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Reconstructing the Cenozoic evolution of the mantle: Implications for mantle plume dynamics under the Pacific and Indian plates

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A B S T R A C T

The lack of knowledge of the initial thermal state of the mantle in the geological past is an outstanding problem in mantle convection. The resolution of this problem also requires the modelling of 3-D mantle evolution that yields maximum consistency with a wide suite of geophysical constraints. Quantifying the robustness of the reconstructed thermal evolution is another major concern. To solve and estimate the robustness of the time-reversed (inverse) problem of mantle convection, we analyse two different numerical techniques: the quasi-reversible (QRV) and the backward advection (BAD) methods. Our investigation extends over the 65 Myr interval encompassing the Cenozoic era using a pseudo-spectral solution for compressible-flow thermal convection in 3-D spherical geometry. We find that the two dominant issues for solving the inverse problem of mantle convection are the choice of horizontally-averaged temperature (i.e., geotherm) and mechanical surface boundary conditions. We find, in particular, that the inclusion of thermal boundary layers that yield Earth-like heat flux at the top and bottom of the mantle has a critical impact on the reconstruction of mantle evolution. We have developed a new regularisation scheme for the QRV method using a time-dependent regularisation function. This revised implementation of the QRV method delivers time-dependent reconstructions of mantle heterogeneity that reveal: (1) the stability of Pacific and African 'large low shear velocity provinces' (LLSVP) over the last 65 Myr; (2) strong upward deflections of the CMB topography at 65 Ma beneath: the North Atlantic, the south–central Pacific, the East Pacific Rise (EPR) and the eastern Antarctica; (3) an anchored deep-mantle plume ascending directly under the EPR (Easter and Pitcairn hotspots) throughout the Cenozoic era; and (4) the appearance of the transient Reunion plume head beneath the western edge of the Deccan Plateau at 65 Ma. Our reconstructions of Cenozoic mantle evolution thus suggest that mantle plumes play a key role in driving surface tectonic processes and large-scale volcanism.

1. Introduction

The first efforts to infer time-dependent changes in lateral heterogeneity in the mantle were based on estimated trajectories of subducted slabs derived from reconstructions of Mesozoic and Cenozoic plate histories (Richards and Engebretson, 1992; Ricard et al., 1993; Gurnis et al., 2012). Although such models of subducted slab heterogeneity have been useful (e.g., Richards et al., 1997; Lithgow-Bertelloni and Richards, 1998; Faccenna et al., 2012), they are based on the prevailing view that the thermal evolution of the mantle is dominated by the process of cooling from above due to slab subduction and that the primary energy source for mantle dynamics is internal heating with only a small contribution (∼10%) provided by heat entering the mantle from the core (e.g., Davies, 1999; Lay et al., 2008). The slab-driven mantle convection models do not account for the presence and evolution of positively buoyant, large-scale hot upwellings (a.k.a. 'superplumes') which have been imaged by global seismic tomography (e.g., Forte et al., 1995; Forte and Mitrovica, 2001; Davies and Davies, 2009; Schuberth et al., 2009; Glišović et al., 2012). To further comprehend the dynamical importance and evolution of these superplumes we will employ an approach in which the past evolution of mantle heterogeneity is estimated on the basis of present-day temperature anomalies derived from seismic tomography and subsequently time-reversing the full set of convective field equations (Forte and Mitrovica, 1997; Steinberger and O'Connell, 1997; Conrad and Gurnis, 2003; Bunge et al., 2003; Spasojevic et al., 2009, 2010).

The principal obstacle in modelling thermal convection backward in time is due to the effects of thermal diffusion and viscous dissipation, both of which are irreversible. Despite this fact, there are a few advanced numerical techniques for solving this problem.

One solution involves data assimilation, defined as the incorporation of present (initial conditions) and past data (observations) in an explicit dynamic model to provide continuity and coupling among the time-evolving physical fields (e.g., velocity

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and temperature). In the recent treatments of the inverse problem for mantle convection there are two particular data assimilation methods: sequential (Bunge et al., 2002) and four-dimensional variational (4-D Var) data assimilation (e.g., Bunge et al., 2003; Ismail-Zadeh et al., 2004).

Ismail-Zadeh et al. (2007) used the quasi-reversible (QRV) method to solve the backward mantle convection problem. The accuracy of the QRV data assimilation is lower than that of the 4-D Var, but the QRV method does not require filtering of temperature noise as the 4-D Var method does (Ismail-Zadeh et al., 2007). Based on the results and the comparison of the methods (Ismail-Zadeh et al., 2007), we consider the QRV method to be an effective and numerically efficient approach to assimilation of data related to mantle dynamics, and it will be tested in the work presented here.

In addition to data assimilation techniques, there is a method that ignores the irreversible terms in the thermal energy conservation equation if the interior of the convective region is characterised by a high Rayleigh number. This approach has been called the BAD (from Backward ADvection) method because it solves only the advection term backward in time, and it will also be used in this study to estimate the past evolution of lateral temperature variations in the mantle.

In the following study we focus on the dynamical evolution of the mantle over the Cenozoic era, a period characterised by a number of significant geological events. From a tectonic perspective, in the last 65 Myr of Earth's evolution the continents moved considerable distances into their current positions. An especially noteworthy example is the rapid India plate motion that begins at the same time as the first pulse of Deccan flood basalts, which is dated at 67 Ma. It has been suggested that this correlation is probably driven by the push force of the Reunion plume head (Cande and Stegman, 2011).

A deeper understanding of the dynamical origin of these geological events and correlations cannot be achieved without a better knowledge of the temporal character of mantle flow. Therefore, our goal in this study is to reconstruct the Cenozoic evolution of mantle thermal structure, with a particular focus on the time-dependent dynamics of mantle superplumes. Another objective of this study is to address the magnitude and importance of uncertainties that arise when using the two time-reversed convection methods: QRV and BAD.

2. Numerical method

We employ a time-dependent, compressible and dissipative thermal convection model in 3-D spherical geometry, using an updated and revised pseudo-spectral method (Glišović et al., 2012). However, it is well-known that a backward time-integration of the energy equation is an ill-posed problem because of the existence of viscous dissipation and thermal diffusion, which are both irreversible terms. One of the proposed numerical methods to transform this ill-posed problem into a well-posed problem is the quasi-reversible (QRV) method (e.g., Lattès et al., 1969; Ismail-Zadeh et al., 2007). The QRV method construction is conceptually simple, and involves the product of a small regularisation parameter, and a high-order temperature derivative in the energy equation introducing additional boundary conditions (see (B.1)). The data assimilation in this case is based on a search for the best fit between the forecast model state and the observations by minimizing the regularisation parameter (Ismail-Zadeh et al., 2007).

The quasi-reversible term is related to diffusion in the 'classical' approach (Lattès et al., 1969), but here we must contend with the existence of the dissipation and highly nonlinear advection terms in the regularised thermal energy equation. This equation has the following form

$$\rho c_p \frac{\partial T}{\partial t} + \beta \Delta^2 \left(\frac{\partial T}{\partial t} \right) = \rho c_p \mathbf{u} \cdot \nabla T - \nabla \cdot k \nabla T - \alpha T \frac{dp}{dt} - \Phi - Q \tag{1}$$

where β is a small regularisation parameter and $\Delta^2(\frac{\partial T}{\partial t})$ is the biharmonic diffusion operator (see Appendix A). Thermodynamical variables are the (absolute) temperature T, the pressure p, the specific heat c_p, the thermal conductivity k and the thermal expansion α, while other variables are the velocity field $\mathbf{u}$ and the density ρ. The regularised equation of energy conservation (1) is constituted by the following terms: $\mathbf{u} \cdot \nabla T$ is the advection of temperature, $\nabla \cdot k \nabla T$ is the thermal diffusion, Φ is the dissipation due to internal viscous friction, $\alpha T \frac{dp}{dt}$ is the work associated with adiabatic changes of volume, and the last term Q is the internal heating rate per unit mass of fluid. The approximate solution of the regularised backward conservation energy problem is stable for $\beta > 0$ and it converges to the solution of the forward conservation energy problem, in some spaces, where the conditions of well-posedness are met (Samarskii and Vabishchevich, 2007).

In order to derive an equation for the backward advection (BAD) method, the energy equation may be rewritten in non-dimensional terms (for more details, see Glišović et al., 2012),

$$\frac{\partial T}{\partial t} = -\mathbf{u} \cdot \nabla T + \frac{1}{\rho Ra_s} (\nabla \cdot k \nabla T + Q) + \frac{Di}{\rho} \left(-\alpha T \frac{dp}{dt} + \Phi \right) \tag{2}$$

where Ra_s is the surface Rayleigh number and Di is the dissipation number (Peltier, 1973) which measures the importance of compressional work and frictional heating. If we assume that the mantle flow is characterised by high Rayleigh number, then we may neglect the diffusion and internal heating term inside the energy equation (2). It is important to note that this simplification is most applicable to the bulk interior of the mantle which is characterised by an adiabatic mean temperature profile. We can thus anticipate that it will not be a good approximation inside thermal boundary layers where significant super-adiabatic gradients exist. The dissipation term is small and thus may be empirically neglected. After these simplifications, and inverting the sign of the advection term, Eq. (2) becomes the simple backward advection equation

$$\frac{\partial T}{\partial t} = \mathbf{u} \cdot \nabla T \tag{3}$$

which will be the base for our second approach (the BAD method) in the reconstruction of mantle flow.

3. Description of models

3.1. Reference properties of the mantle

We use a radial viscosity profile (Fig. 1(a)) constrained by global joint inversion of convection-related surface observables (Forte et al., 2010) and data associated with the response of the Earth to ice-age surface mass loading (Mitrovica and Forte, 2004).

The radial density profile $\rho_0(r)$ which describes the reference hydrostatic state in our compressible convection model is taken directly from the seismic reference Earth model PREM (Dziewonski and Anderson, 1981). The corresponding radial gravity field $g_0(r)$ is obtained by the integration of $\rho_0(r)$.

In this study we employ a thermal conductivity profile given by Hofmeister (1999) that considers the effect of thermal boundary layers (TBLs) inside the mantle and the possibility that thermal conductivity decreases with depth across both layers (Fig. 1(a)).