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The effect of continents on mantle convective stirring

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[1] We have investigated the influence of continental lids on mantle convective stirring efficiency using numerical experiments and analytical theory at infinite Prandtl number with strong temperature dependence of viscosity. Differences between oceans and continents are accounted for by imposing heterogeneous surface boundary conditions for temperature and velocity. We measure the convective stirring efficiency using mixing times and Lyapunov exponent distribution. We quantify systematically the influence of the Rayleigh number, the horizontal extent of continental lids and the rheology on mantle convective stirring efficiency. The presence of continents increases the mantle temperature and therefore reduces mantle viscosity. This in turn leads to an increase of convective vigor and results in a drastic enhancement (3–6 fold, and possibly up two orders of magnitude increase) of mantle convective stirring efficiency.

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1. Introduction

[2] Interpreting surface geochemical data requires an understanding of the dynamic mechanisms that preserve or erase chemical heterogeneities over geological times. One of the most striking and puzzling features of the Earth's mantle is its heterogeneity at various length scales strongly inferred by geochemical data [see *Hofmann*, 1997, and references therein]. These observations contrast with the fact that the Earth's mantle has been vigorously convecting for several billions of years, which would tend to homogenize heterogeneities [e.g., *Olson et al.*, 1984; *Manga*, 1996; *van Keken et al.*, 2003; *Farnetani and Samuel*, 2003; *Tackley*, 2007]. The competition between mechanisms creating heterogeneities and homogenization via mechanical stirring is therefore directly related to mantle dynamic processes.

[3] Among these, the presence of continental lids is known to have a first order impact on convective dynamics and heat transfer. On Earth, oceanic plates are recycled into the mantle and are characterized by a relatively strong heat flux [*Pollack et al.*, 1993], while continents are more insulating [*Pinet et al.*, 1991], lighter and therefore not subductable. Numerical and laboratory experiments have demonstrated that this dichotomy between continents and oceans can have a first order influence on mantle motions, convective wavelength, heat flow and thermal evolution [e.g., *Gurnis*, 1988; *Lowman and Jarvis*, 1993; *Guillou and Jaupart*, 1995; *Lenardic and Moresi*, 2003; *Grigné et al.*, 2007]. One should therefore expect that continents would also influence the efficiency of convective stirring over billions of years. While a number of geodynamic studies have estimated mantle mixing times [see *Tackley*, 2007, and references therein], this effect has not been considered in previous studies.

[4] We have therefore investigated the influence of continental lids on convective stirring efficiency using numerical experiments and analytical modeling.

2. Numerical Experiments

[5] We conducted numerical experiments in a 2D Cartesian domain of thickness L = 3000 km, heated from below and cooled from above, of aspect ratios ranging between 3:1 and 6:1. In this domain we solve the conservation equations for mass, momentum, and energy for a Boussinesq viscous fluid at infinite Prandtl number with the *StreamV* code that uses a stream function, finite volume formulation on a staggered grid [*Samuel*, 2009; *Samuel and Evonuk*, 2010]. The horizontal boundaries are free slip and the vertical boundaries are periodic. Similar to *Gurnis* [1988] or *Cooper et al.* [2006] the continent of variable horizontal extent is modeled as a four orders of magnitude more viscous, 20% lighter material with weak thermal conductivity. Therefore the later is essentially unsubductable, rigid and insulating, but can move freely in the horizontal directions as a result of mantle motions. We used a horizontal and vertical grid resolution ranging between 3 km to 30 km depending on the Rayleigh number in order to resolve properly thermal boundary layers.

[6] The viscosity varies as: $\eta = \eta_0 \exp[-\gamma(T - 0.5)]$, with η_0 a reference viscosity and γ represents the sensitivity of viscosity to temperature T. The governing parameters for our experiments are the continental lateral extent S, γ, and the reference Rayleigh number $Ra_0 = \rho_0 \alpha g \Delta T L^3/(\eta_0 \kappa)$, where $\rho_0 = 4500$ kg m^{-3}, $\alpha = 10^{-5}$ K^{-1}, $g = 10$ m s^{-2}, $\Delta T = 1000$ K and $\kappa = 10^{-6}$ m^2 s^{-1} are reference density, thermal expansion, gravity, temperature contrast imposed between the upper and lower surfaces, and thermal diffusivity, respectively. Similar to *Cooper et al.* [2006] for temperature dependent cases we use a Byerlee-type plastic yielding with a weak yield stress in order to avoid the development of a stagnant lid that would occur otherwise in the cold upper thermal boundary layer.

[7] We measure the convective stirring efficiency using two Lagrangian methods: the first determines the mixing time associated with different wavelengths of heterogeneity following the approach of *Ferrachat and Ricard* [2001]. The second determines the value of the maximum Finite Time Lyapunov Exponents (FTLE), λ^+ as described by *Farnetani and Samuel* [2003], and measures the rate at which heterogeneities will be stretched by mantle motions. These methods

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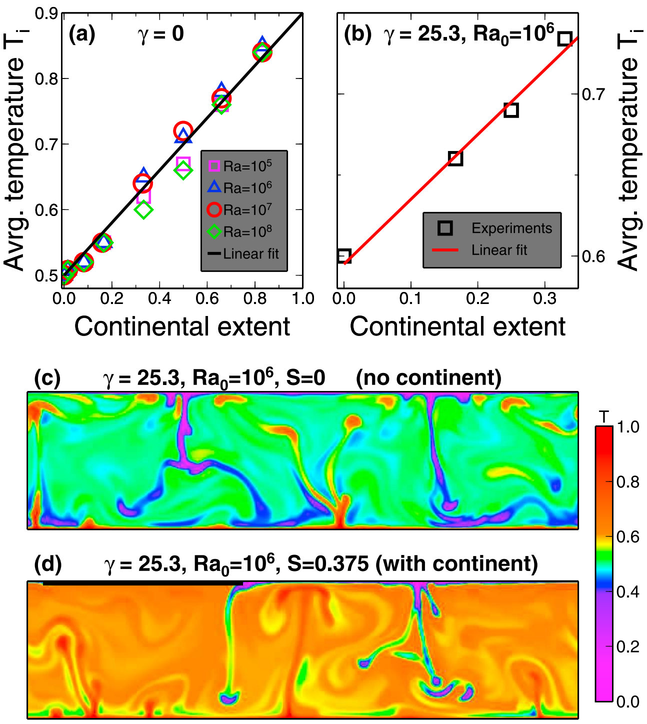

Figure 1. Effect of continents on the thermal structure. (a) Average mantle temperature T_i as a function of the continental surface S for cases with various Rayleigh numbers and for constant viscosity $\gamma = 0$. The experimental data is well fitted by a linear expression (black line). (b) Average mantle temperature T_i as a function of the continental surface S for cases with $Ra_0 = 10^6$ and $\gamma = 25.3$. The experimental trend is well fitted by a linear expression (red line). Dimensionless temperature fields (for $Ra_0 = 10^6$ and $\gamma = 25.3$) at statistically steady state for (c) a case without continental lid and (d) a case with a continental lid (in black) spanning 37.5% of the upper surface.

were applied after each experiment had reached statistical steady state.

3. Results

[8] We first explored a range of Rayleigh numbers $Ra_0 = 10^5 - 10^9$ and $S = 0 - 0.5$ while keeping $\gamma = 0$. In agreement with previous studies [e.g., *Lenardic and Moresi*, 2003; *Grigné et al.*, 2007] the presence of a continent leads to an increase of the average mantle temperature T_i (see Figure 1a). In addition, the calculated mixing times and the maximum FTLE consistently show an increase of convective stirring efficiency with increasing the Rayleigh number Ra_0, therefore confirming the results of previous studies [*Coltice and Schmalzl*, 2006] (see Figure 2a). However, the significant increase in mantle temperature with continental coverage S does not lead to noticeable differences in convective stirring efficiency (see Figure 2c).

[9] Next we considered experiments at a given reference Rayleigh number $Ra_0 = 10^6$, but with temperature dependent viscosity ($\gamma = 25.3 \cong \ln(10^{10})$), and for various continental lateral extents $S = 0 - 0.5$. We find the resulting temperature field is comparable to the constant viscosity cases: the presence of continents insulates a fraction of the upper surface, resulting in a hotter mantle (Figures 1c and 1d). This temperature increase shown in Figure 1b is well described by a linear relationship: $T_i = 0.59 + 0.4S$. In contrast with the constant viscosity cases, the influence of continents on convective stirring efficiency is significant for cases with temperature dependent viscosity. Figure 2b shows that the distributions of the maximum FTLEs are Gaussian for cases without or with a continental lid, which shows that stirring is efficient in both cases. However, the average value of the FTLE is significantly larger for the case with a continent, indicating a more efficient convective stirring. This trend is observed for various continental extents, as displayed in Figure 2c and was also observed for various values of $\gamma > 0$. We therefore conclude that in the light of our experiments, if viscosity is temperature dependent, the stir-

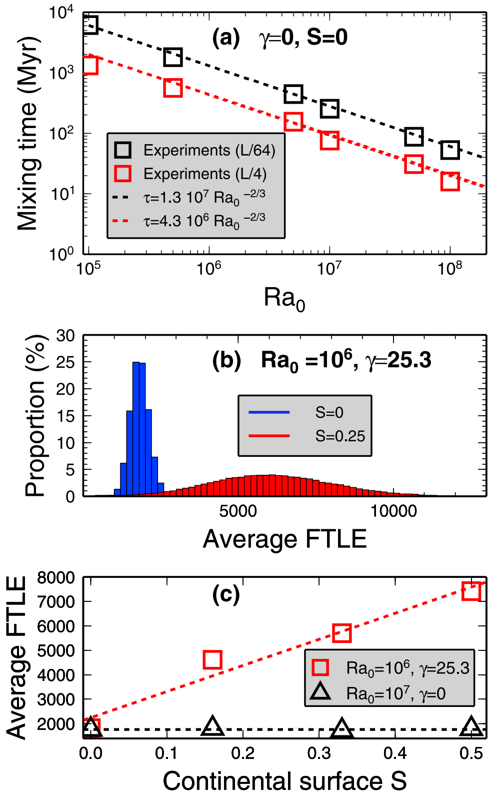

Figure 2. (a) Mixing time corresponding to two selected wavelengths of heterogeneity: L/64 (black) and L/4 (red) as a function of the reference Rayleigh number for constant viscosity and no continent. Squares represent the numerical experiments while dotted lines are a theoretical fits of the chaotic mixing model (equation (2)) with $a = 0.3110^7$. (b) Maximum Lyapunov exponent distributions for two numerical experiments with $Ra_0 = 10^6$ and $\gamma = 25.3$: one without a continent ($S = 0$), the other with a continent ($S = 0.25$). (c) Average value of the maximum Lyapunov exponent, as a function of the continental lateral extent S, for cases with $Ra_0 = 10^7$ and $\gamma = 0$ (black) and for cases with $Ra_0 = 10^6$ and $\gamma = 25.3$ (red). Corresponding linear fits are displayed in by the dotted lines.

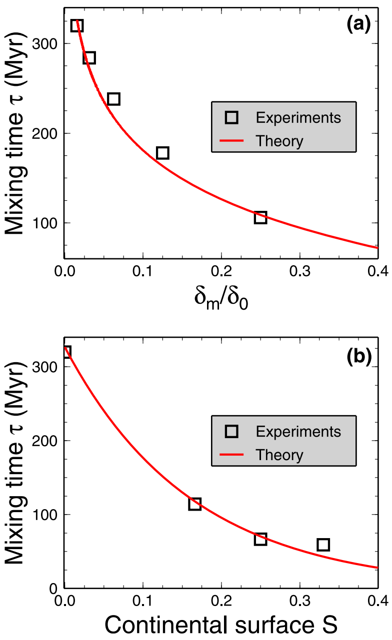

Figure 3. Comparison between the numerical experiments (black circles) and the chaotic mixing model (red curves) for $Ra_0 = 10^6$ and $\gamma = 25.3$. (a) Mixing time τ as a function of the normalized mixing length scale δ_m/δ_0. (b) Mixing time τ as a function of the continental area S.

ring efficiency increases significantly with the continental lateral extent *S*.

4. Chaotic Mixing Model

[10] In order to better interpret our experimental results we derived a chaotic mixing model, along the same lines of *Olson et al.* [1984]. We assume that the mechanical mixing is dominated by pure shear deformation, leading to efficient 'chaotic' mixing where the time evolution of a heterogeneity of size δ can be described by the following differential equation:

$$\frac{d\delta}{dt} = -\dot{\varepsilon}\delta, \qquad (1)$$

where the strain rate $\dot{\varepsilon}$ is assumed to be related to the convective velocities (or to the effective Rayleigh number $Ra_{\rm eff}$) as: $\dot{\varepsilon} \sim Ra_{\rm eff}^{2/3}/L = \{Ra_0 \exp[\gamma(T_i - 0.5)]\}^{2/3}/L$. We use the linear relationship for the mantle temperature $T_i = 0.59 + 0.4S$. The minus sign in the equation above indicates that we are considering the direction where the heterogeneity will be shrinked (i.e., corresponding to the direction perpendicular to the maximum Lyapunov exponent). Assuming that $Ra_{\rm eff}$ remains constant, one can integrate equation (1) and derive an expression for the scale dependent mixing time τ (given in Myrs) defined as the time necessary for a heterogeneity of initial size δ_0, undergoing mechanical stirring, to be reduced to a given size δ_m:

$$\tau = a \ln(\delta_0/\delta_m)\{Ra_0 \exp[\gamma(T_i - 0.5)]\}^{-2/3} \qquad (2)$$

The proportionality constant $a = 0.3110^7$ Myr was determined by least square fitting of the numerical experiments for $\gamma = S = 0$ and $\delta_0/\delta_m = 64$ (see Figure 2a).

[11] We have tested this mixing model by comparing the results obtained with equation (2) with our numerical experiments. Figure 3a displays the mixing time τ as a function of the normalized mixing scales δ_m/δ_0 for $S = 0$, and shows a good agreement between the mixing model and the numerical experiment. The influence of the continental lateral extent S observed in our experiments is also well reproduced by the mixing model (see Figure 3b).

5. Discussion

[12] We have used our chaotic mixing model to address the fundamental question of the survival of passive heterogeneities in the Earth's mantle convective flow. Using equation (3) we have plotted in Figure 4a the mixing time as a function of the continental coverage and the mixing length scale for $\gamma = 25.3$ and $Ra_0 = 10^6$. The results illustrate the dominant importance of the continent lateral extent S on the stirring efficiency. For all length scales of heterogeneity, changes in S affect mixing times by several orders of magnitude.

[13] One can use our chaotic mixing model to address a first order question for the interpretation of geochemical

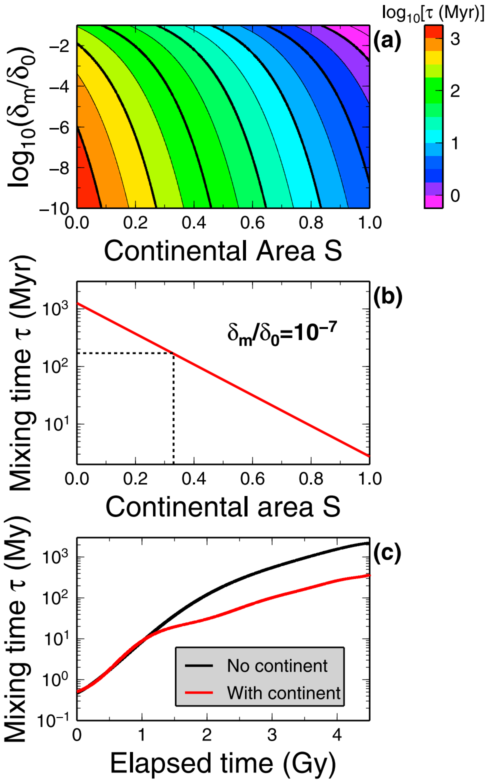

Figure 4. Results of the chaotic mixing model for $Ra_0 = 10^6$. (a) Mixing time τ as a function of the normalized mixing length scale δ_m/δ_0 and the continental area S for $Ra_0 = 10^6$ and $\gamma = 25.3$. (b) Mixing time τ as a function of the continental area S for $Ra_0 = 10^6$, $\gamma = 25.3$ and $\delta_m/\delta_0 = 10^{-7}$. (c) Time evolution of instantaneous mixing times τ for a mantle thermal evolution without a continent (black curve) and a mantle thermal evolution with a continent (red curve), for $\gamma = 37$. The thermal evolution models are taken from *Grigné and Labrosse* [2001].

observations: how long does it take for convective motions to homogenize a 10 km thick oceanic lithosphere recycled back into the mantle? Such homogenization can be achieved if the thickness of the oceanic lithosphere is reduced below centimeter size, a scale at which solid state diffusion of slowly diffusing species (i.e., U) can take over mechanical stirring for reasonably short periods of time. This corresponds to a size reduction $\delta_m/\delta_0 \sim 10^{-7}$. Using equation (2) with $Ra_0 = 10^6$ and $\gamma = 25.3$, one can calculate the corresponding mixing time for various continental extents S. The results displayed in Figure 4b illustrate the important influence of continents on τ. For instance, without continents, the time necessary to mix the recycled crust is about 1.3 Gy. This time is reduced to ~160 Myrs if one considers the presence of continents spanning one third of the Earth's surface, similar to the present day value. Of course, this influence is also determined by the sensitivity of viscosity to temperature, represented by the parameter γ, analogous to an activation energy, which is likely to vary between ~10 and 40 [*Karato and Wu*, 1993]. According to equation (2) the ratio $\tau(0)/\tau(S)$ between mixing times without continent to the mixing time with continent (for any wavelength and any reference Rayleigh number) is $\exp[\gamma(T_i(0) - T_i(S)]$, where the difference between the average temperature without continent and the average temperature with continent is typically ~$0.4S$ as mentioned in the previous section and displayed in Figure 1b. Therefore for $S = 0.33$ and for a larger (yet still plausible) value of γ than previously considered, say 39, $\tau(0)/\tau(S) \cong 172.1$. Therefore the presence of continents could increase mantle stirring efficiency by two orders of magnitude.

[14] Although results displayed in Figure 2 correspond to slowly diffusing species, mixing times should remain comparable for more mobile species, such as *He* [*Ricard*, 2007, and references therein].

[15] These calculations assume that the mantle stirring efficiency remains constant, which is unlikely since mantle convective vigor is expected to have decreased with time, as a result of mantle cooling. To account for this effect we have considered two thermal evolutions based on a convection parameterization with or without continent of *Grigné and Labrosse* [2001, Figure 3]. Each model accounts for radiogenic heating and secular cooling, however one model considers the presence of continents growing from $S = 0$ at $t = 1$ Gy before present to $S = 0.38$ at $t = 1.5$ Gy while the other model ignores the presence of continents. We consider here $\gamma = 37$, corresponding to an activation energy of 400 kJ/mol/K and a characteristic temperature scale $\Delta T = 1300$ K. Before the continental growth ($t < 1$ Gyr), both thermal evolution are comparable, however at $t > 1$ Gy, the presence of continent leads rapidly to a ~100 K hotter mantle thermal evolution. Using equation (2) with $\delta_m/\delta_0 \sim 10^{-7}$ this translates to different mantle convective stirring efficiencies, as displayed in Figure 4c. For more than half of its evolution, mantle convective stirring is about 6 times more efficient for the case with a continent. After 4.5 Gyr of evolution, the mixing time is about 2.2 Gy for the case without a continent, and about 370 My for the case with a continent. Both the thermal evolution and mixing models are too simplified to consider that these numbers are definitive. In addition, the influence of continents is modulated by the sensitivity of viscosity to temperature γ, which is likely to be in the range 10–40. This large uncertainty is due to the fact that γ (or the activation energy) depends on poorly known parameters such as deformation mechanisms and the presence of water [*Karato and Wu*, 1993], not to mention experimental uncertainties and extrapolation to mantle conditions. However, even with $\gamma = 25.3$, a value 1.5 times smaller than what we considered in the calculations shown in Figure 4c, the mixing times between the cases with continent and without continent would still differ by a factor ~3.

[16] For simplicity, our numerical experiments did not consider the presence of internal heating due to radioactive decay of *U*, *K* and *Th*. However, in the case of purely internal heating or mixed heating, the presence of continents will also insulate the mantle which would still result in a nearly linear increase of its temperature [*Cooper et al.*, 2006]. In addition, as shown by *Coltice* [2005] the relationship between convective velocities and stirring efficiency remain similar for basal or internal heating. Therefore, not accounting for internal heating in our numerical experiments has probably a minor influence on our results.

[17] One should also wonder how our results would apply to the three dimensional Earth's mantle, where toroidal motions absent in our 2D experiments could play a role in stirring processes [*Ferrachat and Ricard*, 1998]. In fact the main underlying assumption for our 2D results to remain applicable to 3D geometry is that mantle stirring efficiency is directly related to the convective velocities. This has been demonstrated for infinite Prandtl number Rayleigh Bénard convection for 2D and 3D geometry [*Coltice and Schmalzl*, 2006]. We thus believe that our findings would still hold for 3D geometry. Ongoing three dimensional experiments will allow a more quantitative comparison with our 2D results.

[18] Overall, the significant difference in mantle convective stirring efficiency is a robust feature that should be considered for interpreting geochemical data.

6. Conclusions

[19] We have investigated numerically the influence of continental lids on the efficiency of mantle convective stirring with temperature dependent rheology. The presence of continents lead to a hotter mantle, with a corresponding lower viscosity. This viscosity decrease yields more vigorous convection and consequently more efficient stirring. Using a chaotic mixing model in good agreement with our experiments we have shown that mantle stirring efficiency in the presence of continents and for strongly temperature dependent viscosity is directly related to the magnitude of convective velocities. The presence of continents of lateral extent similar to present day leads to a significant (~3–6 fold, and possibly more) decrease of mantle mixing times which must be taken into account when interpreting geochemical data that directly result from the long term evolution of mantle stirring efficiency.

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