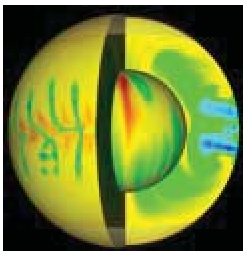

# *Global warming of the mantle at the origin of flood basalts over supercontinents*

**N. Coltice[1], B.R. Phillips[2], H. Bertrand[3], Y. Ricard[3] & P. Rey[4]**

[1]*Laboratoire de Sciences de la Terre, UMR-CNRS 5570, Université de Lyon, Université Lyon 1, ENS Lyon, Bat G'eode, 2 rue Raphael Dubois, 69622 Villeurbanne Cedex, France*; coltice@univ-lyon1.fr

[2]*Earth and Environnemental Sciences Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA*; benp@lanl.gov

[3]*Laboratoire de Sciences de la Terre, UMR-CNRS 5570, Université de Lyon, Université Lyon 1, ENS Lyon, Bat G'eode, 2 rue Raphael Dubois, 69622 Villeurbanne Cedex, France*; herve.bertrand@ens-lyon.fr ; ricard@ens-lyon.fr

[4]*School of Geosciences, University of Sydney, H11 Geology Demountables, NSW2006 Sydney, Australia*

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## Introduction

In a recent paper (*Coltice et al.*, 2007), we proposed an alternative, non-plume model for the generation of continental flood basalts (CFBs) over a supercontinent. A supercontinent imposes its length-scale to the convective flow which becomes less efficient to remove heat. Thus, the subcontinental mantle heats up by around 100°C triggering large-scale melting. This hypothesis is based on the peculiarities of the Central Atlantic Magmatic Province (CAMP) which is the largest phanerozoïc CFB on Earth (~$10^6$ $km^2$), and 3D spherical models of mantle convection with continents [Ed: see also CAMP page].

The CAMP emplaced at a peak rate at 199 Ma during the initial breakup of Pangea and is now preserved over four continents. It is often cited as a type example of a plume-derived CFB (*Hill*, 1991; *Courtillot et al.*, 1999) but this hypothesis is strongly debated because:

1. no hotspot track has been identified (*McHone*, 2000),
2. the geometry of the CAMP is elongated, not radial as would be expected from a plume,
3. the area near the center of the hypothetic plume head does not show evidence of uplift (*McBride*, 1991; *McHone*, 2000),
4. the apparent radiating pattern of the feeder dyke swarms that would result from the impingement a plume head is an oversimplification ignoring the regional lithospheric control (*McHone et al.*, 2005),

5. the geochemical and isotopic signatures are diagnostic of shallow mantle sources that experienced ancient subduction and do not have a deep plume composition (*Verati et al.*, 2005).

In this webpage we show how continental aggregation favors longer lengthscales of flow which naturally generates 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.

**The global mantle warming hypothesis**

Plumes carry the heat coming from the core and heat up the lithosphere locally. Without plumes, it is difficult to have significant temperature oscillations on a 100-Ma timescale unless there is a drastic change in the convective flow pattern. Our hypothesis is that continental aggregation generates a longer wavelength of convection so that the subcontinental mantle can heat up sufficiently to generate melting over a large area. Indeed, it is well known that:

a. longer wavelengths are less efficient at removing heat (*Grigné et al.*, 2005), and

b. continental rafts impose their own wavelength on mantle convection (*Phillips & Bunge*, 2005) by impeding downwellings below them (*Gurnis*, 1988).

As a consequence, the assembly of a supercontinent should force larger lengthscales and drive the underlying mantle toward higher temperatures, even in the absence of plumes.

**Model testing**

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. We refer to our paper (*Coltice et al.*, 2007) for details of the 2D cartesian and 3D spherical models. The first set of experiments aims at characterizing the role of continental distribution. Thus the models have stationary continents. They show that the temperature below a supercontinent is ~100°C hotter than with 2 separate continents (Figure 1), regardless of the geometry (2D cartesian or 3D spherical) or the technique used to model the continental lithosphere. With moving continents, the temperature is stable until aggregation starts and then it takes more than 100 Ma to heat up the subcontinental mantle by 100°C (Figure 2).

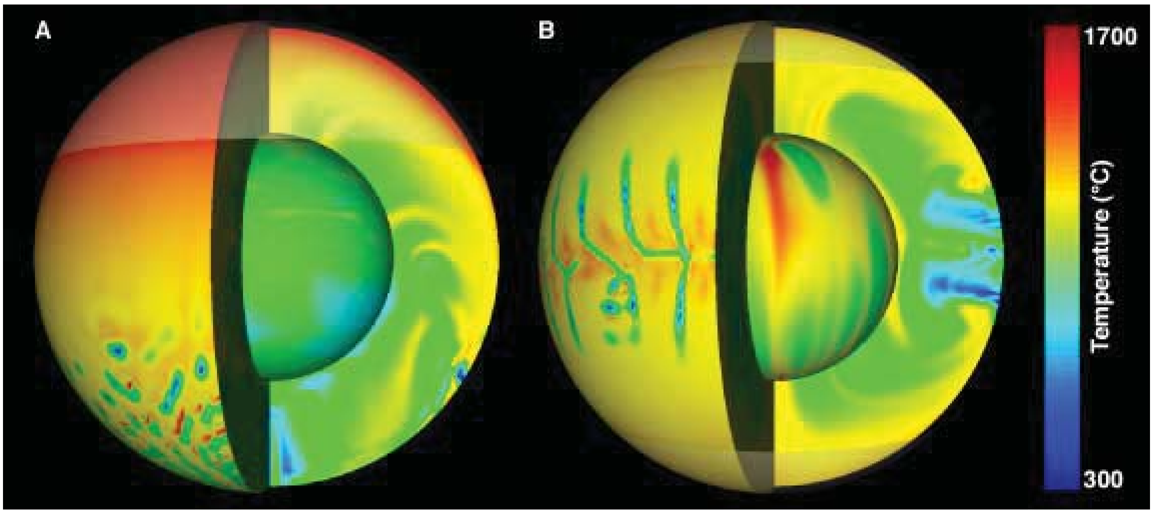

*Figure 1. Temperature field snapshots for models with (A) a supercontinent and (B) two antipodal continents. The mean temperature at the base of the continental thermal boundary layer in (A) is 1614°C (red), while in (B) it is only 1475°C (yellow). Translucent caps denote continents. The outer surface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

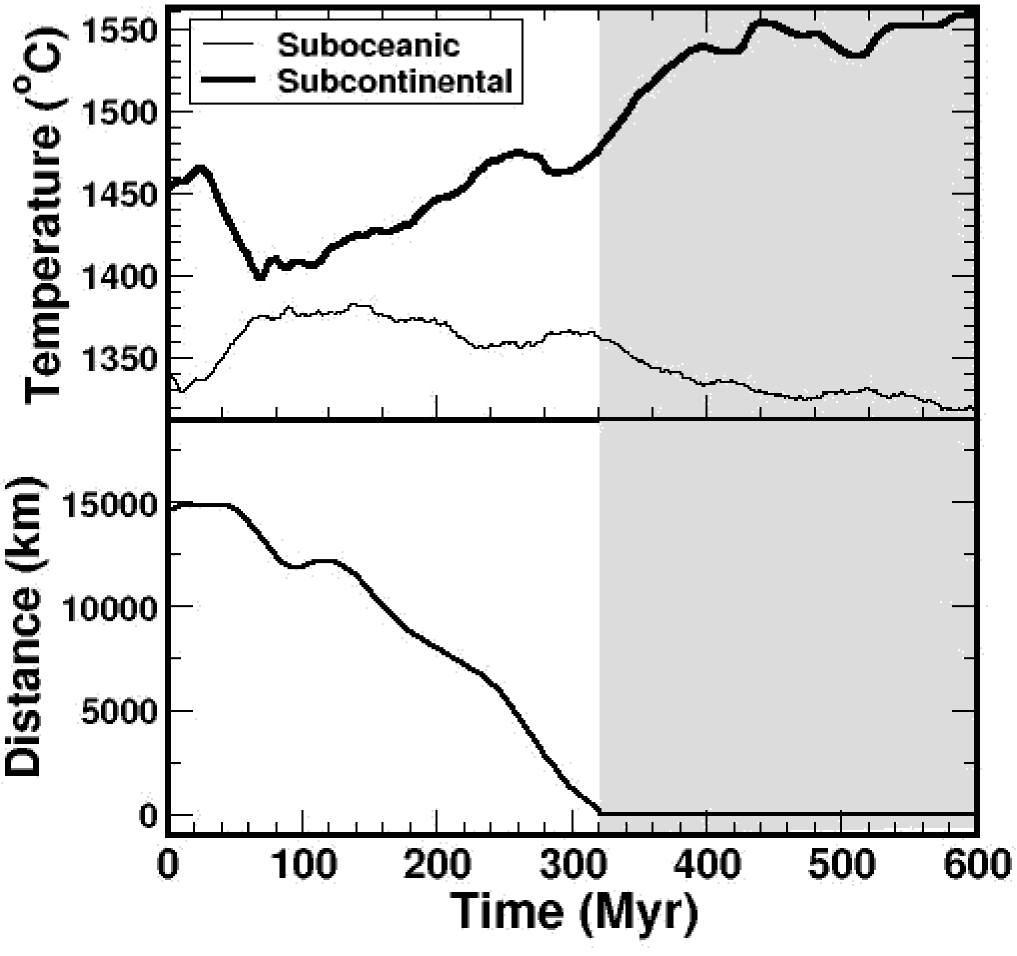

*Figure 2. Temporal evolution of the distance between two moving continents and average temperatures in an internally heated 2D convection simulation at Rayleigh number Ra = $10^8$. Time is scaled by the transit time (30 Ma) which is the time it takes to cross the mantle at the surface horizontal velocity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

**Plumes vs. global mantle warming below a supercontinent**

We suggest that reorganization of the flow during continental aggregation can be responsible for a positive temperature excursion up to 100°C, which might be an upper bound considering some of the shortcomings of our models. Such a large-scale thermal anomaly would be sufficient to partially melt the subcontinental mantle (*Anderson*, 1982), especially if the lithospheric mantle is hydrated, since the edges of colliding continents are vanished subduction zones. The temperature anomaly generated by the global mantle warming is wide and diffuse. It dissipates with continental dispersal and would not leave a hotspot track on the seafloor. Magma drainage is controlled by the lithospheric and tectonic setting. Of course, our model is an end-member and does not preclude plumes. A combination of the two might occur and should be investigated with convection models.

Thus, we propose two end-member mechanisms for CFB generation:

| **Global mantle warming** | **Plume** |
|---|---|
| Wide and diffuse magmatism (*e.g* CAMP: 7000 km) | Radiating magmatism over a restricted area (< 2000 km) |
| No hotspot track | Linked with a hotspot track |
| < 100°C excess temperature | 200°C excess temperature |
| Low rate of magma supply | High rate of magma supply |
| Shallow mantle source | Deep mantle source |
| A supercontinent is needed | Anywhere |

The global mantle warming model accounts for the characteristics of the CAMP and might also apply to other CFBs such as the Karoo [Ed: see also Karoo page]. The CFB linked to the breakup of the supercontinent Pannotia during late Neoproterozoic times (the Central Iapetus Magmatic Province (CIMP); *Doblas et al.*, 2002) might also be due to global mantle warming. This model also offers an alternative view to explain episodic creation of juvenile crust from the upper-mantle (*Condie*, 2004) without invoking deep-seated mantle plumes.

*Acknowledgments*

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## Discussion

*6th August, 2007, Sami Mikhail* (s.mikhail@gl.rhul.ac.uk)

I recommend that all who found the modelling of this webpage and *Coltice et al.* (2007) interesting read also *Yale & Carpenter* (1998). This previously published work supports it in many ways. The authors show a temporal link between supercontinent assembly and break-up with LIP emplacement. This suggests that the supercontinents cause a reduction in heat flow out of the mantle simply by insulating it. This can give rise to thermal anomalies, or ‘hot spots’ in the upper mantle, and generate the heat for continental flood basalt (CFB) petrogenesis.

So either theses regions heated up enough to melt and form giant dyke swarms and possibly continental large igneous provinces (LIPs), and drive rifting, or supercontinent rifting caused by plate tectonic processes caused these heated regions to decompress thus triggering CFBs.

This model is useful for explaining CFBs but not ocean island basalts. It requires no deep-mantle-sourced thermal anomaly (plume), just a progressive build-up of heat caused by lithospheric insulation of the mantle by (super)continents, *i.e.,* top down tectonics (*Anderson*, 2001).

The global warming model (*Yale & Carpenter*, 1998; *Coltice et al.*, 2007) can be used to explain some CFBs (Siberia: *Yale & Carpenter*, 1998; CAMP: *Coltice et al.*, 2007) using observation and modelling. However it falls short in explaining the mechanisms responsible for the petrogenesis of oceanic plateaus (*e.g.,* the Ontong Java plateau) and ocean island chains (*e.g.,* the Emperor seamount chain).

*Coltice et al.*, 2007 compare their model to the plume model, but I have a few problems:

- Why must we assume that plumes are shaped like tadpoles causing radial magmatism with a predictable radius? Surely the geometry of any thermal plume will be controlled by the laws of thermodynamics? Thus the direction in which the energy (heat) is able to move defines its shape?
- Why, when discussing the dynamic Earth, must the geometry and size of a plume be regarded as uniform?
- What about giant dyke swarms as fractals for ‘plumes’?
- The idea that all plumes must have a hotspot track is primitive. If we were to have a plume that has a replenishing source beneath a moving plate then yes it should have a hotspot track. However if the plume is caused by an instability that is short lived it may not produce a hotspot track, but just a single LIP. What is wrong with a plume only producing a single LIP and then dying out?

If one can devise a model that can explain the petrogenesis of a specific LIP (*e.g., Coltice et al.*, 2007 with CAMP), then it explains the petrogenesis of the LIP in question, not all LIPs. In a similar way, one could argue that volcanoes are found in many geological settings, including subduction zones, rift zones and my favourites the tectonically inert ‘hot-spots’. We would be wrong, however, to study Santorini and conclude that all volcanoes on Earth are a direct result of subduction. Surely the same goes for LIPs.

*8th August, 2007, Don Anderson (dla@gps.caltech.edu)*

Mikhail raises valid points about the philosophy of science and the process of falsification and asks a series of astute questions. These issues are discussed elsewhere.

The geometry of a thermal plume is indeed controlled by the laws of thermodynamics. This means that not only must the effects of temperature be considered (for density, elastic moduli, viscosity, expansivity, conductivity, specific heat) as in plume theory, but also the effects of pressure. The Earth is too big to ignore pressure and thermodynamics requires that volume changes are associated with both heating and compression. Pressure reverses the effects of temperature and broadens plumes with depth, if they can form at all. Narrow plumes do not exist when self-consistent thermodynamics is allowed for. Internal heating leads to broad diffuse upwellings, that move around so that heat can be removed from all parts of the interior. Deep slabs cool off the mantle from below. These are the opposite of the plume scenerio.

Continental delamination is an instability that is short lived and may not produce a hotspot track, just a single LIP at the delamination site, and another one when the fertile blob emerges. Many mechanisms have been proposed that produce a single LIP and then die out.

The process by which large thick plates trap mantle heat is usually referred to as **continental insulation**. This process also applies to any large long-lived plate, *e.g.,* Pacific (*Parmentier & Sotin*, 2000) or plates in compression. More generally, the presence of a lid that is either buoyant or has **strong subduction zones** can cause the whole mantle to run a fever compared to a homogeneous fluid with a purely thermal boundary layer (TBL) that becomes unstable when still relatively thin. Mantle temperature in this case is not **buffered by mantle viscosity**. A realistic mantle model not only has a variable thickness crust, lithosphere and TBL, but also has the accumulated refractory depleted buoyant peridotite debris of billions of years of melt extraction, the perisphere. When the crust thickens into the eclogite stability field, near 50 km depth, it can delaminate and place mafic low-melting components into the upper mantle, thereby cooling it. Such a mantle operates differently from a homogeneous fluid heated from below, *e.g.,* the plume scenerio. If the mantle is only slightly hotter than generally assumed then plumes are both unnecessary and implausible. But it is **homologous temperature**, rather than absolute temperature, that is the key parameter.

The insulation model is useful for explaining both CFBs and ocean island basalts (*Anderson*, 2000, 2001) and the high ambient temperature of the mantle. A more fundamental issue is the following; what is the ambient temperature of a mantle, insulated from above, that is unaffected by deep mantle plumes? Can it be as high and as variable as 1420 ± 180°C (*Kaula*, 1983; *Green et al.,* 1999; temperature pages)? Related questions are;

- Can we assume that the mantle is subsolidus except at plate boundaries and at hotspots?
- Are mid-ocean ridge potential temperatures and melting points representative of the whole upper mantle, including under large plates?
- Can large plates or **strong subduction zones** cause the mantle to overheat?
- Does lower continental crust delamination cool the mantle under supercontinents, so that it is actually colder than under large oceanic plates?
- Why are there not volcanoes everywhere?

Note: phrases in **boldface** are Googlets. Enter these into a search engine for supplementary material.

*9th August, 2007, Nicolas Coltice (coltice@univ-lyon1.fr) & Benjamin R. Phillips*

There are many proposed hypotheses for the origin of LIPs and it was not the objective of our work to propose another. As we stated, the role of a supercontinent has already been highlighted by Anderson (1982). Our goal was then to test the hypothesis with dynamic simulations. Indeed, there is a difference between a hypothesis and a model. A model can be used to make predictions that can be compared to independent datasets. Contrary to *Yale & Carpenter* (1998), we propose simulations and make predictions *e.g.,* the temperature below a continent as a function of its size, the shape of the thermal anomaly, and the time needed to increase the temperature. All of these can be tested independently now. Second, we explained the physics associated with the phenomenon. As a consequence, we can predict that each time there is a supercontinent, ~100°C of subcontinental warming occurs. Our model is not designed to explain the CAMP but to show a general physical mechanism.

This mechanism is related to continental insulation. But if there is no convection simulation to explore what continental insulation really is, many questions could be raised such as:

- Is the thermal effect of continental insulation a function of the total area of continents and/or of the distribution of continents?
- Does the size of a continent affect its sublithospheric temperature?

Most numerical models that study the impact of continents on the mantle explore the effects of basal heating and plumes, very often below a single continent (*Gurnis*, 1988; *Lowman & Jarvis*, 1999; *Lenardic et al.*, 2003). We investigated the effects of the distribution of continents on mantle convection heated from within and were able to make a link with a proposed hypothesis (*Anderson*, 1982) and a peculiar CFB for which a huge amount of data is available (the CAMP).

Concerning the size and shape of plumes, we totally agree that it is not as simple as a little mushroom, especially taking into account chemical anomalies at the base of the mantle (*Farnetani & Samuel*, 2005). However, plumes are small because their viscosity is low and this is why tomographic models fail to see some of them. The tail developed by plumes must exist at least for some time. Indeed, a rising viscous drop experiences stresses (pressure gradients and viscous stresses) on its boundary and the velocity gradients produce the tail that sometimes can be short-lived.

The shape of the CAMP is not the only observation that leads us to question the plume model and more is discussed elsewhere by *McHone* (2000) [Ed: and in the CAMP webpage]. It is difficult to build a testable hypothesis, test it against the law of physics, make predictions and find the unambiguous independent observations. But one of the roles of modellers is to make quantitative predictions that distinguish a realistic model from a reasonable hypothesis.

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