Global warming of the mantle at the origin of flood basalts over supercontinents

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ABSTRACT

Continents episodically cluster together into a supercontinent, eventually breaking up with intense magmatic activity supposedly caused by mantle plumes (Morgan, 1983; Richards et al., 1989; Condie, 2004). The breakup of Pangea, the last supercontinent, was accompanied by the emplacement of the largest known continental flood basalt, the Central Atlantic Magmatic Province, which caused massive extinctions at the Triassic-Jurassic boundary (Marzoli et al., 1999). However, there is little support for a plume origin for this catastrophic event (McHone, 2000). On the basis of convection modeling in an internally heated mantle, this paper shows that continental aggregation promotes large-scale melting without requiring the involvement of plumes. When only internal heat sources in the mantle are considered, the formation of a supercontinent causes the enlargement of flow wavelength and a subcontinental increase in temperature as large as 100 °C. This temperature increase may lead to large-scale melting without the involvement of plumes. Our results suggest the existence of two distinct types of continental flood basalts, caused by plume or by mantle global warming.

Keywords: continental flood basalts, supercontinent, mantle convection, plumes, large igneous provinces.

INTRODUCTION

The breakup of continents is often associated with intense mantle magmatic activity at the origin of continental flood basalts. This temporal coincidence, together with domal uplift and subsequent hotspot tracks rooted in the breakup sites, has led several authors to propose that a deep mantle plume head could soften the lithosphere, initiate rifting (Morgan, 1983; Richards et al., 1989), and trigger continental flood basalt emplacement. The largest Phanerozoic continental flood basalt on Earth (~10 million km^2) is the Central Atlantic Magmatic Province, which was emplaced with a peak rate at 199 Ma during the initial breakup of Pangea and is now preserved over four continents (Marzoli et al., 1999). The Central Atlantic Magmatic Province is often cited as a reference example of plume-derived continental flood basalt (Hill, 1991; Courtillot et al., 1999); yet this hypothesis is severely debated because (1) no hotspot track has been identified (McHone, 2000), (2) the geometry of the Central Atlantic Magmatic Province is elongated, not radial, as would be expected from a plume model, (3) the area near the Blake Plateau (that would record the maximum uplift above the center of the hypothetic plume head) does not show evidence of uplift—only thin subhorizontal lava flows are preserved (McBride, 1991; McHone, 2000), (4) the apparent radiating pattern of feeder dike swarms that would result from the impingement of a plume head is an oversimplification that ignores regional lithospheric control (McHone et al., 2005), and (5) the geochemical and isotopic signatures are diagnostic of shallow-mantle sources that experienced ancient subduction and do not bear a deep plume composition (Pegram, 1990; Puffer, 2001; Verati et al., 2005).

In this paper, we propose an alternate nonplume model for the generation of the Central Atlantic Magmatic Province on the basis of numerical simulations of mantle convection involving continents. We show that continental aggregation favors longer length scales of flow and naturally generates a subcontinental warming of 100 °C without the involvement of hot active plumes. Our model supports and quantifies the idea of Anderson (1982) who proposed that continental assembly would cause an increase in mantle temperature and the breakup of Pangea.

HYPOTHESIS AND TESTING

Without hot plumes, a significant change of the convective flow is needed to decrease heat transport efficiency and significantly elevate the temperature. Our hypothesis is that the subcontinental heating is generated by an increase of the flow wavelength caused by continental aggregation. Indeed, in convection, the larger the wavelength, the less efficient the heat removal and hence the higher the temperature (Grigné et al., 2005). Continental rafts are known to impose their own wavelength on mantle convection (Guillou and Jaupart, 1995; Zhong and Gurnis, 1993; Phillips and Bunge, 2005) by impeding downwelling below them (Gurnis, 1988). As a consequence, the assembly of a supercontinent should force larger length scales and drive the underlying mantle toward higher temperatures. This agrees with the proposal of Anderson (1982), who argued for higher temperatures generated by the aggregation of Pangea.

To test this hypothesis, we set up numerical models of mantle convection incorporating continental lithosphere. The models are purely heated from within in order to eliminate hot plumes. The vigor of convection is expressed by the Rayleigh number

$$\mathrm{Ra} = \frac{\rho^2 g H \alpha h^5}{k \kappa \mu}, \quad (1)$$

where ρ, g, H, α, h, k, κ, and μ are the density, the acceleration due to gravity, the heat production, the thermal expansivity, the depth, the thermal conductivity, the thermal diffusivity, and the viscosity, respectively.

Continents are defined to first-order by their buoyancy, limited internal deformation, and low surface heat flux. There are several approaches for representing these characteristics in a mantle convection model. We tried two of them. In the two-dimensional (2-D) calculations performed with ConMan (King et al., 1990), we followed Gurnis (1988) by introducing ~290-km-thick, highly viscous and buoyant rafts, to mimic the cratonic lithosphere (Artemieva and Mooney, 2001). Additional complexities, such as weak zones on the edge of the continents (Zhong and Gurnis, 1993) or deformable continents (Lenardic et al., 2003), were not considered in this study. To account for realistic wavelength (five times the thickness of the mantle) and continental cover (30%), the aspect ratio of the model had to be 16:1. Wraparound boundary conditions were used in the simulations in order to allow relative motion between the mantle and the rafts.

In the three-dimensional (3-D) spherical simulations performed with TERRA (Bunge and Baumgardner, 1995), continents were modeled by rigid semispherical caps covering a total of 30% of the surface. As in Phillips and Bunge (2005) and Davies (2002), the surface temperature over the continental regions was set to the mean mantle temperature at the base of the upper boundary layer. This technique prevented high heat flow and subduction below the cap and yielded upper bounds on subcontinental temperature anomalies.

We also investigated the role of a viscosity increase with depth since it generates a long wavelength structure that can compete with the influence of the continents. For this reason, most of the models incorporated a mid-mantle viscosity jump of a factor of 30 as suggested by geoid inversions (Ricard et al., 1993). We did not use temperature-dependent viscosity because it leads to a stagnant lid regime that prohibits continental drift, which is irrelevant to Earth. The heat production was determined for a given Ra in order to obtain 1350 °C for the average temperature at the base of the boundary layer outside continental regions.

RESULTS

We first studied the intrinsic temperature difference between the supercontinent and configurations with dispersed continents. We fixed the positions of the continents and computed an equilibrium temperature field by stacking the temperature fields over several billion years to remove the time-dependent features and obtain a statistical steady state. We compared the average temperature at the base of the boundary layer below the continents. Figure 1 displays the temperature fields for aggregated and dispersed models in 3-D. The temperature below the supercontinent is ~10% higher than that below the two continents. Figure 2 shows that subcontinental temperature correlates inversely with the number of continents (at constant continental area). As we move from eight to two continents, subcontinental temperatures remain within 40 °C. However, with a single supercontinent, the convection planform is dominated by spherical harmonic degree 1 (Phillips and Bunge, 2005), and temperatures are on the order of 100 °C higher than with dispersed continents.

The large temperature excess observed in the supercontinent configuration is maintained as we vary the convection parameters (Fig. 3). Although we used different methods, the 2-D and 3-D results are consistent and confirm the hotter subcontinental temperatures of the aggregated state across a range of Rayleigh numbers. In the isoviscous models, the excess temperature does not depend on convective vigor. However, with depth-dependent viscosity, the larger the Rayleigh number, the lower is the temperature excess. This shows that the length scale of the flow imposed by the viscosity jump increases with convective vigor and competes with that of the supercontinent.

We then present 2-D simulations of continental aggregation to investigate the time scale of subcontinental heating. This transient state between dispersed and aggregated continents is modeled by allowing

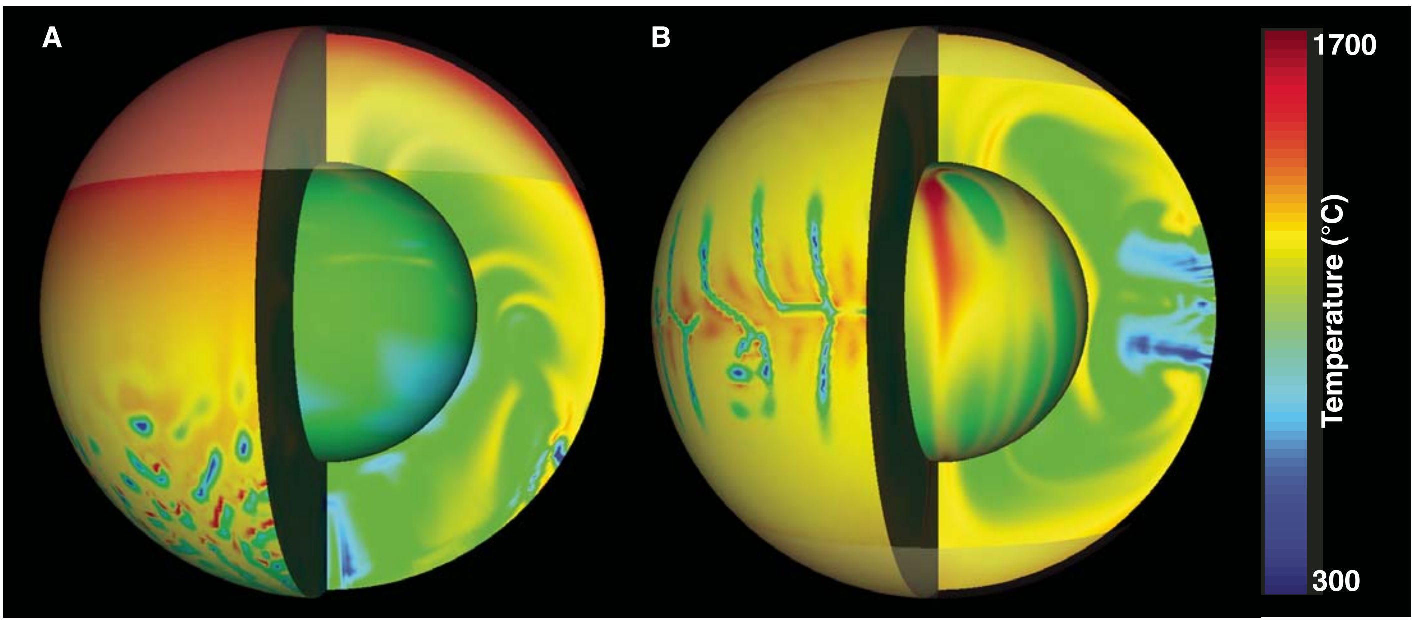

Figure 1. Temperature field snapshots for models with (A) a supercontinent and (B) two antipodal continents. Mean temperature at base of continental thermal boundary layer in (A) is 1614 °C (red), while in (B), it is only 1475 °C (yellow). Translucent caps denote continent locations. Outer surface is at 100 km depth. Heating is purely internal, with a heat production rate of $H = 4 \times 10^{-12}$ W kg^{-1}, viscosity is layered, and the Rayleigh number is Ra = 10^7. Linear features on planetary surfaces delineate regions of cold, subducting material.

one raft to move freely and respond as a rigid body to convective viscous stresses, as in Gurnis (1988). Figure 4 displays the results of a simulation at Ra = 10^8 with layered viscosity. The transition between dispersed and aggregated continents is continuous: the temperature starts to increase before aggregation and does not reach its final value until 300 m.y. after continental assembly. 100 m.y. after continental aggregation, a time scale comparable to the lifetime of Pangea (Van der Voo and Torsvik, 2001), the temperature has already increased by 75 °C. Subcontinental warming is not caused by accumulation of radiogenic heat under the cap, since the required time scale is 1 b.y., but by transfer of heat from outside the continent to the subcontinental domain. Indeed, subcontinental warming is compensated by cooling outside the continental domain in our experiment (Fig. 4).

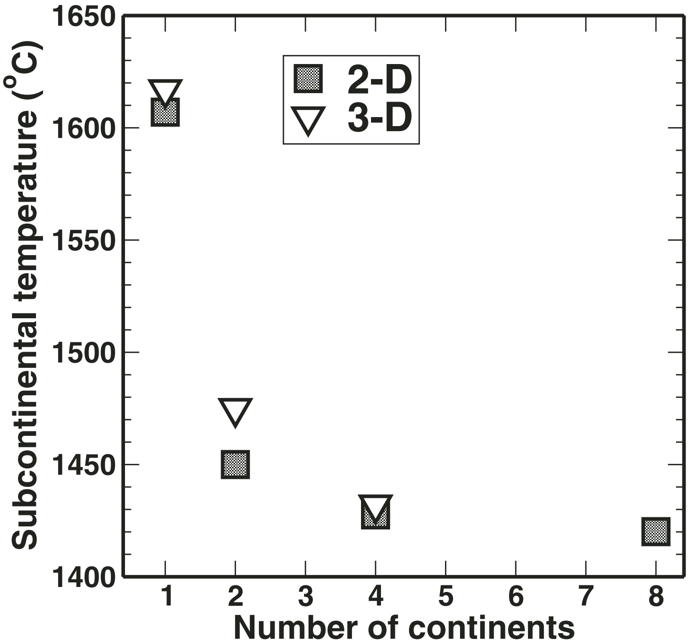

Figure 2. Subcontinental temperature (averaged over 1 b.y. for three-dimensional [3-D] calculations and 5 b.y. in two-dimensional [2-D] calculations) as a function of number of continents at constant continental area (30%). Results are given for Ra = 10^7, layered viscosity, and heat production of $H = 1.2 \times 10^{-12}$ W kg^{-1} in 2-D and $H = 4 \times 10^{-12}$ W kg^{-1} in 3-D.

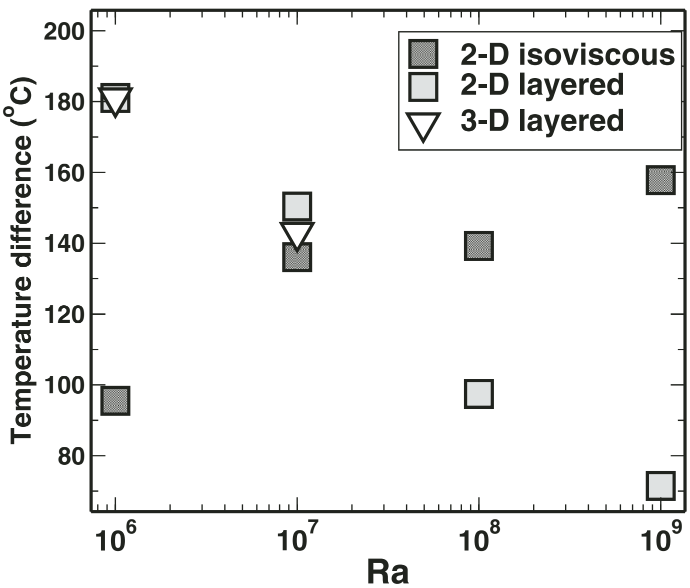

Figure 3. Subcontinental temperature excess (averaged over 5 b.y. in two dimensions [2-D] and 1 b.y. in three dimensions [3-D]) of aggregated state relative to two-continent dispersed state as a function of Rayleigh number for isoviscous and layered viscosity cases.

DISCUSSION

Our simulations suggest that the reorganization of convective flow during continental aggregation can be responsible for a positive temperature excursion up to 100 °C, which could be considered as an upper bound given the lack of 3-D spherical models that include self-consistent plate-like rheology. Such a large-scale thermal anomaly would be sufficient to trigger partial melting of the subcontinental mantle (Anderson, 1982), especially if the lithospheric mantle were hydrated (Gallagher and Hawkesworth, 1992), which would be expected since continents collide at the position of a vanished subduction zone (Lowman and Jarvis, 1999). The temperature anomaly generated by the global warming is wide and diffuse, and it disappears with continental dispersal and would not leave a hotspot track on the seafloor. This differs from the plume model, in which heating is localized, on the order of 200 °C, stable in time, and located at the origin of a hotspot track (Sleep, 1990). While the plume model fits the observations for typical traps like the Deccan (high rate of magma supply producing a thick lava pile, hotspot track; see Courtillot et al., 1999), the global warming model accounts for the characteristics of the Central Atlantic Magmatic Province (wider surface but thinner lava pile, no hotspot track). Our model might also apply to earlier continental flood basalts such as the one linked to the breakup of the supercontinent Pannotia during late Neoproterozoic times (Doblas et al., 2002).

Pure internal heating convection is an end member chosen here to highlight a physical phenomenon, bearing in mind that the mantle is certainly heated mostly from within (Sleep, 1990). However, our results are

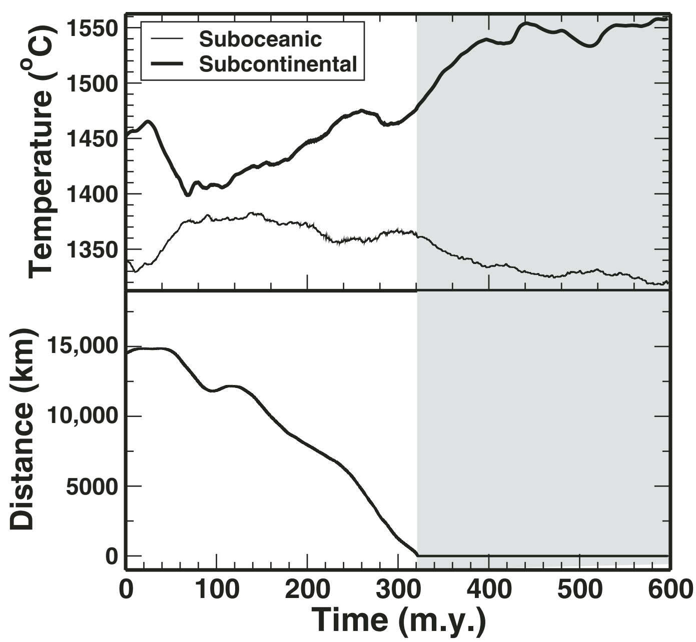

Figure 4. Temporal evolution of distance between two moving continents and average temperatures in internally heated two-dimensional (2-D) convection simulation at Rayleigh number Ra = 10^8. Time is scaled by transit time (30 m.y.), which is the time it takes to cross the mantle with surface horizontal velocity (Gurnis, 1988). The heat production is $H = 2.6 \times 10^{-12}$ W kg^{-1}.

by no means incompatible with the existence of plumes beneath supercontinents. We suggest instead that there are two end members of continental flood basalts: (1) plume-derived continental flood basalts that are characterized by a very brief and high rate of magma supply over a restricted and radiating area followed by continuous hotspot activity; and (2) global warming–derived continental flood basalts that occur over a supercontinent and are characterized by wide and diffuse magmatism at a lower magma supply rate that disappears with continental dispersal. Mantle global warming is also an alternate model that can explain the episodic creation of juvenile crust from the upper mantle (Condie, 2004) without invoking deep-seated mantle plumes.

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