Linking magma-ocean crystallization and compositional heterogeneity within LLSVPs in the deep mantle

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Seismic tomography reveals two antipodal large low shear-velocity provinces (LLSVPs) in the Earth's mantle, each extending from the core-mantle boundary (CMB) up to ~1000 km depth. LLSVPs are thought to host primordial mantle materials, and/or subducted basalt.. A compositional (in addition to a thermal) origin for LLSVPs 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 LLSVP bottom domains (2300~2900 km depth), or "deep distinct domains" (DDD). Seismic sensitivity analysis suggests that DDDs are more likely to be composed of primordial mantle material than of basaltic material. The seismic signature of LLSVP shallow domains (1000~2300 km depth) instead is consistent with a basaltic composition. Substantial vertical gradients in Vs at 400-700 km above the CMB support compositional layering within LLSVPs.

Using 2D geodynamic models, we explore the dynamics of compositionally double-layered LLSVPs. Depending on the density difference between primordial and basaltic materials (and ambient-mantle pyrolite), materials either mix with each other or remain separate. The coverage of the CMB by primordial material and LLSVP shapes also depends on the densities of materials. Accordingly, seismic observations bracket the density anomaly of DDD material. We use this constraint to evaluate the origin of DDDs from magma-ocean cumulates. Magma-ocean models predict the formation of at least a thin, strongly Fe-enriched layer in the late stages of freezing, during which progressive exhalation of a steam atmosphere has decelerated freezing to promote fractional crystallization. The very dense Fe-rich material is predicted to sink to the base of the mantle, cover the CMB and never be entrained by mantle convection, inconsistent with seismic constraints for DDDs. However, we estimate that the strongly Fe-rich material thermally equilibrated during sinking, underwent melting and infiltrated the ambient mantle to form moderately Fe-rich hybrid pyroxenitic lithologies, out of which DDDs may be made up today. Therefore, DDDs may host an Early Enriched Reservoir. According to our models, DDDs indeed remain very poorly sampled by plumes, as they are covered by basaltic material within double-layered LLSVPs. This scenario reconciles estimates for DDD density, composition and volume, as well as CMB coverage by DDDs.