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Compositional layering within the large low shear-wave velocity provinces (LLSVPs) in the lower mantle

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Seismic tomography reveals two antipodal LLSVPs in the Earth's mantle, each extending from the core-mantle boundary (CMB) up to ∼1000 km depth. The LLSVPs are thought to host primordial mantle materials that bear witness of early-Earth processes, and/or subducted basalt that has accumulated in the mantle over billions of years. A compositional distinction between the LLSVPs and the ambient mantle is supported by anti-correlation of bulk-sound and shear-wave velocity (Vs) anomalies as well as abrupt lateral gradients in Vs along LLSVP margins. Both of these observations, however, are mainly restricted to the LLSVP bottom domains (2300∼2900 km depth), or hereinafter referred to as "deep distinct domains" (DDD). Seismic sensitivity calculations suggest that DDDs are more likely to be composed of primordial mantle material than of basaltic material. On the other hand, the seismic signature of LLSVP shallow domains (1000∼2300 km depth) is consistent with a basaltic composition, though a purely thermal origin cannot be ruled out.

Here, we explore the dynamical, seismological, and geochemical implications of the hypothesis that the LLSVPs are compositionally layered with a primordial bottom domain (or DDD) and a basaltic shallow domain. We test this hypothesis using 2D thermochemical mantle-convection models. Depending on the density difference between primordial and basaltic materials, the materials either mix or remain separate as they join to form thermochemical piles in the deep mantle. Separation of both materials within these piles provides an explanation for LLSVP seismic properties, including substantial internal vertical gradients in Vs observed at 400-700 km height above the CMB, as well as out-of-plane reflections on LLSVP sides over a range of depths. Predicted geometry of thermochemical piles is compared to LLSVP and DDD shapes as constrained by seismic cluster analysis. Geodynamic models predict short-lived "secondary" plumelets to rise from LLSVP roofs and to entrain basaltic material that has evolved in the lower mantle. Long-lived "primary" plumes rise from LLSVP margins and entrain a mix of materials, including small fractions of primordial mantle material. These predictions address the geochemical and geochronological record of intraplate hotspot volcanism on the Pacific plate. In general, the parameter range spanned by models that are able to reconcile observations provides a constraint for the intrinsic density anomaly (or composition) of DDDs. We use this constraint to evaluate a possible origin of DDDs from (basal) magma ocean cumulates. The study of LLSVP compositional layering has indeed important implications for our understanding of heat and material fluxes through mantle reservoirs, as well as bulk Earth chemistry and evolution.