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The effect of plate motion history on the longevity of deep mantle heterogeneities

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ABSTRACT

Understanding the first-order dynamical structure and evolution of Earth's mantle is a fundamental goal in solid-earth geophysics. Tomographic observations reveal a lower mantle characterised by higher-than-average shear-wave speeds beneath Asia and encircling the Pacific, consistent with cold slabs beneath regions of ancient subduction, and lower-than-average shear-wave speeds in broad regional areas beneath Africa and the Central Pacific (termed LLSVPs). The LLSVPs are not well understood from a dynamical perspective and their origin and evolution remain enigmatic. Some numerical studies propose that the LLSVP beneath Africa is post-Pangean in origin, formed as a result of return flow in the mantle due to circum-Pangean subduction, countered by an older Pacific LLSVP, suggested to have formed during the break up of Rodinia. This propounds that, prior to the formation of Pangea, the lower mantle was dominated by a degree-1 convection pattern with a major upwelling centred close to the present-day Pacific LLSVP and subduction concentrated mainly in the antipodal hemisphere. In contrast, palaeomagnetic observations which proffer a link between the reconstructed eruption sites of Phanerozoic kimberlites and Large Igneous Provinces with regions on the margins of the present-day LLSVPs suggest that the anomalies may have remained stationary for at least the last 540 Myr and further that the anomalies were largely insensitive to the formation and subsequent break-up of Pangea. Here we investigate the evolution and long-term stability of LLSVP-like structures in Earth's mantle by integrating plate tectonics and numerical models of global thermochemical mantle dynamics. We explore the possibility that either one or both LLSVPs existed prior to the formation of Pangea and improve upon previous studies by using a new, true polar wander-corrected global plate model to impose surface velocity boundary conditions for a time interval that spans the amalgamation and subsequent break-up of the supercontinent. We find that, were only the Pacific LLSVP to exist prior to the formation of Pangea, the African LLSVP would not have been created within the lifetime of the supercontinent. We also find that, were the mantle to be dominated by two antipodal LLSVP-like structures prior to the formation of Pangea, the structures would remain relatively unchanged to the present day and would be insensitive to the formation and break-up of the supercontinent. Our results suggest that both the African and Pacific LLSVPs have remained close to their present-day positions for at least the past 410 Myr.

1. Introduction

Numerical studies of mantle convection have attempted to explain tomographic observations that reveal a lower mantle dominated by broad regional areas of lower-than-average shear-wave speeds beneath Africa and the Central Pacific (Fig. 1) (e.g., Dziewonski et al., 1977; Grand, 1994; Su et al., 1994; Masters et al., 1996; Ritsema et al., 1999, 2004; Mégnin and Romanowicz, 2000; Ishii and Tromp, 2004; Trampert et al., 2004; McNamara and Zhong, 2005; Bull et al., 2009). The anomalous regions, termed LLSVPs ("**l**arge **l**ow **s**hear **v**elocity **p**rovinces"), are encircled by regions of higher-than-average shear-wave speeds associated with Mesozoic and Cenozoic subduction zones (e.g., Richards and Engebretson, 1992; Ricard et al., 1993; van der Hilst et al., 1994; Grand et al., 1997; Bunge et al., 1998; Lithgow-Bertelloni and Richards, 1998). Geochemical inferences of multiple chemical

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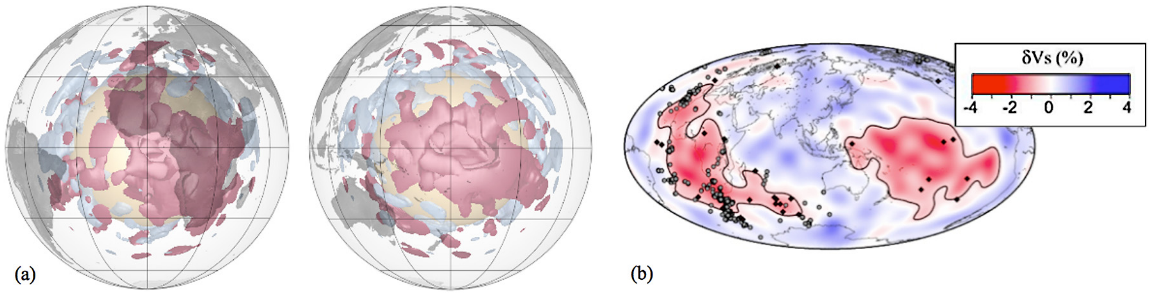

Fig. 1. Shear-wave velocity heterogeneity for the tomographic model S20RTS (Ritsema et al., 1999, 2004) shown (a) as 3D dVs isosurfaces centred on Africa (left) and the Pacific (right) and (b) in map view at 2750 km depth in the mantle with superimposed reconstructed eruption sites of LIPs (circles) and Kimberlites (diamonds) for the past 500 Myr (Torsvik et al., 2010a). The black outline in (b) represents the −2% dVs boundary of the seismic model. Both views reveal a lower mantle dominated by the large low shear-wave velocity anomalies beneath Africa and the Pacific. Present-day continental boundaries are superimposed on each plot.

reservoirs at depth (e.g., Hoffman, 1997), strong seismic contrasts (e.g., Breger and Romanowicz, 1998; Ritsema et al., 1998; Wen, 2001; Ni et al., 2002; Wang and Wen, 2004; Ford et al., 2006), an anti-correlation of shear-wave velocity to bulk sound velocity (Su and Dziewonski, 1997; Ishii and Tromp, 1999; Masters et al., 2000) and increased density (Ishii and Tromp, 1999, 2004; Deschamps and Trampert, 2003; Resovsky and Trampert, 2003; Deschamps et al., 2007; Hernlund and Houser, 2008) in the anomalous regions suggest a thermochemical origin for the LLSVPs. Consequently, heterogeneous mantle models define the anomalies as thermochemical piles (e.g., Tackley, 1998, 2002; Jellinek and Manga, 2004; McNamara and Zhong, 2004, 2005), metastable superplumes (e.g., Tan and Gurnis, 2005) or thermochemical superplumes (e.g., Davaille, 1999), characterised by an anomalous component whose intrinsic density is a few percent higher relative to that of the surrounding mantle (e.g., Kellogg et al., 1999; Ni et al., 2002; Davaille et al., 2005; Tan and Gurnis, 2007; Lassak et al., 2007; Simmons et al., 2007; Bull et al., 2009).

The origin and long-term evolution of the LLSVPs remains enigmatic. Some numerical studies propose that the LLSVP beneath Africa is post-Pangean in origin, formed as a result of return flow in the mantle due to circum-Pangean subduction (Zhong et al., 2007; Li and Zhong, 2009; Zhang et al., 2010), in contrast to a much older (and thus more stable) Pacific LLSVP, which is linked to the earlier Rodinia supercontinent and thought to have remained largely unchanged since Rodinian break-up ca. 750–700 Ma (Maruyama, 1994; Maruyama et al., 1997, 2007; Condie, 2003). This suggests that prior to the formation of Pangea, the lower mantle was dominated by a degree-1 convection pattern with a major upwelling centred close to the present-day Pacific LLSVP and subduction concentrated mainly in the antipodal hemisphere. It is further proposed (Zhong et al., 2007) that a cyclic alternation between a degree-1 pattern of mantle convection (whereby the mantle is dominated by one large upwelling surrounded by downwellings) and a degree-2 pattern (whereby the mantle is dominated by two large upwellings surrounded by downwelling regions) may accompany the supercontinent cycle and characterise the convective evolution of Earth's mantle.

In contrast, long-term stability for both the African and Pacific LLSVPs, and thus for the platform of mantle convection within the Earth as a whole, is suggested by recent palaeomagnetic plate motion models which propose a geographic correlation between the surface eruption sites of Phanerozoic kimberlites (Torsvik et al., 2010a), major hotspots (Burke et al., 2008) and Large Igneous Provinces (Burke and Torsvik, 2004; Burke et al., 2008) to deep regions of the mantle termed "Plume Generation Zones" (PGZs), which lie at the margins of the LLSVPs (Fig. 1(b)). If the surface volcanism was sourced from the PGZs, such a link would suggest that the LLSVPs may have remained stationary for at least the age of the volcanics i.e., 540 Myr. This relationship further implies that the structures were largely insensitive to the formation and subsequent break-up of Pangea.

Thus we pose the questions: was the African LLSVP initiated as a result of Pangea assembly, or is it older?; what effect does supercontinent assembly and break-up have on large-scale mantle structure? To answer these questions, we integrate plate tectonic histories and numerical models of mantle dynamics and perform a series of 3D spherical thermochemical convection calculations. We improve upon previous studies by employing a new, true polar wander (TPW) corrected global plate motion model to impose surface velocity boundary conditions for a time interval that spans the amalgamation and subsequent break-up of Pangea (0–410 Ma). TPW is the motion of the geographic pole in a reference frame representative of the entire solid Earth and caused by the rotation of Earth relative to the spin axis. Both the mantle and the crust are affected by TPW but mantle heterogeneities (including LLSVPs) are kept fixed in our correlative exercises and the motion of the continents must therefore be corrected for TPW. In addition to TPW correction of palaeomagnetic data, one should also theoretically correct for net lithosphere rotation (NR). NR is small for the past 50 Myr (Torsvik et al., 2010b), however NR calculations are extremely unreliable before 100 Ma and thus such corrections are not recommended. The plate model used in this work is not corrected for NR. The model does contain substantial NR (see Domeier and Torsvik, 2014) but the orientation of the NR axis changes with time and thus minimises the cumulative effect.

1.1. Previous work

Several geodynamical studies, both numerical and experimental, have investigated the dynamical consequences of a dense component existing in Earth's mantle, in the form of thermochemical piles (e.g., Christensen and Hofmann, 1994; Tackley, 1998, 2002; Kellogg et al., 1999; Davaille et al., 2002; Jellinek and Manga, 2002, 2004; Ni et al., 2002; McNamara and Zhong, 2004; Tan and Gurnis, 2005, 2007; Nakagawa and Tackley, 2006). Although invaluable to our understanding of the dynamical behaviour of a thermochemical component in a planetary mantle, these models lacked an imposed Earth-like plate tectonic history, a parameter which is hypothesised to play a controlling role in the development of LLSVP-like structures (McNamara and Zhong, 2005).

Fully time-dependent 3D spherical thermochemical calculations with an imposed plate motion history were introduced by McNamara and Zhong (2005). Their work detailed thermochemical calculations that employed surface velocity boundary conditions consistent with 11 stages of plate history from the present-day to the Mid-Cretaceous, spanning the period 0–119 Ma (Lithgow-Bertelloni and Richards, 1998). The plate motion model was based on the fixed hotspot reference frame of Gordon and Jurdy (1986) and followed a straightforward model of mantle density