The thermal evolution of the Earth: Long term and fluctuations

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July 26, 2006

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Abstract

The total heat loss through oceanic lithosphere has been classically computed using the distribution of seafloor ages, which allows to express it as proportional to the mantle reference temperature. While most models for the thermal evolution of the Earth try to fit the constraint of the total heat loss of the Earth, they never deal with the actual distribution of seafloor ages and base their approach on scaling laws for the heat transfer by convection in systems that may not be able to produce such a distribution. A model for the thermal evolution of the Earth based on the present observation of the seafloor shows that the time scale for the evolution of the Earth is of the order of 10 Gyrs, which leads to a slow cooling over its history. On the other hand, large (at least 30%) fluctuations of the heat flow on the time scale of plate re-organization have to be expected. Comparison of the distribution of seafloor ages and what would be obtained from typical mantle convection models shows that the later are unable to produce the peculiarities of the former, namely the ability of the mantle to subduct a lithosphere of any age with an equal probability.

1 Introduction

The thermal evolution of the Earth has been a subject of considerable concern since the time of Joseph Fourier (1768–1830)[1] and is still a largely unresolved problem. Since the advent of plate tectonics, it is usually addressed using the so-called parameterized convection approach where scaling laws derived from numerical or analog experiments are used to relate the heat flux at the surface of the Earth to the mantle temperature T. In dimensionless form, this scaling law is usually written as

$$q = ARa^{\beta}T^{1+\beta}, \tag{1}$$

with $\beta \simeq 1/3$ in most parameterizations. The Rayleigh number $Ra = \alpha g \Delta T d^3/\kappa\nu$ characterises the vigor of convective motions, with α the coefficient of thermal expansion, g the acceleration due to gravity, ΔT the super-adiabatic temperature difference between the core mantle boundary and the surface, κ and ν the thermal and viscous diffusivities.

Tozer [2] proposed that, due to the decrease of mantle viscosity with temperature, the terrestrial planets reach, early in their history, a state of thermal equilibrium, where most of the surface heat flow can be attributed to heat production by the decay of radioactive elements. The mechanism by which this equilibrium is reached is simple: If the planet starts hot, the viscosity of its mantle is low and its Rayleigh number high. This results in a large surface heat flow, and a rapid cooling. This feedback mechanism leads to a thermal evolution that is quite insensitive to initial conditions and has pushed most geophysicists to argue for a present radiogenic heat production in the mantle accounting for more than 70% of the total heat loss, that is a present Urey ratio greater than 0.7.

On the other hand, the progress of cosmo- and geochemistry has brought ever more convincing evidences that the total radiogenic heat production in the silicate Earth is of the order of 20 TW or less [e.g. 3], to be compared to a total heat loss of 46 TW[4], which means a present Urey ratio lower than about 0.5. To solve this problem, many studies have proposed different parameterizations of heat transfer by mantle convection, generally in the form of equation (1) but with an exponent β much lower than the traditional 1/3. This reduces the effect of the variations in viscosity and the associated self regulation. The reason invoked for lowering this exponent has been dependence of viscosity on temperature [5] or grain size [6], resistance of lithospheric plates to bending at subduction zones [7], or dependence of depth of melting on mantle temperature [8, 9]. However, the importance of such phenomena in the Earth is difficult to assess and the risk of missing another important effect is always present.

Here, we propose another approach to the problem of the thermal evolution of the Earth, based on the present observations and a few assumptions and we show that its result is quite different from the usual parameterized models. The main observation in the present analysis is the distribution of seafloor ages which allows one to compute the present heat loss of the Earth and, solving for a differential equation, its thermal evolution. Moreover, the comparison between this distribution and the one typically obtained in convection models, shows that plate tectonics is a very peculiar regime that is not captured by standard heat flux parameterization.

In addition, this approach can be used to estimate the amplitude of short term fluctuations of the heat loss of the Earth, which are found to be about 30% of the total oceanic heat loss. This value is larger than the total evolution of this heat loss since the crystallisation of the magma ocean.

2 Distribution of seafloor age

Many features of the seafloor point to interpreting oceanic plates as the upper boundary layer of mantle convection. In particular the increase of seafloor depth as a square root

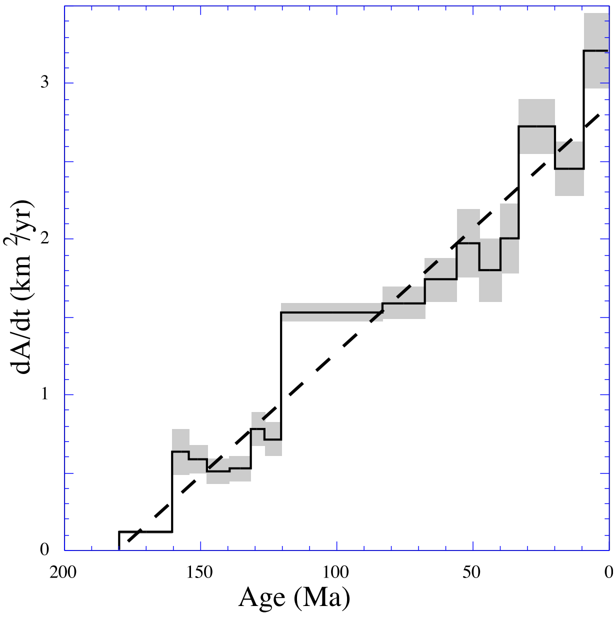

Figure 1: Distribution of seafloor age. Adapted from [10].

of age, at least for ages up to 80 Ma, is interpreted as the growth of the cold conductive boundary layer and the contraction associated.

Using a half-space approximation, heat flux through an oceanic lithosphere of age a can be estimated as

$$q = \frac{kT_m}{\sqrt{\pi \kappa a}}, \tag{2}$$

with T_m, k, κ the mantle temperature, thermal conductivity and diffusivity. All seafloor younger than 80 Ma where good heat flux data are available corroborate this interpretation [4]. Since heat flux data are much more difficult to get than age data, the latter have been used to compute the total heat loss through the oceanic surface in place of the former. A systematic deviation from this law is observed for ages higher than 80 Ma and can be associated with the onset of small scale convection under the lithosphere [e.g. 11]. This observation is of course very important for its implication on small-scale dynamics in the mantle but it only interests regions where the heat flux is already low and the contribution of this process to the total heat loss of the Earth is negligible in the present discussion. See [4] for a more complete discussion.

The surface distribution of seafloor ages is shown on figure 1 [10] and can be fitted quite nicely by a linear relationship [10, 12, 13]

$$\frac{dA}{da} = C_0 \left(1 - \frac{a}{a_{max}}\right) = C_0 f\left(\frac{a}{a_{max}}\right), \tag{3}$$

the distribution function f being linear at present time, C_0 being the present rate of plate creation and a_{max} the maximum age of oceanic lithosphere. These two parameters are linked by the total area of oceans, A_{oc}:

$$A_{oc} = \int_0^{a_{max}} \frac{dA}{da} da = C_0 a_{max} \int_0^1 f(u) du = \frac{C_0 a_{max}}{2}, \tag{4}$$

where the expression (3) for the present distribution has been used to get the last result.

From the distribution of seafloor ages, one can compute the heat loss through oceans by simply summing the contributions from each age,

$$Q_{oc} = \int_0^{a_{max}} q(a) \frac{dA}{da} da = C_0 k T_m \sqrt{\frac{a_{max}}{\pi\kappa}} \int_0^1 \frac{f(u)}{\sqrt{u}} du = \frac{4}{3} C_0 k T_m \sqrt{\frac{a_{max}}{\pi\kappa}}. \qquad (5)$$

the last expression corresponding to the present distribution of seafloor age. Eliminating C_0 with equation (4), we get

$$Q_{oc} = \frac{A_{oc} k T_m}{\sqrt{\pi\kappa a_{max}}} \frac{\int_0^1 \frac{f(u)}{\sqrt{u}} du}{\int_0^1 f(u) du} = \frac{8 A_{oc} k T_m}{3\sqrt{\pi\kappa a_{max}}}. \qquad (6)$$

Parameter	value
k	3.15 $\mathrm{Wm^{-1}K^{-1}}$
κ	8 10^{-7} $\mathrm{m^2s^{-1}}$
A_{oc}	3.09 10^{14} $\mathrm{m^2}$
T_m	1333 °C
a_{max}	180 Ma
C_P	1200 $\mathrm{Jkg^{-1}K^{-1}}$
M	6 10^{24} kg

Table 1: Input parameters to compute the total oceanic heat flow and the thermal evolution.

This shows that three possibly varying factors can influence the total oceanic heat loss, the mantle potential temperature T_m, the maximum age of the oceanic lithosphere, a_{max}, and the distribution shape factor $\lambda(f) \equiv \int_0^1 f(u)/\sqrt{u} du / \int_0^1 f(u) du$. The present situation, using the parameters of table 1, gives a total oceanic heat flow of 29 TW. This value is very close to the one obtained when taking into account separately the seafloor older than 80 Ma [4].

3 An empirical thermal evolution model

The heat balance of the Earth can be written as,

$$M C_P \frac{dT_m}{dt} = -Q_{tot} + \sum_i H_i e^{-t/\tau_i}, \qquad (7)$$

M being the mass of the Earth, C_P its averaged heat capacity, including the effect of compressibility and thermal evolution of the core on the link between the mantle potential temperature T_m as defined above and the average Earth temperature. The total heat loss of the Earth, Q_{tot}, can be separated in its contributions from oceans, Q_{oc}, and continents,

Q_{cont}. The different radioactive isotopes contribute each a total of H_i at present time and exponentially more in the past, with a corresponding half life of $\tau_i \ln 2$.

The continental heat flux is much more complex to understand than the oceanic one. However, continents staying at the surface can be seen as thermal insulators [14, 15] and, indeed, most of their surface heat flux is sustained by radiogenic heat in the continental crust. Heat flux studies in archean cratons have shown that the heat flux from the mantle to the continents is lower than 15 mWm^{-2} [4], whereas the averaged oceanic heat flux is 100 mWm^{-2}. To simplify the analysis, we will then assume that the continental heat flow is entirely due to radioactive heating of the crust and the corresponding radioactive heating is subtracted from the internal sources, to get H_{oi}. The modified heat budget reads

$$MC_P \frac{dT_m}{dt} = -Q_{oc} + \sum_i H_{oi} e^{-t/\tau_i}. \tag{8}$$

The oceanic heat flow can now be replaced by its expression (eq. 6), giving

$$MC_P \frac{dT_m}{dt} = -\frac{A_{oc} k \lambda(f)}{\sqrt{\pi \kappa a_{max}}} T_m + \sum_i H_{oi} e^{-t/\tau_i}. \tag{9}$$

Equation (9) allows to identify the intrinsic timescale for the thermal evolution of the Earth. Indeed, the first two terms of this equation define the cooling time scale,

$$\tau_C = \frac{MC_P \sqrt{\pi \kappa a_{max}}}{A_{oc} k \lambda(f)} = 10 \text{ Gyr}, \tag{10}$$

where the numerical value is obtained using the parameters of table 1. This time scale characterises the time needed for the mantle to adjust to a new boundary condition or heat production. This time scale is about twice the age of the Earth, meaning that the quasi-steady state assumption usually made in parameterised thermal evolution models is not valid [16]. It also means that very little cooling has occurred in the history of the Earth. Over the last 2.5 Gyr, the continental area has been approximately constant [e.g. 17] and the only potentially varying parameters in the definition of τ_C are a_{max} and $\lambda(f)$. We first assume that these two parameters are constant, and delay the discussion of this assumption to section 5 for a_{max} and section 7 for $\lambda(f)$.

With the assumptions given above, an analytic solution of equation (9) is:

$$T_m = \left(T_{m0} - \frac{1}{MC_P} \sum_i \frac{H_{oi}}{\tau_C - \tau_i} \right) e^{-t/\tau_C} + \frac{1}{MC_P} \sum_i \frac{H_{oi}}{\tau_C - \tau_i} e^{-t/\tau_i}. \tag{11}$$

Using the parameters of table 1 and 2, the thermal evolution that can be computed from this equation for both the CI and EH chondritic models are represented on figure 6. As foreseen from the estimate of τ_C above, the change in both temperature and heat loss is moderate. In fact, this leads to an exact balance between heat production and heat loss about 3 Gyr ago. The extension of these evolutions to earlier times should not be taken too seriously since the continental area may not have been the same then as it is now, violating

			CI model, TW	EH model, TW
$\tau_{^{235}U}$	704 Myr	$H_{^{235}U}$	0.21	0.13
$\tau_{^{238}U}$	4.47 Gyr	$H_{^{238}U}$	4.84	3.1
$\tau_{^{232}Th}$	14 Gyr	$H_{^{232}Th}$	5	2.5
$\tau_{^{40}K}$	1.25 Gyr	$H_{^{40}K}$	2.32	4.23
		Total	12.37	9.96

Table 2: Radioactivity input data, for the two models used here. Heating rates are obtained by multiplying the concentrations by the rates of heat production per mass and the mass of the mantle. Concentrations are given by [18] for the CI model and by [3] for the EH model.

one of our assumptions. However, the almost constancy of total heat loss for the period over which the continental area was constant and plate tectonics has been operating [19] is in sharp contrast with standard thermal evolution models based on the parameterized convection approach.

4 Constraints from petrology

We have shown that the present heat loss of the Earth argues for a moderate cooling since the onset of plate tectonics. Other lines of arguments can be used to support this idea, coming from experimental determinations of phase diagrams of mantle minerals [e.g. 20–22]. These data provide a constraint on the maximum allowed temperature in a mostly solid mantle, hence on the initial conditions for mantle convection as we know it.

The large impact that resulted in the formation of the Moon is energetic enough to melt the entire Earth [e.g. 23] and the crystallisation of the magma ocean that followed set the initial condition for convection in the mostly solid mantle. The transition from the magma ocean phase, controled by the rheology of the liquid, to a regime controled by the rheology of the solid occured when the solid fraction close to the surface (possibly below a thin solid crust) reached about 60% [e.g. 24]. According to the latest phase diagrams of pyrolite [22] and KLB-1 peridotite [21], this corresponds to a temperature about 200 K higher than the present potential temperature. This places a strong constraint on the maximum allowed cooling since the crystallization of the magma ocean.

A question remains concerning the time at which this temperature has been reached, that is to say the time needed to crystallize the magma ocean up to the rheological transition. The dynamics of the crystallising magma ocean is quite complex and far from being understood [25] but the time scale relevant for its thermal evolution is likely to be very small, owing to the large heat flow out of its surface. Typical parameterized model of this process [24] give a time scale of about 10 Myr. In addition, recent progress on isotopic geochemistry allowed to find evidence for early crust formation as far back as 4.46 Gyr [26], supporting this time scale.

Igneous petrology can also be used to infer melting condition from lava compositions.

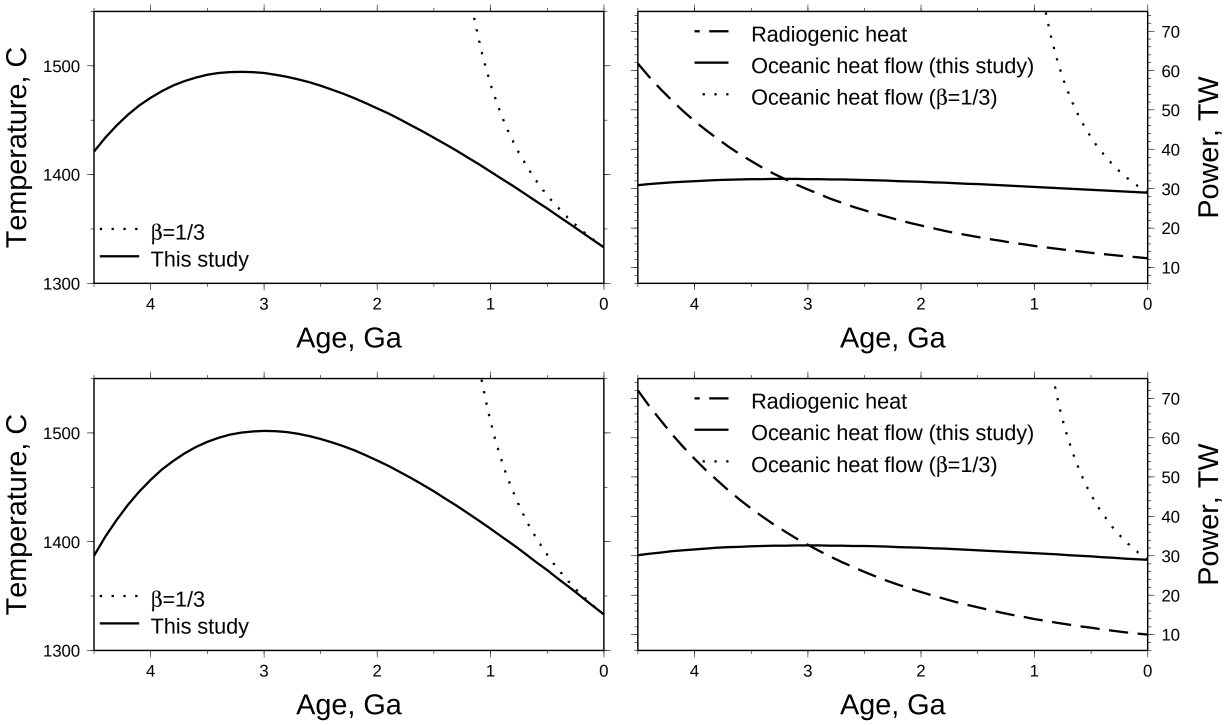

Figure 2: Thermal evolution for the CI model (top) and the EH model (bottom). The dotted lines are obtained by backward in time numerical integration of equation (8) assuming a classical heat flow parameterization.

Komatiites have been used in that prospect to constrain the thermal evolution of the Earth [27]. However, an important debate exists on the origin of komatiites, either related to high temperature (plume) deep melting [28] or coming from low temperature melting of wet material in a subduction environment [29]. The debate is complex but in no case the inferred temperature of melting can be used as a record of ancient averaged temperature. A feature that is nevertheless noteworthy is the spread in melt composition at each given age, which can argue for large lateral variations of mantle temperature, an observation that has also been made for present ridges [30], a point to which we will return below.

5 Comparison with parameterized convection approaches

We have seen that a thermal evolution model of the Earth constructed using the present observation of a long time scale of thermal adjustment poses no difficulty, compared to the standard parameterized models. Let explain here where the difference comes from.

Parameterized models use a scaling law similar to equation (1) to link the heat flow at the surface to mantle temperature. Taking into account the variation of viscosity with averaged temperature in the definition of the Rayleigh number leads to a relationship of the form

$$q = CT_m^{1+\beta}\nu^{-\beta}. \tag{12}$$

Using as viscosity law $\nu = \nu_0(T_m/T_0)^{-n}$, Christensen [31] obtained, after linearising around the present temperature T_0, a thermal evolution equation of the form

$$MC_P\frac{dT_m}{dt} = -Q_0(1+\beta+\beta n)\frac{T_m - T_0}{T_0} + \sum_i H_i e^{-t/\tau_i}. \tag{13}$$

The time scale for thermal adjustment coming from this equation is

$$\tau_a = \frac{MC_P T_0}{(1+\beta+\beta n)Q_0}. \tag{14}$$

Using the classical value $\beta = 1/3$ and $n \simeq 35$ that approximate best the Arrhenius law of mantle materials [31, 32] gives $\tau_a \sim 800$ Ma. This leads to a heat flow at the mantle surface that closely follows the decay of heat production, leading to a present time Urey ratio larger than 0.7. On the other hand, decreasing β leads to an increase in τ_a and a value of 10 Gyr is recovered by assuming $\beta = 0$. This explains why many authors have proposed to decrease the value of β, using different models. However, the arguments used to justify each choice may not apply to the Earth. For example, Christensen [31] argued that, based on models of convection with temperature dependent viscosity, $\beta = 0.1$. However, the models on which this result is based [5] had variations of viscosity that were too small compared to what is expected for Earth's mantle. If larger viscosity contrasts are used, a new regime is obtained where all the viscosity contrast is restricted to the top boundary that becomes too stiff to be recycled by convective movements, a situation hence qualified as stagnant lid regime. Heat transfer in this regime that poorly represents the dynamics of the mantle follows a typical relationship of the form of equation (1) with $\beta \sim 1/3$, although with a different definition of the temperature scale [33].

Another ingredient that has been proposed to modify the value of β is the resistance of plates to bending at subduction zones [7]. In this model, old plates are thicker and more difficult to bend, which counteracts the effect of a larger buoyancy. However, statistical analysis of subduction zone parameters [34, 35] show that slab dip does not correlate with the age of the subducting lithosphere, whereas is does correlate with the absolute velocity of the overriding plate and its nature, oceanic or continental. This disqualifies plate bending energy as an important limiting factor of subduction, at least for the present time.

The effect of chemical buoyancy of the crust and depleted residuum has been emphasized as being a key ingredient to understand the limitation of heat transfer by a hot mantle [8, 9]. However, recent experimental data [36] show that this effect has been previously over-estimated compared to thermal expansion and the importance of this effect for early thermal evolution of the Earth needs a reevaluation.

Other ingredients such as grain size [6] or volatile [37] dependent rheology can also play a role but need further inestigation. We will argue now that the long time scale obtained from the present observations actually results from the Earth operating in a plate tectonic regime, which points to the necessity of rethinking mantle convection far more than by merely changing the value of β.

The classical parameterization represented by equation (12) comes from the concept of boundary layer stability (Howard's model [38]), valid for high Prandtl number fluids. In this model, boundary layers grow by conduction following a infinite half-space law (eq. 2) and become unstable when a critical amount of buoyancy has accumulated. The boundary layer then breaks off, mix with the interior, and a new boundary layer develops. The time taken for the buildup of the boundary layer is much larger than that taken for mixing, and heat transfer characteristics can all be obtained by a time-average of the conduction period. This model provides a fairly good fit to a space average convective system [e.g. 39] and results in a local boundary layer Rayleigh number of a fixed averaged value (different from the critical one [39]), Ra_δ:

$$Ra_\delta = \frac{\alpha g T_m \delta^3}{\kappa \nu} = Ra \left(\frac{\delta}{d}\right) \left(\frac{T_m}{\Delta T}\right), \tag{15}$$

with δ and d the thicknesses of the boundary layer and the whole domain, respectively, T_m and ΔT the temperature differences across the boundary layer and the whole domain, respectively. The heat flux can be simply retrieved from this:

$$Q \equiv \frac{kT_m}{\delta} = \frac{k\Delta T}{d} \left(\frac{Ra}{Ra_\delta}\right)^{1/3} \left(\frac{T_m}{\Delta T}\right)^{4/3}, \tag{16}$$

which provides the classical scaling with $\beta = 1/3$. To summarize, the classical scaling law for heat transert at high Rayleigh number comes from two ideas: heat transfer is controlled by the conductive growth of thin boundary layers (meaning that an infinite half-space approximation holds) and vertical movement is triggered where and when a critical amount of buoyancy has accumulated. From the present distribution of seafloor ages we know that subduction occurs independently of seafloor age, contradicting the second point, whereas the first one is clearly valid [4]. For this reason, we assumed in § 3 that the maximum seafloor age has been constant with time. If, on the other hand, we assume that this maximum age is controlled by the local buoyancy of the plate, its thickness at that age is such that the Rayleigh number of the boundary layer at that point is equal to the critical one R_c, that is $\sqrt{\pi \kappa a_{max}} = (R_c \kappa \nu / \alpha g T_m)^{1/3}$. From equation (6), the oceanic heat flux is then

$$Q_{oc} = \lambda(f) A_{oc} k \left(\frac{\alpha g}{R_c \kappa \nu}\right)^{1/3} T_m^{4/3}. \tag{17}$$

The scaling law classically used to compute the thermal evolution of the Earth (eq. 12) is recovered. Using this parameterization of the oceanic heat flow, a viscosity depending on temperature as $\nu \propto \exp(40000/T_m)$ [e.g. 31], we solved numerically equation (8) backward in time starting with the same present state as that used above and obtained the dotted lines of figure 6. As usual with such a scaling law [e.g. 31] and a present Urey ratio of about 0.5, a runaway increase of temperature is found, disqualifying this parameterization and the argument that the maximum age of the lithosphere is controlled by its stability.

Another argument can be put forward to claim that the maximum age of the sea floor is not set by a local stability issue. It is well known that the lithosphere stops thickenning after an age of about 80 Myr [see 4, for a recent discussion], and thermal buoyancy does not accumulate further. The local Rayleigh number does not change significantly for oceanic lithosphere aging from 80 to 180 Myr and there is no reason for it to be more unstable at the latter age than at the former.

6 Significance of the observed age distribution

To understand what makes the heat flow out of the Earth follow a scaling different from standard convection systems, we need to understand the significance of the age distribution displayed on figure 1 and the prediction that these models would give.

We have seen that equation (2) relating the surface heat flux to the age of the oceanic lithosphere gives a rather accurate description of the observations. Although the notion of age of the lithosphere is not straightforward in convection models, their dynamics at high Prandtl number is still well understood in terms of conductive growth of the boundary layer following equation (2) (Howard's model, see § 5). We can then use the heat flux as a proxy to attribute a pseudo age to each point on the surface of any given convection model (analog or numerical) by writing $age = 1/q^2$. This is what we do in the following in order to compare the pseudo age distribution from convection models to that of the Earth.

Figure 3 shows the result of such a computation for the simplest possible convection model, Rayleigh-Bénard convection with internal heating with constant physical parameters. The snapshot is typical of this type of dynamics, controlled mostly by down welling plumes [40]. The heat flux distribution has a pic at 42, that is close to the average (42.246) and the median (42.875) and very similar to the time-averaged value (43.1) [39]. However, the distribution is skewed, which is typical of internally heated convection [42]. The pseudo-age distribution has a strong pic at small values, corresponding to the high heat flux patches on the map. The decrease as function of age is clearly not linear and is actually faster than exponential (not shown) reflecting the small surface occupied by cold down welling currents.

The model just presented being admittedly simplistic, we performed the same analysis on a result from a model that allows self-consistent plate tectonics using a pseudo-plastic rheology [43]. This model was shown to follow a classical heat transfer scaling, with a coefficient that depends on plate sizes [41]. Figure 4 shows that different plates, despite having different sizes, have similar velocities, which is well understood in the framework of a loop model [41]. The surface heat flux closely follows equation (2) except in the narrow plate boundaries, as can be seen from the pseudo-age plot. We can see that the maximum pseudo-age (excluding the convergent plate boundaries where the concept does not apply) is then different on each plate. The pseudo-age distribution is then square for each plate as well as globally, their sizes being similar.

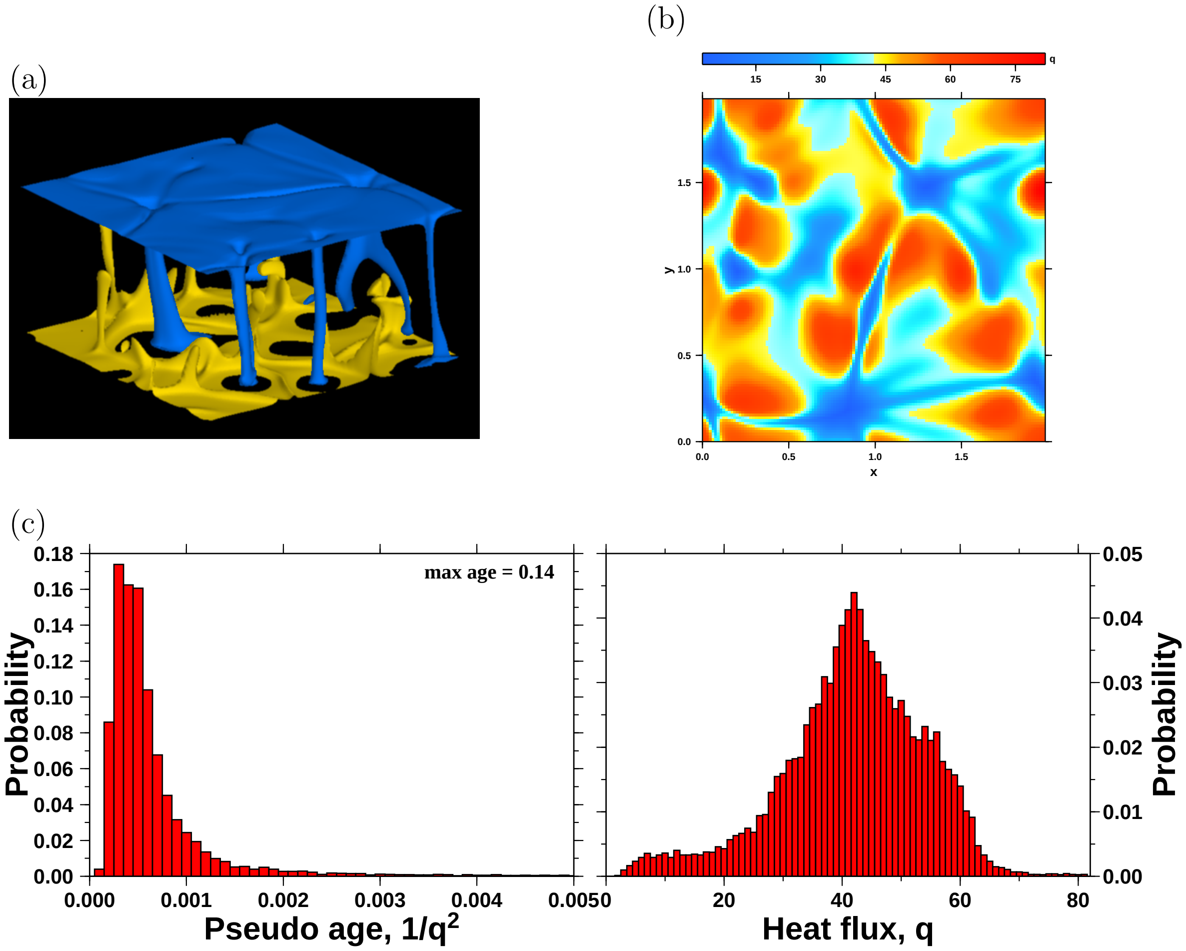

Figure 3: Snapshot of temperature (a), surface heat flux (b) and the corresponding heat flux (q) and pseudo age ($1/q^2$) distribution (c) in a convection system with a Rayleigh number $Ra = 10^7$ and an internal heating rate $H = 20$. From the model of [40].

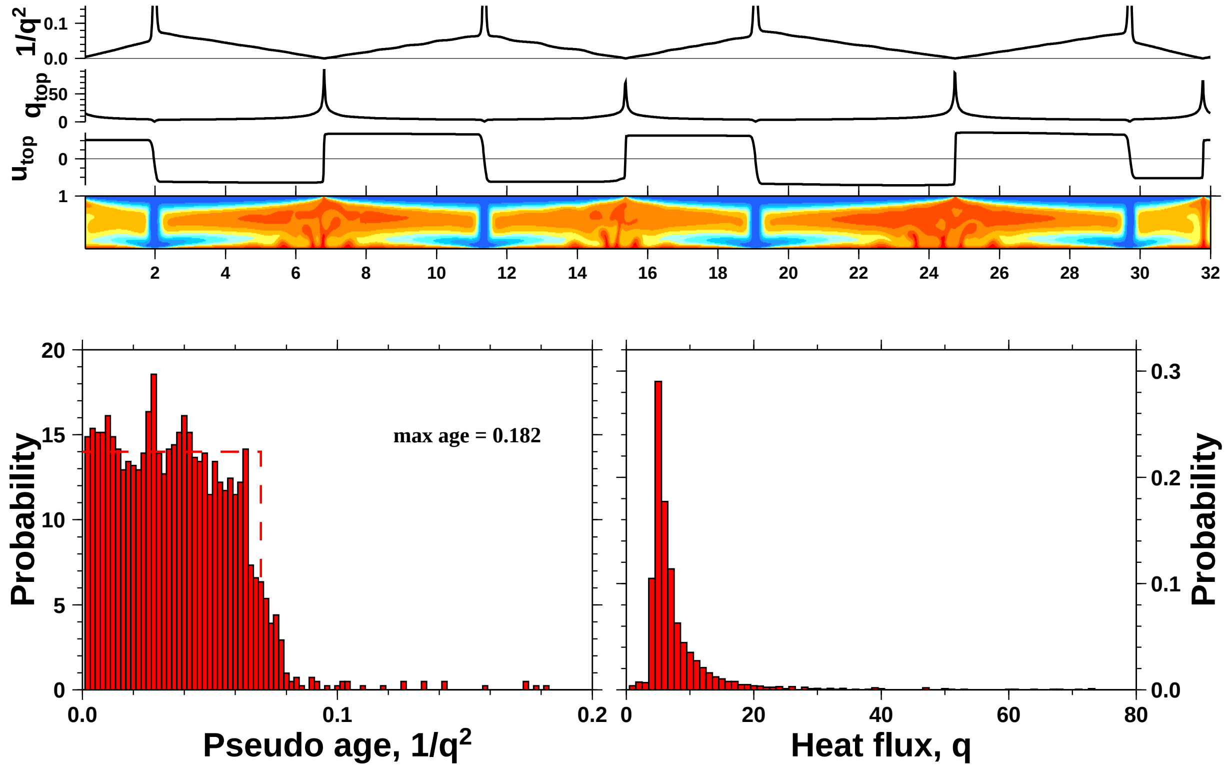

Figure 4: Snapshot of temperature, surface velocity (u_{top}), heat flux (q_{top}) and pseudo-age ($1/q^2$) and corresponding distributions (bottom) for a model with plate like behavior. Data from [41].

We have shown that usual convective plan forms correspond to age distribution functions very different from the one observed on Earth today. It seems then important to try and understand this basic observation in order to understand better mantle convection. The main difference between the models presented above and the Earth is that down welling in the formers occurs only in places that have a low heat flux (large pseudo-age) since they need to be negatively buoyant whereas Earth is able to subduct young warm lithosphere (even ridges). Based on that observation we can construct a schematic plate system that gives the observed age distribution. Figure 5(a) presents a situation similar to that of figure 4 and has a uniform age distribution. If part of the oceanic surface is now masked by continents (represented in gray on the figure 5(b)) so that subduction has an equal probability for each age, we get distribution of ages that is similar to that of the Earth. This requires that plate velocities are not modified in direction or amplitude when compared to the case without continents, which is clearly a gross simplification [44–46]. However, this helps to understand how this linear distribution is possible on Earth: young and warm lithosphere can be subducted when it encounters a continent, provided it is part of a plate that has an overall negative buoyancy. Plate velocities can indeed be rather well explained from the balance of the age dependent thermal buoyancy of slabs

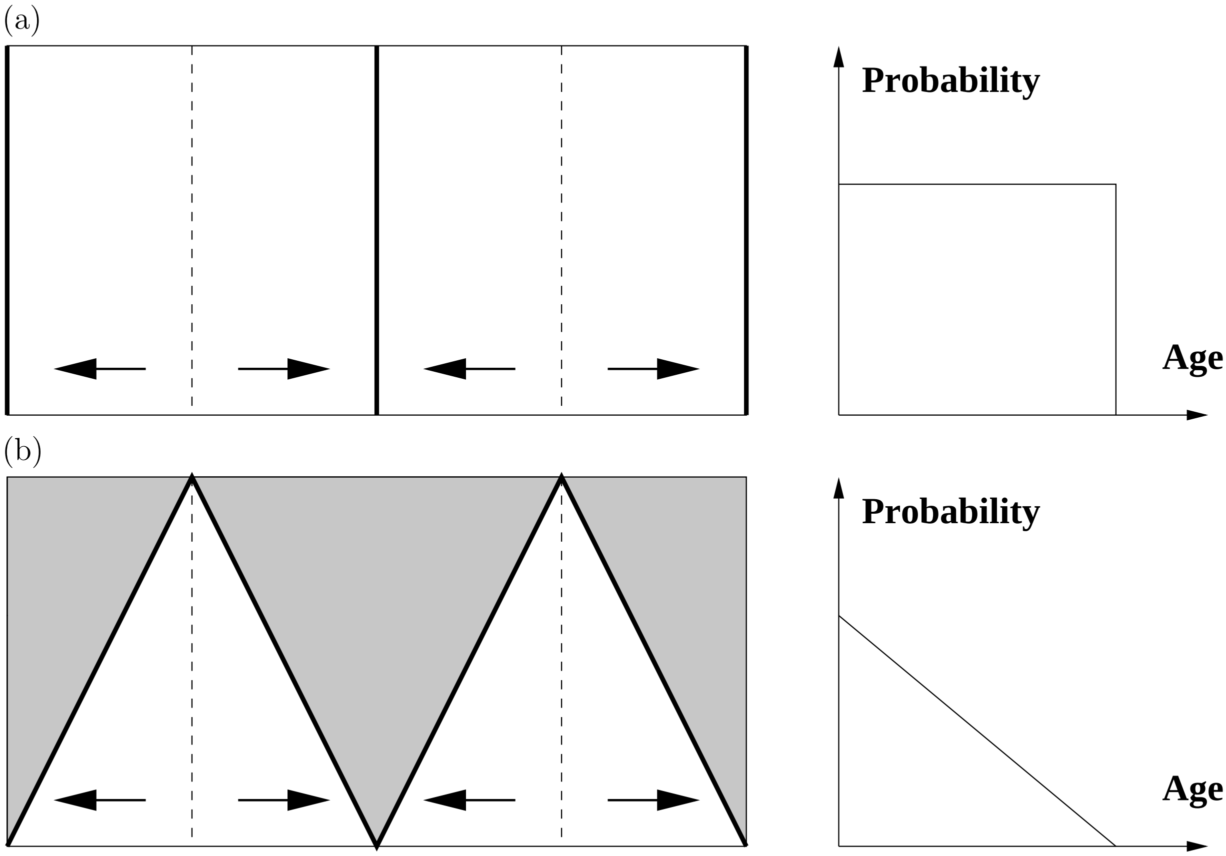

Figure 5: Sketch of possible plate-tectonics systems and the associated age distributions. Thick solid lines are subduction zones and dashed lines are ridges. All plates are assumed to have the same velocity. Case (a) is similar to that of figure 4 and gives a uniform distribution between minimum and maximum age (top right). Case (b) is obtained by masking case (a) with continents (in gray). This gives an Earth-like linear age distribution (bottom right).

and viscous drag of the mantle when integrated over whole subduction segments [45]. The crossing of convergent and divergent plate boundaries that is necessary to get the observed linear distribution of seafloor ages is a clear indication of the peculiarities of plate tectonics when compared to standard convective systems. A good fit in both direction and amplitude of plate velocities requires that the buoyancy of slabs is transmitted to plates by a combination of viscous drag in the mantle and strength of the lithosphere [46] which again is not present in purely viscous models of mantle convection on which heat transfer parameterizations are based.

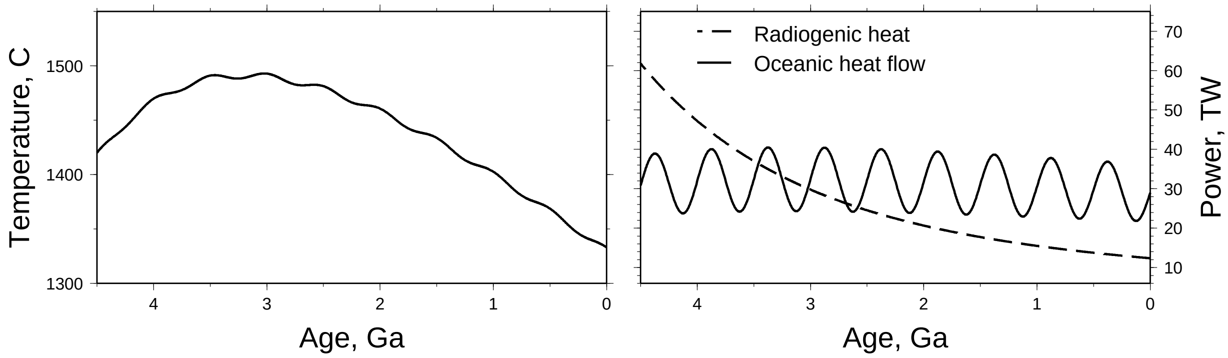

Figure 6: Thermal evolution for a shape factor $\lambda(f)$ varying with time according to $\lambda(f) = 8/3 - 2/3\sin(2\pi a/500\mathrm{Myr})$.

7 Short period fluctuations

The previous thermal evolution calculations are, by construction, smooth. However, plate tectonics is not a steady process and important variations of the heat flow on the time scale of the Wilson cycles are to be expected [41]. Variations in temperature have to be moderate and so should be the maximum age of oceanic lithosphere. The only room for variability in equation (6) lies in the distribution of seafloor ages which is expected to be influenced by the distribution of continents. An extreme case of distribution, which is obtained with two-dimensional rolls of uniform sizes, is a square distribution, $f(u) = 1$, for which $\lambda(f) = 2$ instead of the 8/3 corresponding to the present situation. This would give, for the present time, a total oceanic heat loss 30% below what is actually observed, that is 22 TW. This provides an estimate of the variability in the total heat loss of the Earth to be expected on a 500 Ma timescale. Assuming a sinusoidal evolution of the shape factor with age a acording to $\lambda(f) = 8/3 - 2/3\sin(2\pi a/500\mathrm{Myr})$, we get the thermal evolution represented on figure 6. The short term fluctuations of the oceanic heat flow exceed by far the evolution expected on the long term.

One can get convinced of that estimate by realizing that 6 TW come out the Earth due to the medio-atlantic ridge only, a contribution that was inexistent 180 Myr ago. Another argument for these fluctuations comes from the present time lateral variations of the temperature below ridges, as evidences by the chemistry of erupted lavas [30] and the variations of subsidence rates [47]. The amplitude of these large scale variations is about 150 K, of the same order as the total long term evolution obtained above.

A similar variability has been proposed by Grigné et al (2005) [41] from the variability in wavelength of plate tectonics. This variability is rather large and actually much larger than the long term evolution predicted from the present analysis. It then seems that the real challenge in understanding the thermal evolution of the Earth lies in predicting these fluctuations.

8 Conclusion

Convection at infinite Prandtl number is rather well described by the model of Howard [38] for convection at high Rayleigh number. In this model, convection is described as a cycle of conductive growth of boundary layer, instability when a critical amount of buoyancy has accumulated, growth of a new boundary layer, and so on. Using an ergodicity assumption and the fact that the instability accounts for a small fraction of the total cycle time, this allows the computation of the averaged temperature profile and a scaling law for the heat transfer of the form of equation (16). One important assumption behind this model is that vertical flow starts from the boundaries *at the places where the critical Rayleigh number for thermal instability is reached*. This assumption appears to be rather good for convection in systems with constant [e.g. 39, 40, 48, 49] or temperature dependent [e.g. 11, 33] viscosity, or even more complex rheologies [e.g. 41].

On the other hand, as evidenced by the present distribution of seafloor ages, the Earth mantle behaves very differently since it is able to subduct a lithosphere of any age, even ridges, with the same probability. This means that local buoyancy has little to do with subduction. However, the only available force is buoyancy but whole plates have to be considered [46], instead of the buoyancy at the subduction only. In addition, continents are stable and resist subduction, due to their positive chemical buoyancy. This buoyancy overwhelms thermal buoyancy and allows subduction of ridges. The importance of continents in controling the subduction process means that their effect in the thermal evolution of the Earth is of first importance. The growth of continents over time needs to be taken into account not only in the long term evolution [50] but also for the short term fluctuations. Variations in the surface heat flow due to the change of seafloor age distribution can be as high as 30%, and likely occurs on the timescale of the Wilson cycle, about 500 Ga. On the other hand, the time scale for the long term evolution of the Earth is about 10 Ga, and results in a small total variation since the onset of plate tectonics.

The solution presented here (§ 3) is based on the assumption that the maximum age of seafloor has been constant over time, supported by the present time observation that subduction is not related to seafloor age. The classical parameterized models could be recovered within this framework by assuming that the maximum seafloor age depends on the mantle viscosity, which itself depends strongly on temperature. The model would then run into the same problem as previous ones, a very late crystallization of the magma ocean. One can then turn the problem around and argue that the maximum seafloor age cannot depend strongly on temperature and has been almost constant over time.

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