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On the relationship between volcanic hotspot locations, the reconstructed eruption sites of large igneous provinces and deep mantle seismic structure

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ABSTRACT

It has been proposed that volcanic hotspots and the reconstructed eruption sites of large igneous provinces (LIPs) are preferentially located above the margins of two deep mantle large low shear-wave velocity provinces (LLSVPs), beneath the African continent and the Pacific Ocean. This spatial correlation has been interpreted to imply that LLSVPs represent long-lived, dense, stable thermo-chemical piles, which preferentially trigger mantle plumes at their edges and exert a strong influence on lower-mantle dynamics. Here, we re-analyse this spatial correlation, demonstrating that it is not global: it is strong for the African LLSVP, but weak for the Pacific. Moreover, Monte Carlo based statistical analyses indicate that the observed distribution of African and Pacific hotspots/reconstructed LIPs is consistent with the hypothesis that they are drawn from a sample that is uniformly distributed across the entire areal extent of each LLSVP: the stronger spatial correlation with the margin of the African LLSVP is expected as a simple consequence of its elongated geometry, where more than 75% of the LLSVP interior lies within 10° of its margin. Our results imply that the geographical distribution of hotspots and reconstructed LIPs does not indicate the extent to which chemical heterogeneity influences lower-mantle dynamics.

1. Introduction and motivation

Geochemistry provides clear evidence for a mantle that is heterogeneous in major- and trace-element composition, with mantle-sourced magmas regularly including recycled plate tectonic material and, occasionally, primitive material dating back to the early Earth (e.g. Hofmann and White, 1982; Zindler and Hart, 1986; Hofmann, 1997, 2003; Tackley, 2007; Davies, 2011; Jackson and Carlson, 2011; Campbell and O'Neill, 2012). However, the distribution, scale and dynamical significance of this heterogeneity remain unclear. Recent debate has focussed upon whether or not the primary seismic features of Earth's lowermost mantle, large low shear-wave velocity provinces (LLSVPs) beneath the African continent and the south-central Pacific Ocean, represent long-lived, dense, discontinuous thermo-chemical piles (e.g. Masters et al., 2000; Forte and Mitrovica, 2001; Tackley, 1998, 2002; Ni et al., 2002; Trampert et al., 2004; McNamara and Zhong, 2005; Garnero and McNamara, 2008; Simmons et al., 2009; Schuberth et al., 2009, 2012; Davies et al., 2012, 2015). If this is the case, their scale and volume would imply that chemical heterogeneity plays a key role in governing lower-mantle dynamics (e.g. McNamara and Zhong, 2005; Deschamps and Tackley, 2008, 2009).

LLSVPs are proposed to be thermo-chemical in nature based upon their: (i) strong shear-wave velocity anomalies; (ii) disparate signatures in shear and compressional-wave velocities; (iii) anti-correlated shear and bulk-sound velocities; (iv) sharp sides, expressed in strong shear-wave velocity gradients; and (v) anti-correlated shear-wave velocity and density anomalies (e.g., Ishii and Tromp, 1999; Masters et al., 2000; Karato et al., 2001; Ni et al., 2002; Trampert et al., 2004; Hernlund and Houser, 2008; Garnero and McNamara, 2008). However, several recent studies demonstrate that the majority of these attributes can be equally well explained by thermal and phase related heterogeneity alone (e.g. Schuberth et al., 2009, 2012; Davies et al., 2012, 2015), which is consistent with earlier studies showing that the lower mantle's long-wavelength structure can be reproduced by thermal subduction history (e.g. Richards and Engebretson, 1992; Ricard et al., 1993). Only an anti-correlation between shear-wave velocity and density anomalies would provide unambiguous evidence for dense chemical heterogeneity. Although some studies have found such an anti-correlation (e.g. Ishii and Tromp, 1999; Trampert et al., 2004), our ability to resolve lower-mantle den-

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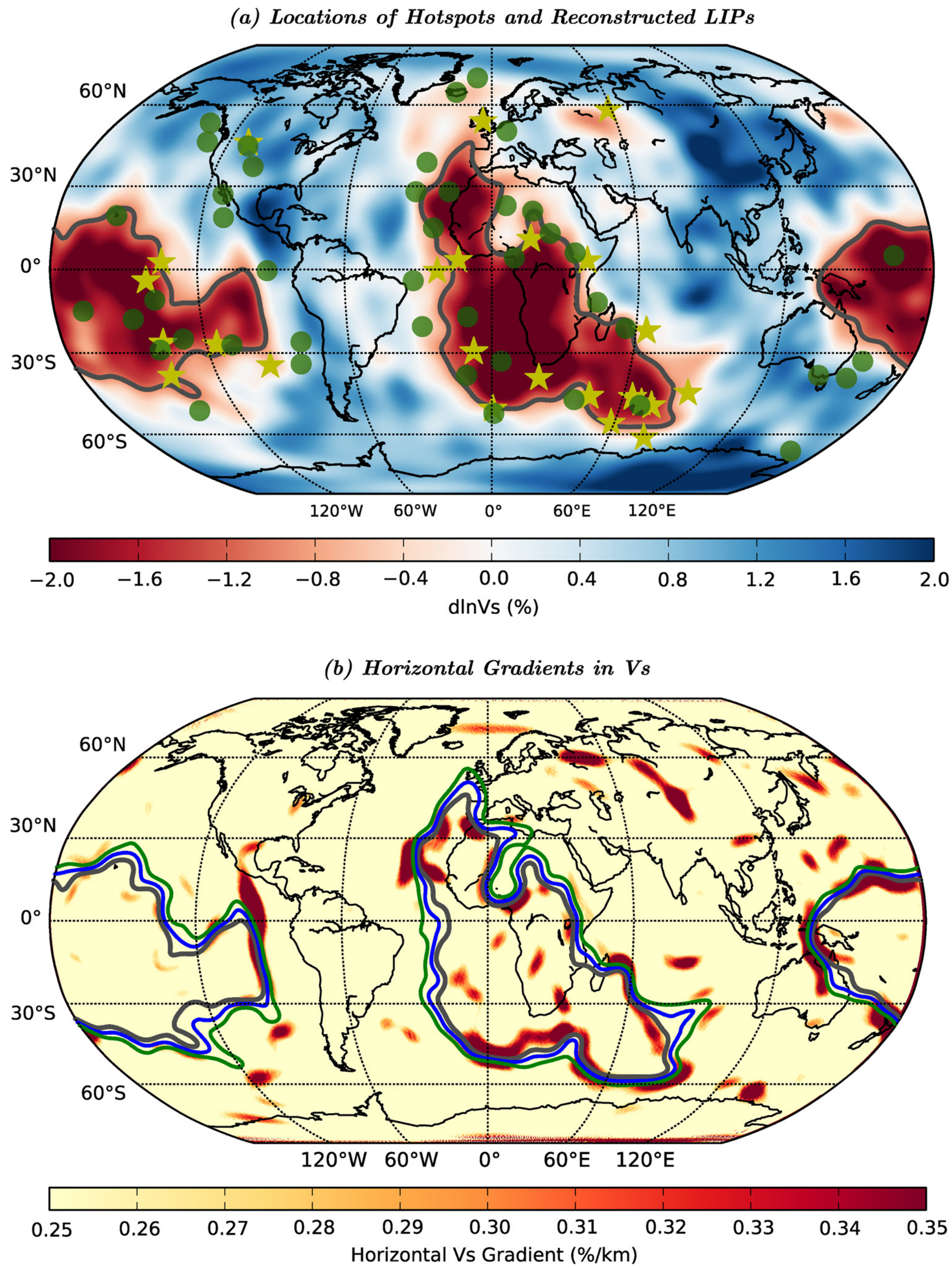

Fig. 1. (a) Surface hotspot locations (Green circles: Steinberger, 2000) and the reconstructed eruption sites of large igneous provinces (Yellow stars: Torsvik et al., 2006, 2008b), plotted above the shear-wave tomography model SMEAN (Becker and Boschi, 2002), at 2800 km depth. The −1.0% $\mathrm{dln}\, V_S$ contour, which approximately outlines large low shear-wave velocity provinces (LLSVPs) beneath Africa and the Pacific, is shown in grey; (b) Magnitude of horizontal shear-wave velocity anomaly gradients from the SMEAN model, at 2800 km depth. The −1.0% $\mathrm{dln}\, V_S$ contour is shown once again (grey), alongside the −0.7% (blue) and −0.4% (green) $\mathrm{dln}\, V_S$ contours. All contours consistently pass through the regions of highest $\mathrm{dln}\, V_S$ gradients at the margins of the African and Pacific LLSVPs. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

sity heterogeneity is debated (e.g. Resovsky and Ritzwoller, 1999; Romanowicz, 2001; Masters and Gubbins, 2003). Furthermore, the seismic evidence seems to require that the volume fraction of dense chemical heterogeneity is less than 1–3% of the mantle's volume (Hernlund and Houser, 2008; Davies et al., 2015). Whilst this may be significant in generating geochemical heterogeneity with a range of residence times (e.g. Tackley and Xie, 2002; Huang and Davies, 2007b, 2007a; Brandenburg et al., 2008), it would have a limited influence on the geometry and vigour of lower-mantle dynamics.

An additional and key observation that is often invoked as evidence for the thermo-chemical nature of LLSVPs and, hence, the dynamical significance of chemical piles, is that surface hotspot locations and the reconstructed eruption sites of large igneous provinces (LIPs) appear to concentrate above LLSVP margins (e.g. Thorne et al., 2004; Torsvik et al., 2006, 2008b, 2010; Burke et al., 2008) (Fig. 1a). In a dynamically isochemical mantle, plumes would be expected to rise throughout LLSVP interiors, with no clear preference for their margins (e.g. Davies, 1999). Accordingly, the plume localisation implied by this observation is generally attributed to the interaction of mantle flow with the edges of deep mantle thermo-chemical piles (e.g. Thorne et al., 2004; Torsvik et al., 2006; Tan et al., 2011; Steinberger and Torsvik, 2012; Bower et al., 2013). A recent global Monte Carlo based statisti-