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Plume Generation Zones at the margins of Large Low Shear Velocity Provinces on the core–mantle boundary

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Abstract

Large Igneous Province (LIP) eruption sites of the past 300 My lie vertically above 1% slow shear wave velocity (V_s) contours bounding the African and Pacific Large Low Shear Velocity Provinces (LLSVPs) at the core–mantle boundary (CMB), or in the cases of the Siberian and Columbia River LIPs, bounding one or other of two smaller, Low Shear Velocity Provinces (LSVPs). Steep gradients in V_s at the CMB coincide with those 1% slow contours. The sites of 24 active hotspot volcanoes project down to the same narrowly defined borders of the LLSVPs at the CMB. Plumes that have generated LIPs and major hotspot volcanoes have risen only from the immediate neighbourhoods of the 1% slow V_s contours at the CMB which thus define Plume Generation Zones (PGZs). PGZs projected vertically upward approximately match the +10 m elevation contour of the geoid showing that the LLSVPs are a dominant control on the positively elevated geoid. Minima in the frequency distribution of shear wave velocities in the lowermost mantle near $V_s = -1\%$ indicate that regions with more negative velocities, forming ~2% of total mantle mass, are likely to be of material compositionally different from the rest of the mantle. Because all LIP eruption sites with ages younger than 300 Ma lie above the borders of LLSVPs or LSVPs at the CMB, PGZ footprints are inferred to have remained in the same places for the past 300 My. Because no plumes have risen from the interior of the LLSVPs and because no lithospheric slabs have penetrated those bodies the volumes of the LLSVPs are inferred to have also remained unchanged for the past 300 My. Because the LLSVPs are the dominant control on the positively elevated areas of the geoid those too must have remained as they now are since 300 Ma. The LLSVPs are not rising buoyant objects but stable features of the deep mantle. LIPs have been erupted throughout the past 2.5 Gy indicating that PGZs comparable to those of the past 0.3 Gy and LLSVPs (of which PGZs mark the margins at the CMB) have also existed for at least that long. LLSVPs could thus form the isolated reservoir invoked by some to explain the distinctive isotopic compositions of terrestrial rocks. PGZs lie at places where the boundaries of: (i) The outer core, (ii) one of the LLSVPs or LSVPs, and (iii) the seismically faster part of the deep mantle meet. Horizontal temperature gradients across the steeply inclined margins to the LLSVPs, the interiors of which are hotter than the surrounding mantle, at the CMB are key controls for the generation of plumes. Near the CMB the association of the high temperature of the outer core with an inclined thermal boundary layer at the margins of LLSVPs facilitates the generation of mantle plumes in the PGZs.

Keywords: Large Igneous Provinces; Plume Generation Zones; Large Low Shear Velocity Provinces; core–mantle boundary; mantle plume; hotspot

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1. Introduction

Large Igneous Provinces (LIPs) are commonly viewed as caused by eruptions from major plumeheads risen from the core–mantle boundary (CMB) (e.g. Richards et al., 1989). Since this view is not universally accepted, it is important to look for relations between LIP sites and features near the CMB, and to devise models that provide explanations for the relations.

Burke and Torsvik (2004) and Torsvik et al. (2006, submitted for publication-a) showed that the centres of most LIPs of the past 300 My, when restored to their eruption sites, lie vertically above one or other of two narrow belts centred on the 1% slow shear wave velocity contour of the SMEAN model (Becker and Boschi, 2002) at the CMB (92 km contour, Fig. 1a). They also found that 24 active hot spot volcanoes project down to the CMB within 10° of this contour and that steep horizontal gradients in shear wave velocity are concentrated along that contour (Fig. 1).

The two narrow belts occupy the margins on the CMB of the Earth's two Large Low Shear wave Velocity Provinces (LLSVPs, Garnero et al., in 2007). The Siberian LIP eruption site is not related to either of those two narrow belts but lies vertically above the margin of a separate, much smaller, low shear wave velocity province ("LSVP"). We estimate that LLSVPs and LSVPs occupy approximately one fifth of the CMB area. The belts around the LLSVPs and LSVPs have been the Plume Generation Zones (PGZs) of the Earth's deep mantle for 300 My.

In this paper we use the frequency distribution of velocity in tomographic models as evidence that the LLSVPs are chemically distinct bodies and estimate their sizes and shapes. Using probability theory, we show that the chance coincidence of reconstructed LIPs and LLSVP boundaries is extremely unlikely. Recognition of PGZs helps to shed light on the nature and the history of the deep mantle and more generally on Earth dynamics for the past 300 My and possibly for a much longer time. As newly recognized features of the deep mantle the PGZs represent a challenge to understanding that is unlikely to be soon fully resolved. Here we describe PGZs and present some of the more obvious implications of PGZ discovery.

2. LLSVPs in the lowermost mantle as bodies of distinct material: Evidence for their existence, size and shape

The concentration of steep gradients along the −1% contour can be understood from the frequency distribution of the SMEAN tomography model shown in Fig. 1b: These graphs show, at each depth level, the area with a given shear wave velocity anomaly, in bins of 0.1% width, multiplied with a constant factor. In its lowest layer (92 km above the CMB) the model has a distinct bimodal frequency distribution with a large peak at +0.6%, a smaller peak at −1.6% and a saddle in between at −1%. The bimodal distribution may be caused by the presence of two different kinds of material: If material within the LLSVPs and LSVPs on one hand, and material elsewhere on the other, each have shear wave velocity anomalies approximately characterized by a normal (Gaussian) distribution, but with different mean values, the total distribution will be bimodal. A bimodal frequency distribution can also be discerned in the D'' tomography models of Kuo et al. (2000) and Castle et al. (2000), although less clearly.

For the SMEAN model, the area of the peak at negative velocity anomaly diminishes and the peak becomes less clear higher up in the mantle (Fig. 1b). Nevertheless, we assume that the −1% contour marks the boundary between LLSVP material and "normal" mantle (Fig. 1a). The LLSVPs so defined are bodies that gradually taper upward in the mantle; the Pacific LLSVP extends up to a height 1384 km above the CMB (1507 km below the surface) and the African LLSVP reaches a height of 1814 km (1077 km below the surface) (Fig. 2). The uppermost parts appear as narrow cones or columns, and it is difficult to say whether they are still part of the chemically distinct bodies. Those might well be restricted to the lowermost few hundred kilometres of the mantle, where the bimodal frequency distribution in the tomography models is most distinct (Fig. 1b). The relation between what appears to be thermochemical bodies and present-day mantle plume conduits in tomography models is further discussed by Boschi et al. (2007).

The LLSVP area reduces from 21% at 92 km above the CMB to 13% at 235 km and 6% at 378 km (Fig. 1c) and we estimate that the LLSVPs together contain 1.6 vol.% and 1.9 mass% of the mantle (Table 1). Volume % are converted to mass % using the PREM (Dziewonski and Anderson, 1981) mantle density structure. The African LLSVP is slightly larger with 0.9 vol.% and 1.1 mass% of the mantle. The centres of mass of the two LLSVPs are almost exactly 180° apart in longitude, but they are both located at slightly southerly latitudes (Table 1). The centre of mass (not considering curvature of the Earth) of the Africa LLSVP lies ~400 km above the CMB while the centre of mass of the Pacific LLSVP is at ~200 km (Table 1).