Effects of Continents on Earth Cooling: Thermal Blanketing and Depletion in Radioactive Elements

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Effects of continents on Earth cooling: thermal blanketing and depletion in radioactive elements.

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Abstract. Estimate of mantle heat flow under continental shields are very low, indicating a strong insulating effect of continents on mantle heat loss. This effect is investigated with a simple approach: continents are introduced in an Earth cooling model as perfect thermal insulators. Continental growth rate has then a strong influence on mantle cooling. Various continental growth models are tested and are used to compute the mantle depletion in radioactive elements as a function of continental crust extraction. Results show that the thermal blanketing effect of continents strongly affects mantle cooling, and that mantle depletion must be taken into account in order not to overestimate mantle heat loss. In order to obtain correct oceanic heat flow for present time, continental growth must begin at least 3 Gy ago and steady-state for continental area must be reached for at least 1.5 Gy in our cooling model.

Introduction

Thermal blanketing effect of continents on mantle heat loss is made clear by the difference between the mean oceanic heat flow and the estimated mantle heat flow under continents . Oceanic heat flow is estimated to be around 100 mW/m^2. The mean heat flow at the surface of continents is estimated to be between 49 and 64 mW/m^2 [*Sclater et al.*, 1980], but is due for a large part to the radioactive heat production within continental crust. Mantle heat flow under continental shields can be as low as 11 mW/m^2 [*Pinet et al.*, 1991]. *Lenardic* [1998] pointed out that continents can introduce strong lateral heterogeneity on mantle convection, and that the higher mantle heat loss in the past was accommodated mainly by higher oceanic heat loss, while heat flow below continents stayed broadly constant and low. One of the key parameters in cooling models is the radioactive heating rate of the mantle, and most of the models consider an undepleted mantle, with a present primitive mantle concentration in U over 20 ppb. Our cooling model with U=21 ppb and without continents gives a present day mean heat flow of 77 mW/m^2 and a total heat loss of the Earth of 39 TW. But we consider that radioactive elements extracted from the mantle through continental crust formation do not participate in mantle convection, and must not be taken into account in the present day thermal state of the mantle. With the concentration of a present depleted mantle U=14 ppb, our cooling model gives a present day mean heat flow of 60 mW/m^2(total 30.8 TW), lower than the estimate by *Sclater et al.* [1980], who give a mean surface heat flow of 83 mW/m^2 (total 42 TW). To obtain these correct values, either concentrations in radioactive elements higher than geochimists' estimates are to be taken: U concentration must be raised up to 24 ppb, or the cooling rate of the mantle must be slowed down. Introducing insulating continents may provide a means for the latter solution. *Spohn and Breuer* [1993] studied the thermal blanketing effect of continents and their effect on mantle depletion with a parameterized convection model in which the crust production and recycling rates are proportional to the mantle convection speed. As the relation between convective vigor and continental crust formation is not known, we prefer to test the continental growth rate as an independant parameter, and using mantle concentrations in radioactive elements given by geochimists, we compute the radiogenic heating rate as a function of continental growth. The initial thermal state is chosen in order to obtain the correct present day inner core radius. We investigate the influence of continental growth curves on the obtained present day mantle heat loss.

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Earth cooling model

Parameterized convection model

Our mantle cooling model is based on the parameterization of convection obtained by *Sotin and Labrosse* [1999]. This model is coupled to the core cooling model by *Labrosse et al.* [1997]. The inner core formation and growth can be followed and the obtained present day inner core radius is the main constraint on the model. The dimensionless heat flow at the top of the mantle is $Q_t = (Ra/Ra_\delta)^{1/3}\theta^{4/3}$, where θ is the dimensionless mean temperature of the mantle, Ra its Rayleigh number and Ra_δ the thermal boundary layer Rayleigh number, equal to 24.4 [*Sotin and Labrosse*, 1999]. The actual coefficient ζ in $Q_t \propto Ra^\zeta$ obtained by *Sotin and Labrosse* [1999] is 0.306 and not 1/3, but we keep the latter value since it implies no significant modifications and allows a simpler handling of the spherical case. Although our parameterization was obtained from numerical experiments of convection with no insulator, we introduce continents in the cooling model considering them as perfect thermal insulators: the upper surface through which mantle heat is lost is reduced to the oceanic surface only. The conservation of energy in dimensionless form is then

$$(1-S)Q_t = f^2 Q_b + \frac{H_s}{3}\left(1+f+f^2\right) \qquad (1)$$

where S is the continental areal percent, f the ratio between core and Earth radii ($f = 0.546$), H_s the internal heating rate and Q_b the heat flow at the core-mantle boundary. *Sotin and Labrosse* [1999] showed that θ can be written as a function of H_s and Ra and their relation, modified here by the introduction of continents, is:

$$\theta = \left[1 + \frac{(1-S)^{\frac{3}{4}}}{f^{\frac{3}{2}}}\right]^{-1} + C\left[\frac{1+f+f^2}{3(1-S)}\right]^{\frac{3}{4}} \frac{H_s^{3/4}}{Ra^{1/4}} \quad (2)$$

where C is a constant depending on f, S and Ra_δ. H_s includes both radiogenic heating rate and secular cooling $-\partial\theta/\partial t$. Eq.2 is used to calculate the evolution of the mantle mean temperature with time.

Continental growth curves

A model of continental growth curve $S(t)$ is needed. *Allègre and Jaupart* [1985] pointed out that numerous geochemical studies, based for instance on a direct model of crust/mantle transfer phenomena [*O'Nions et al.*, 1979] or on the evolution curves of Rb/Sr and Sm/Nd ratios in the depleted mantle [*Allègre*, 1982], as well as their own tectonic model taking into account continental material extraction along subduction zones and its destruction in collision zones, all suggest a sigmoidal shape for continental growth curves. We choose to test sigmoidal growth curves with two parameters varying: the beginning t_1 of continental growth ranges between 0 and 3 Gy after the core-mantle segregation (t=0), t_2 ranges between 1.5 and 10 Gy. If a growth curve has an ending time t_2 larger than 4.5 Gy, it means that steady-state of continental area is not reached at present time. All the models tested have a present day continental areal percent of 38%. The shapes of continental growth curves tested in this study are shown on Fig. 1.

Mantle heat production

In most of the models of Earth thermal history, mantle heat production decreases with time only because of the decay of radioactive isotopes: ^{235}U, ^{238}U, ^{232}Th and ^{40}K.

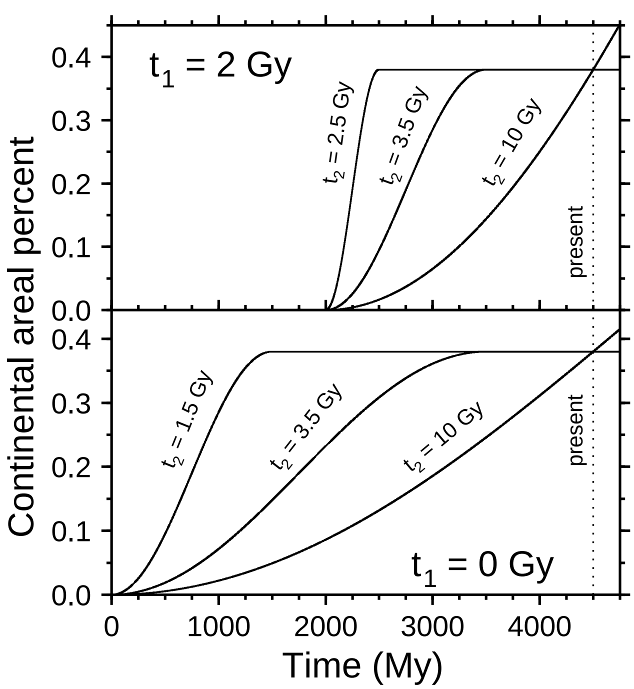

Figure 1. Examples of continental growth curves tested in this study, given in ratio between continental area and Earth total area. t_1 and t_2 are the beginning and the end of continental growth.

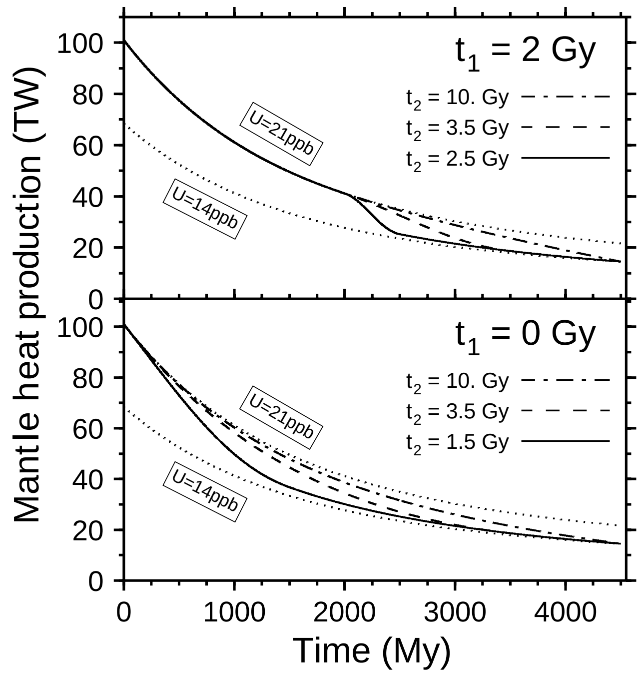

Figure 2. Total heat production of the mantle in TW corresponding to the continental growth curves presented on Fig.1. In dotted lines are the heat productions decreasing with time only because of radioactive elements decay for U=14 ppb (depleted mantle) and U=21 ppb (undepleted mantle).

The ratios Th/U and K/U are well constrained and only the present primitive mantle concentration in U is needed to calculate mantle heat production. This concentration is estimated to be 21±1 ppb [*Allègre et al.*, 1988]. With such a concentration, the mantle heat production is overestimated since a part of the mantle is depleted in radioactive elements. If one considers a depleted upper mantle with the value of 3.5 ppb given by *Allègre et al.* [1988] and a primitive lower mantle with U=21 ppb, the mean concentration for the whole mantle is then U=14 ppb. We calculate the mantle depletion in radioactive elements assuming a constant continental thickness: continental mass is directly proportionnal to the continental areal percent $S(t)$. We use concentrations in radioactive elements in the primitive mantle and in the continental crust given by *Allègre et al.* [1988], and a ratio between the present day continental mass and the mass of the primitive mantle of 0.00538. As *Spohn and Breuer* [1993], we consider that the average concentration in radioactive elements in the continental crust is constant with time. Mantle heat production thus computed as a function of continental growth models is presented on Fig. 2. Its value decreases with time from 101 to 14.5 TW, instead of 21.6 TW for a present undepleted mantle.

Results

The obtained mantle thermal evolution results from the two effects introduced: effect on mantle depletion and thermal blanketing effect. The mean temperature of the mantle and its secular cooling as a function of time are presented on Fig. 3 and Fig. 4. The explicit computation of mantle depletion results in a higher initial temperature compared to the case of an always depleted mantle, due to an excess of radiogenic heating. This effect does not last if no continental blanketing is introduced (dotted line): the initial high temperature only results in a lower viscosity, a more vigorous convection and then a higher cooling rate (see Fig. 4). The obtained present day thermal state is then roughly the same as in the case of a depleted mantle with no continents (see Fig. 3). The insulating effect of continents clearly slows down mantle cooling (dashed lines) and this effect is stronger when continental growth is rapid. It increases the obtained present day mean temperature by around 90 K. Fig. 5 presents the obtained present day surface heat flow for the different continental growth curves tested. For a given beginning of growth t_1, the heat flow decreases with the continental growth ending time t_2. For t_2 running from 6 to 10 Gy, the heat flow stops its decrease because continental growth curves do not vary significantly anymore. The same study was carried out for models where only mantle depletion in radioactive elements is taken into account, with no effect of thermal blanketing (noted DE on Fig.5). The present day surface heat flow is then higher when continental growth is late and slow, because the initial excess of radioactive heating then lasts longer (see Fig.2). But this effect is small and the present day surface heat flow is still always lower than 70 mW/m^2. The study was also carried out for models with only a thermal blanketing effect and no effect of mantle depletion (noted TBE on Fig.5). The present day surface heat flow then obtained is always lower than in the case with both thermal blanketing effect and depletion effect, for the same times t_1 and t_2, if we take an always depleted mantle (U=14 ppb), and always higher if we take an undepleted mantle (U=21 ppb). For reasonable models of continental growth, that is to say for $t_1 < 2$ Gy and $t_2 < 3$ Gy, taking into account mantle depletion raises the obtained final heat flow by around 5 mW/m^2 compared to the model of an always depleted mantle. On the other side, not taking into account mantle depletion and using U=21 ppb can lead to an overestimate of the final oceanic heat flow by more than 20 mW/m^2. In our models, continents are taken as perfect thermal insulators and mantle can be cooled down only through oceanic surface. The obtained oceanic heat flow is then to be larger than the 100 mW/m^2 measured. Our models, considering both insulating and depleting effects of continents, predicts that such values can be obtained only if continental growth begins before 1.5 Gy after the beginning of the modelization and ends before 3 Gy, that is to say that continental areal percent is unchanged for at least 1.5 Gy. The maximum heat flow obtained is equal to 105 mW/m^2. This heat is lost through 62% of the total terrestrial area. The present day total heat loss of the mantle is then at most of 33 TW. The continental concentrations in radioactive elements we use give a radioactive heat production within continents of 7 TW. We thus obtain a maximum total heat loss of the Earth of 40 TW.

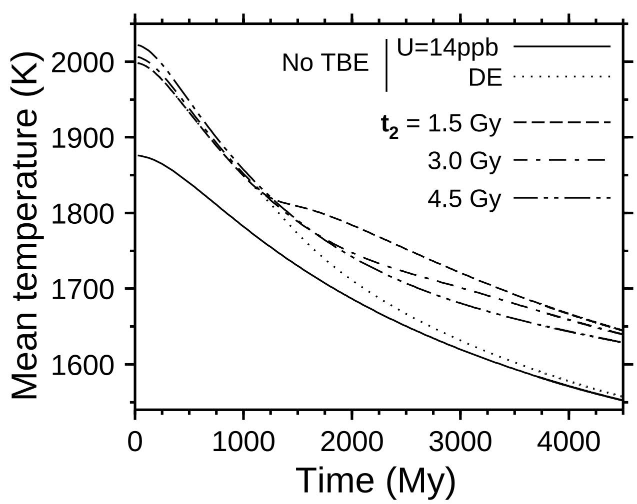

Figure 3. Evolution of mantle mean temperature with a continental growth beginning at t_1 =1 Gy and ending at various times t_2. Dashed lines are obtained with both thermal blanketing effect and explicit computation of mantle depletion. No TBE indicates no thermal blanketing effect: solid line (U=14 ppb) for an always depleted mantle and dotted line (DE) for an initial undepleted mantle and a final depleted mantle.

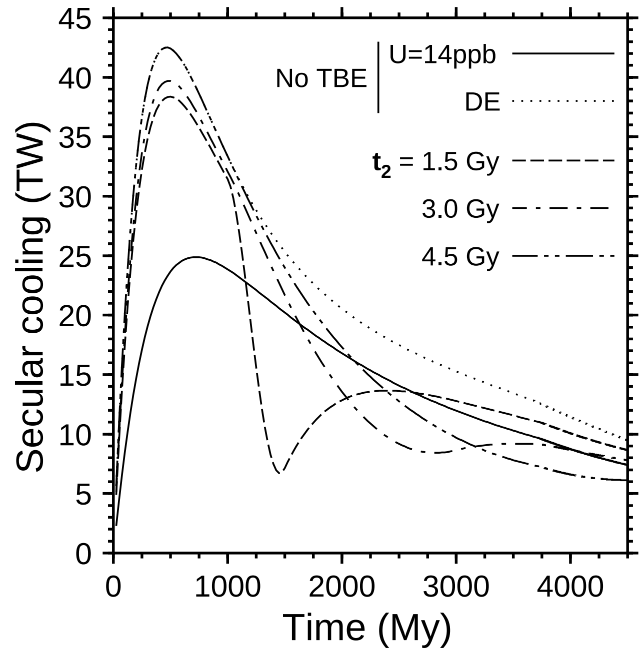

Figure 4. Evolution of mantle secular cooling with continental growth beginning at t_1=1 Gy. For notations see Fig.3.

Discussion and conclusion

Two continental effects on mantle cooling are investigated in this study and various continental growth curves are tested. Our models show that the effect of thermal blanketing of continents on mantle cooling has a much stronger influence on the obtained present day surface heat flow than the effect of mantle depletion in radioactive elements. The explicit calculation of this depletion as a function of continental growth induces an excess of radioactive heating before the formation of continents but this excess is rapidly lost by a more vigorous convection, and the obtained present day surface heat flow is higher than in the case of an always depleted mantle only by a few mW/m^2. Mantle depletion must however always be introduced in models with insulating continents, otherwise the oceanic heat flow can be overestimated by more than 20 mW/m^2. The insulating effect of continents slows down mantle cooling and increases the present day surface heat flow. However to simple to allow

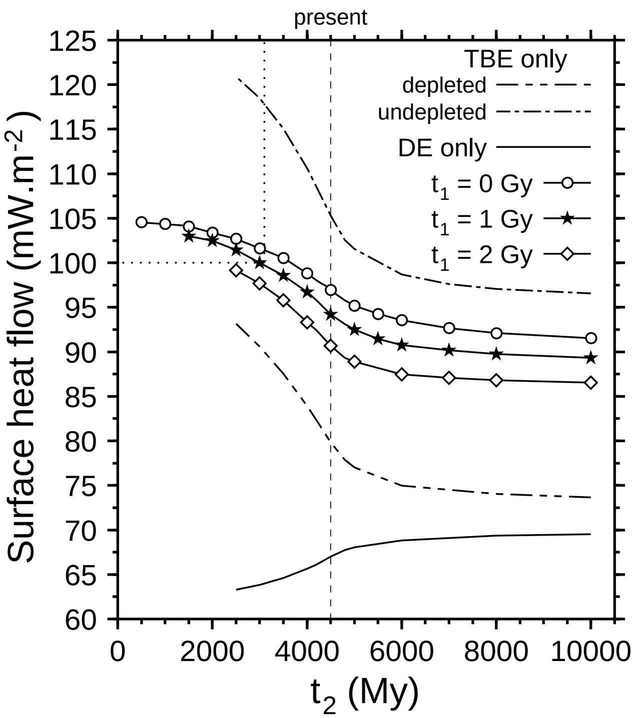

Figure 5. Present day surface heat flow obtained for different continental growth curves. t_1 and t_2 are the beginning and end of continental growth. Solid lines with symbols are obtained with both thermal blanketing effect (TBE) and depletion effect (DE). Dotted lines bound the continental growth curves which give a heat flow higher than 100 mW/m^2. Also presented are the models with TBE only, for a depleted (U=14 ppb) and for an undepleted mantle (U=21 ppb), and the models with DE only, both for t_1=2 Gy.

a discrimination between continental growth curves shapes, our model constrains the timing of the curve: oceanic heat flows larger than 100 mW/m^2 can be obtained only if continental growth has begun before an age of 3 Gy, which is compatible with the age of the oldest known minerals containing a component of re-worked continental crust (4.3 Gy-old zircons, *Mojzsis et al.*, 2001), and if most of the present continental area has been produced for at least 1.5 Gy, in agreement with recent geochemical studies [*Collerson and Kamber*, 1999]. Continents are taken as perfect thermal insulators but the total heat loss of the Earth we calculate is still a little too low compared to the estimates by *Sclater et al.* [1980]. The parameterized convection model used in this study is based on numerical experiments of convection of a fluid layer with no insulator. Numerical experiments of convection with insulating plates, built up on the same scheme as the experiments by *Guillou and Jaupart* [1995], are now carried out in order to improve this parameterization by taking into account continents dynamical effect. A further decrease in heat transfer efficiency is expected.

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