Asia, North America, South America, Europe, and Australia) using its own hypsography and flooded fraction, and then taking their average (treating each continent equally regardless of its area), and (2) calculating sea-level change from the global hypsography and the total flooded area. These estimates are remarkably similar, and this similarity indicates that, although the flooding of individual continents can substantially be influenced by epeirogeny (Fig. 1b), the continental average or the global average can provide a stable constraint on long-term eustasy. Harrison's estimate has ~150 m sea-level rise at 100 Ma, and this value still seems to stand well given the most recent estimate on the Cretaceous high (100±50 m) [17]. The residual amplitude of uplift and subsidence of individual continents (±150 m, Fig. 1b) places an upper bound on the amplitude of dynamic topography induced by mantle convection, as previously suggested by Gurnis [25] with a different line of reasoning.

From the time of the supercontinent Pangea to the present day, therefore, it is most likely that the global sea level first gradually rose from the present-day level to the maximum of 100–150 m and then gradually returned to the present-day level.

3. Physical causes for long-term eustasy

We can classify the above-listed causes for eustasy into two categories: lithospheric and convective. Probably the most important lithospheric cause is changes in the area–age distribution of seafloor, which is directly related to fluctuations in oceanic heat flux. The relationship between sea level and heat flux according to this process can be modeled reasonably well and will be explored later. Here I first discuss other processes in order of increasing depth.

3.1. Lithospheric causes not related to spreading rates

Temporal variations in the volume of sediment in the ocean basins can affect sea level by ~60 m [17]. The most important variation was due to the evolution of planktonic foraminifera since the Cretaceous, which is estimated to be responsible for most of carbonates on the seafloor [18]. The ocean sediment volume was thus lower in the past, which by itself should lead to sea-level fall (by ~50 m [18]). The emplacement of oceanic plateaus also affects the age–depth relationship of seafloor and causes sea-level rise. Most of large oceanic plateaus were formed during the Cretaceous, which must have contributed to the Cretaceous transgression. The volumetric significance of Triassic and early Jurassic (i.e., ~200 Ma) oceanic plateaus is uncertain, but the number of potential candidates for such plateaus is very limited [26]. Even if a massive plateau like Ontong Java were present in the Panthalassa, its influence on the global sea level would be small. The spatial extent of the Ontong Java Plateau (the largest oceanic plateau in the world) is $\sim 1.6 \times 10^6$ km^2 and it is shallower than the ambient seafloor by ~2 km on average [27], so the plateau displaces $\sim 3 \times 10^{15}$ m^3 of seawater, which translates to ~6 m increase in sea level (using the relation of [18]).

To compensate the sea-level fall due to the absence of planktonic foraminifera, therefore, we need a multitude of such gigantic plateaus, for which geological evidence is lacking. Though they may have been completely subducted, I will not place an emphasis on this extreme possibility when considering the sea level at ~200 Ma.

Geological and geochemical data suggest that the volume of continental crust increased by ~ 5% over the last 500 My [28,29]. Though this effect is fairly minor for the time scale of 100 My or so, reduced continental volume in the past by itself corresponds to sea-level fall. Also, continental collision tend to decrease the spatial extent of continental crust, which lowers sea level. Because the formation of a supercontinent is characterized by global-scale collisional processes, the spatial extent of continental crust then is expected to have been minimized (for a given continental volume). Thus, changes (if any) in the volume and spatial distribution of continental crust should have lowered sea level at ~200 Ma.

3.2. Convective causes

What remains to be discussed is deeper, convective causes. The most significant buoyancy source in the convection of Earth's mantle is undoubtedly subducting slabs, and convective stress associated with subduction could be large enough to generate dynamic topography on the order of 1 km or more [16,24]. This type of large dynamic topography is limited at regional scales, however, and when averaged over continental scales, it is probably on the order of a few hundred meters (Fig. 1b). Though subduction-induced dynamic topography is expected to vary among different continents because each continent has a different plate boundary, its net effect on the global sea-level change may not be trivial if it can constructively add up. In fact, based on the numerical simulation of spherical mantle convection, Gurnis [16] suggested that dynamic topography could result in large sea-level changes (up to ~200 m). This suggestion is based on the success of his model prediction for the Phanerozoic inundation, though a good match with observation was achieved only for the Paleozoic (see Fig. 2c of [16]). His model tends to overpredict the flooded area of continents for the Mesozoic and the Cenozoic (Fig. 3b and c of [16]). This is interesting because the history of subduction, which has to be assumed to calculate subduction-induced dynamic topography, is clearly much less constrained in the Paleozoic; seafloor spreading data are entirely absent before 200 Ma. If one focuses on the last 200 My, his model predicts that the global sea level at 200 Ma was *lower* than the present by ~50 m. As far as the last 200 My is concerned, therefore, subduction-induced dynamic topography may also result in a sea-level fall when Pangea started to break up. The amplitude of the predicted sea-level change must be viewed with caution given the overflooding nature of his model prediction, but the sign of sea-level change is probably robust.

Subducting slabs may have another global effect. Hager [30] first noted that, because of more efficient convective cooling, faster spreading could lead to cooler oceanic mantle, which itself leads to seafloor subsidence and thus sea-level fall. Gurnis [31] pursued this idea later by conducting the numerical modeling of mantle convection, and suggested that this effect could be significant. The claimed convective effect is, however, likely to originate in the combination of (1) the prolonged period (>100 My) of rapid (50% faster) seafloor spreading and (2) a very thick (~500 km) thermal boundary layer due to the low Rayleigh number ($\sim 4 \times 10^4$) employed. The possible duration of faster spreading in the Cretaceous is on the order of a few tens of million years [14,20], and even the existence of such a period is in question [21,22,49]. Because the thickness of oceanic plate is up to only ~100 km, the slab mass flux into the mantle is less than $\sim 10^{15}$ kg yr^{-1} at the present day (with the plate creation rate of ~3 $km^2\ yr^{-1}$ [32]). Increasing the spreading rate by 50% and maintaining it for 50 My results in the excess amount of cold slab only by ~2.5×10^{22} kg (or ~ 0.6% of the mantle mass). Thus, the global cooling effect by faster spreading is likely to be insignificant even if the Cretaceous transgression was indeed caused by faster spreading. The same argument applies to global warming by slower spreading.

Another major non-lithospheric cause to be discussed is supercontinental insulation [33], which could cause the uplift of the entire supercontinent, thus resulting in a fall in the global sea level. The degree of supercontinental insulation that can be achieved in the real mantle, however, may not be as high as commonly believed. The original paper by Anderson [33] suggests that the mantle can be warmed up by ~70 K for 100-My-long insulation. His argument is the following. The mean oceanic heat flux is ~100 mW m^{-2} whereas the mean continental heat flux is ~60 mW m^{-2}. Thus, with respect to suboceanic mantle, subcontinental mantle may be considered to be warmed up with the heat flux of ~40 mW m^{-2}. He then assumes that the oceanic heat flux is entirely due to radiogenic heating, and also that the radiogenic heat sources mostly reside in the upper 500 km of the mantle (note: this is in accord with his arguments for a chemically stratified mantle [34]). A temperature increase, ΔT, due to insulation over the period of Δt can then be estimated by the following balance in volumetric heat flux:

$$\rho C \frac{\Delta T}{\Delta t} \sim \frac{\Delta q}{D} \tag{1}$$

where ρ is mantle density (~3300 kg m^{-3}), C is specific heat (~1 kJ K^{-1} kg^{-1}), Δq is relative surface heat flux, and D is the depth extent of the subcontinental mantle under consideration. The above assumptions by Anderson imply Δq of ~ 40 mW m^{-2} and D of 500 km, which yield ΔT of 76 K for Δt of 100 My. Neither of these assumptions are, however, likely to be correct. First, as noted in Introduction, internal heating due to radiogenic elements in the convecting mantle can account for only <30% of convective heat flux. Second, the upper mantle sampled by mid-ocean ridge magmatism is known to be depleted in heat-producing elements, and if the estimated upper mantle composition is valid for the entire mantle, internal heat production is only ~15% of convective heat flux [6,35,36].

Our current understanding of Earth's thermal budget [36] suggests the following way of estimating the effect of insulation. As ~2/3 of continental heat flux is due to radiogenic elements within continental crust, subcontinental mantle is cooled at the rate of ~20 mW m^{-2}. Thus, Δq can actually be as high as ~80 mW m^{-2}, but the mantle depth D should be ~3000 km and ρ should be the average density of the entire mantle (~4450 kg m^{-3}). Note that this relative 'heating' of subcontinental mantle is achieved by the cooling of suboceanic mantle. Subcontinental mantle is not heated in a common sense; it is merely uncooled less than the suboceanic mantle. As seismic tomography for deeply subducting slabs indicates [37,38], the cooling of suboceanic mantle is likely to be of whole-mantle scale. Thus, we should take the whole-mantle depth as the relevant length scale for subcontinental uncooling as well. Eq. (1) then yields ΔT of only 20 K for Δt of 100 My. A similarly low ΔT can also be derived from the thermal history of Earth. As we can infer from the petrogenesis of Archean igneous rocks, mantle potential temperature has decreased by not more than 300 K over the last 3 Gy [6,8], that is, the global cooling rate for Earth's mantle is less than 100 K/Gy. Thus, if the subcontinental mantle occupies 40% of the entire mantle and all of secular cooling is concentrated in the rest of the mantle, the subcontinental mantle becomes warmer by ~16 K/100 My with respect to the suboceanic mantle.

Though this degree of temperature increase is probably insignificant in terms of its effect on terrestrial magmatism, it can still be important for the long-wavelength geoid, which has a good sensitivity to broad and deep structures [39], and also for the global sea-level change because the corresponding isostatic uplift is ~ 100 m assuming the compensation depth of 200 km [40]. Thus, supercontinental insulation remains to be an important sublithospheric cause for eustasy, and it could cause sea-level fall when a supercontinent is present. One may question the above order-of-magnitude estimate on supercontinental insulation by noting that it contradicts with the enhanced activity of mantle plumes, which is often invoked to explain continental breakup magmatism [27]. Continental breakup magmatism, however, does not necessarily require the presence of mantle plumes, and the careful examination of relevant geophysical and geochemical data often points to the role of chemical (not thermal) anomalies in excess magmatism [41–43].

3.3. Changes in the area–age distribution of seafloor

Smaller sediment volume, smaller areal extent of continental crust, and supercontinental insulation are all expected when Pangea was present, and all of them predict sea-level fall as discussed above. Yet, continental flooding records indicate that the global sea level must have been close to the present-day level (e.g.,

Fig. 1a). Does this suggest that the global spreading rate (and thus oceanic heat flux) at 200 Ma may have been higher than present, in order to compensate this likely sea-level fall? If this is the case, the temporary variability of oceanic heat flux would be in the opposite sense to what Grigné et al. [10] speculated. However, the relation between heat flux and sea level is more than a function of spreading rate, and it can be influenced by subtle changes in the area–age distribution of seafloor [32]. There may exist some area–age distributions, which may allow lower heat flux with higher sea level.

To explore this possibility, I will calculate the relationship between heat flux and sea level using several different types of area–age distribution. One may regard this exercise as ad hoc or arbitrary because past distributions are essentially unknown, but as will be shown, geologically plausible distributions are rather limited. I follow the theoretical formulation by Parsons [32], in which seafloor subsidence and heat flux are calculated using the plate cooling model. For the parameters of the plate cooling model, I use the more recent model by Stein and Stein [44]. Note that the plate cooling model is so parameterized to predict shallower seafloor than the half-space cooling model does when seafloor becomes older than ~ 80 Ma (because this is what is observed on the present-day seafloor), and it is still unsettled why this shallowing takes place. We certainly need some kind of excess buoyancy (e.g., by hot mantle plumes) to counterbalance the subsidence due to surface cooing. The exact origin of this deviation from half-space cooling is immaterial for our present discussion. An important point is that, if such excess buoyancy was not available in the past and so oceanic plates followed simple half-space cooling, this would lead to sea-level fall even with the same area–age distribution.

The present-day area–age distribution of seafloor is well approximated by the following 'triangular' form [32] (Fig. 2a):

$$\frac{\mathrm{d}A}{\mathrm{d}t} = C_0\left(1-\frac{t}{t_m}\right) \tag{2}$$

where $\mathrm{d}A/\mathrm{d}t$ denotes the area per unit age, C_0 is the rate of generation of new seafloor (3.45 km^2 yr^{-1}), and t_m is the maximum age (180 Ma). The total area of seafloor is then given by $\frac{1}{2}C_0 t_m (= 310.5 \times 10^6\ \mathrm{km}^2)$, which compares well with the actual measured area of $308.6\times10^6\ \mathrm{km}^2$. The corresponding heat flow is 32.0 TW. This triangular distribution is believed to have resulted from the nearly constant production rate of seafloor combined with random subduction regardless of seafloor age [22,32].

If this age-independent nature of subduction has been persistent in the past, we expect that the area–age distribution is always close to triangular. With no change in the total area of ocean basins, an increase in seafloor production should be accompanied with a decrease in the maximum seafloor age, and vice versa (Fig. 2a). If we restrict ourselves to this type of distribution, then, the relationship between sea level and heat flow is nearly linear (Fig. 2e, solid). To reduce oceanic heat flux by 25% (i.e., down to 24 TW), the ridge production rate has to be dropped by ~40% (the maximum age is then ~300 Ma), and the corresponding sea-level change is ~200 m fall, which is clearly inconsistent with the observation (Fig. 1a).

Of course, the triangular distribution is a strong assumption. If subduction does not take place randomly and all seafloor subducts at one particular age, t_f, we instead have a rectangular distribution (Fig. 2b):

$$\frac{\mathrm{d}A}{\mathrm{d}t} = C_r\ (t \le t_f) \tag{3}$$

with $C_r t_f = \frac{1}{2}C_0 t_m$. Note that two-dimensional convection models are always characterized by this rectangular distribution. Compared to the triangular distribution, the rectangular distribution gives lower heat flux for a given sea level (Fig. 2e). This is because the triangular distribution has a larger fraction of younger seafloor. Heat flux is proportional to $\sim 1/\sqrt{t}$, so the distribution biased toward younger seafloor has higher heat flux. If the area–age distribution of the Panthalassa ocean basins was rectangular, it is possible to have a reduction in heat flux by ~2 TW, without affecting the global sea level.

This motivates us to consider yet another distribution, which is biased toward older seafloor (Fig. 2c):

$$\frac{\mathrm{d}A}{\mathrm{d}t} = (C_0 - C_1) + C_1 t\ (1 \le t_f) \tag{4}$$

with $(C_0 - C_1/2)t_f = \frac{1}{2}C_0 t_m$. Note that it is impossible to have this distribution for a steady state. It may be possible when the ridge production rate is decreasing with time, but then older seafloor must be preferentially preserved. So this distribution is highly unlikely even as a transient one, and it is presented here simply for the sake of discussion. Even with this radical distribution, oceanic heat flow must still be close to ~30 TW in order to keep the present-day sea level (Fig. 2e).

A likely change in the area–age distribution associated with the Wilson cycle is usually considered to be

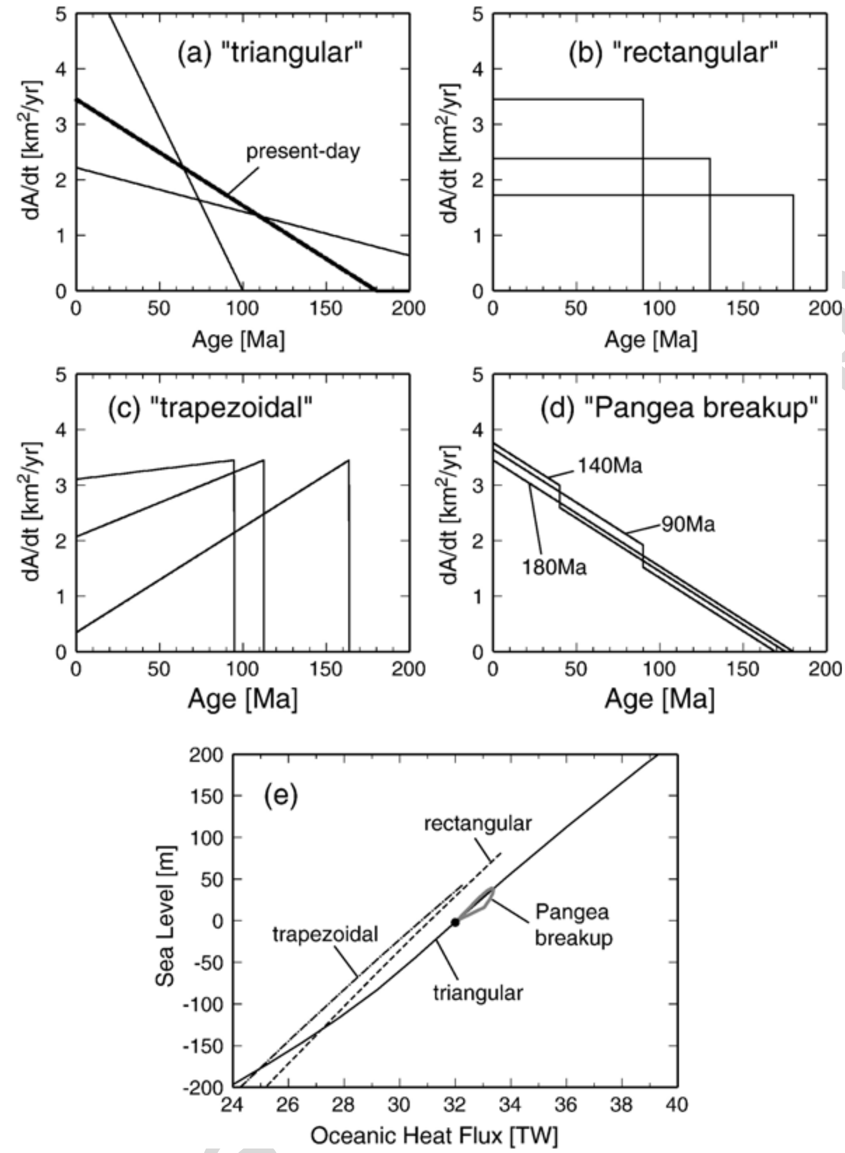

Fig. 2. Various area–age distributions of seafloor and their predictions for the relationship between sea level and heat flux. (a) Triangular distribution (Eq. (2)). Thick line corresponds to the present-day situation. (b) Rectangular distribution (Eq. (3)). (c) Trapezoidal distribution (Eq. (4)). (d) Changes in distribution accompanying the breakup of Pangea, which reduces the Pacific-type seafloor and increases the Atlantic-type seafloor [45,46]. The production rate of the Atlantic-type seafloor is set to 0.4 $km^3\ yr^{-1}$ in this example. (e) Covariation between oceanic heat flux and sea level according to the above distributions: triangular (solid), rectangular (dashed), trapezoidal (dot-dashed), and Pangea breakup (thick gray).

more subdued [45,46]. The breakup of Pangea resulted in the opening of the Atlantic, which has a rectangular area–age distribution because of no subduction. The increase of the Atlantic-type ocean accompanied with the concurrent reduction of the Pacific-type ocean (assumed to follow the triangular distribution) can result in a fluctuation in the mean age of seafloor as well as sea level and heat flux. A model similar to that of Heller and Angevine [46] is given in Fig. 2d, and this produces a cyclic fluctuation through the reference state (Fig. 2e). As has been repeatedly emphasized [32,46,50], sea-level rise up to ∼100 m or so can easily be produced by the Wilson cycle, without calling for an increase in the seafloor spreading rate.

Thus, it is theoretically possible to reduce oceanic heat flux without lowering sea level, but such reduction is limited to a few percent of the present-day heat flux even if we assume a drastic change to the rectangular distribution in the Panthalassa. Moreover, we may actually need a sea-level rise from a change in the area–age distribution to maintain the normal sea level, because there are other processes that are likely to lower sea level when continental masses are assembled into a supercontinent. Though it is currently difficult to quantify how much of sea-level rise is needed for such compensation, the above exercise should be sufficient to discount the notion of substantially lower heat flux at ~200 Ma.

4. Conclusion

The likely long-term eustatic variation in the last 200 My is characterized by the Cretaceous sea-level rise of the amplitude of ~ 100–150 m, with the present-day sea level as the lowest baseline. That is, there has been no major period when the sea level was substantially lower than the present-day level, and the sea level when Pangea was present was similar to what we have today. There are various causes that affect the long-term sea level. Sediment volume change, changes in the volume and distribution of continental crust, and supercontinental insulation all predict sea-level fall at ~200 Ma. There is no geological record to suggest the presence of massive oceanic plateaus in the Panthalassa to compensate such sea-level fall, so in order to bring the sea level to normal, the area–age distribution of seafloor must have been different from today to cause some sea-level rise. At the very least, changes in the area–age distribution must not result in sea-level fall. This constraint can be used to suggest that the oceanic heat flux at ~200 Ma must have been higher than ~30 TW, given the geologically plausible forms of area–age distribution. Moreover, the likely change in the area–age distribution with the Wilson cycle indicates that the present-day oceanic heat flux is at the minimum, not the maximum, of temporal fluctuations. Thus, the present-day oceanic heat flux of ~32 TW is unlikely to be substantially higher than a long-term average, and is probably slightly lower than such an average.

Given that temporal fluctuations in oceanic heat flux are likely to be limited to a few percent (which is similar to the uncertainty of the present-day estimate [1,2]), I may conclude that it is safe to use the present-day heat flux as a representative value when calculating the long-term thermal evolution of Earth. This is indeed what most of previous studies have done. Though the long-term dynamics of plate-tectonic convection on Earth is yet to be understood and may have many surprises, we would all benefit from considering how such dynamics would be reflected on Earth's surface and how we could test it with geological observations.

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