Origin of the vast height difference between the African and Pacific LLSVPs

Qian Yuan (✉ qyuan23@asu.edu)

Arizona State University

Mingming Li

Arizona State University <https://orcid.org/0000-0003-4335-5066>

Article

Keywords: LLSVPs, Velocity Provinces

Posted Date: November 2nd, 2020

DOI: <https://doi.org/10.21203/rs.3.rs-59076/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Version of Record: A version of this preprint was published at Nature Geoscience on March 10th, 2022.
See the published version at <https://doi.org/10.1038/s41561-022-00908-3>.

Origin of the vast height difference between the African and Pacific LLSVPs

Qian Yuan^{1*}, Mingming Li¹

¹ Arizona State University, School of Earth and Space Exploration, PO Box 876004, Tempe, AZ85287-6004, USA

Correspondence: gyuan23@asu.edu

Abstract

Seismic observations have revealed two Large Low Shear Velocity Provinces (LLSVPs) beneath Africa and the Pacific Ocean in the lowermost mantle¹⁻⁴. However, the detailed morphology and stability of the LLSVPs and their interaction with the surrounding mantle remain unclear. Here we show that, whereas the maximum height of the Pacific LLSVP is ~500 – 700 km, the African LLSVP reaches a height of ~1,500 – 1,800 km from the core-mantle boundary. With numerical modeling experiments, we find that the height of the Pacific LLSVP can be reconciled by a wide range of the LLSVP density and surrounding mantle viscosity. However, the large height of the African LLSVP indicates that it may be less dense and thus less stable than the Pacific LLSVP.

Main Text

Understanding the density and viscosity structure of the Earth's deep mantle remains one of the most challenging and important tasks in solid Earth sciences. Seismic observations have revealed two large low shear velocity provinces (LLSVPs) in the lowermost mantle beneath Africa and the Pacific Ocean¹⁻⁴. The morphology of the LLSVPs is controlled by the nature of mantle convection, which is in turn controlled by, and thus provides important information on, the density and viscosity structure of the deep mantle⁵⁻⁷.

The morphology of the LLSVPs has been investigated through seismic observations⁸⁻¹², which have shown that the height of the LLSVPs varies from place to place. However, the maximum height of the two LLSVPs reach remains unclear^{8,10}. Here, we used a novel approach to estimate the maximum height of the LLSVPs. For each global seismic shear wave tomography model, we calculated the average dVs as a function of depth in vertical cross-sections that cut

through the LLSVP regions (e.g., Fig. 1a). We computed this depth- dVs profile for 17 global tomography models (see Extended Data Fig. 1 for references) and calculated their average (Fig. 1b-1c). It is found that the dVs is the most negative near the core-mantle boundary (CMB) and increases linearly with radius (Figs. 1b-1c) until a turning point (e.g., gray regions in Figs. 1b-1c) where the rate of increase changes significantly. The increase of the average dVs with radius below the turning point may be caused by that the LLSVPs have wider base and narrower top. The turning point may therefore mark the transition from depths with LLSVPs to depths without LLSVPs and is thus defined as the maximum height of the LLSVPs. If there are two or more turning points, as is the case for the African_Bb curve in Fig. 1c, the one with dVs value closest to zero is adopted. We examined 31 vertical cross-sections through the LLSVPs (Extended Data Figs. 1-3) and found 4 of them with the maximum height of the LLSVPs. With this approach, the maximum height estimated is $\sim 500 - 700$ km for the Pacific LLSVP, and $\sim 1,500$ to $1,800$ km for the African LLSVP (Figs. 1b-c).

The question is what causes the large height difference between the two LLSVPs. The LLSVPs have been hypothesized to be caused by compositionally-distinct materials that are intrinsically denser than the surrounding mantle¹³⁻¹⁶. Previous numerical modeling and laboratory experiments have shown that the height of a thermochemical pile is greatly controlled by its density and viscosity compared to the surrounding mantle^{5,14,17-20}. However, it remains unclear through what mechanism these properties control the height of a pile, and how to explain the vast height difference between the two LLSVPs.

Here, we perform systematic numerical calculations to quantify the relationship between the height of thermochemical piles and the density and viscosity structure of the mantle. The conservation equations of mass, momentum and energy were solved under the Boussinesq approximation with the Citcom code in a 2D Cartesian geometry²¹. Most models have an aspect ratio of 1:1, with 256×256 elements. Our models contain 2 compositional components: the pile material and the background mantle material. The intrinsic density anomaly of the pile materials is non-dimensionalized as the buoyancy number, which is defined as $B = \Delta\rho/\rho\alpha\Delta T$, where $\Delta\rho/\rho$ is the intrinsic density anomaly of the pile material compared to the background mantle, α is thermal expansivity and ΔT is reference temperature. Non-dimensional Rayleigh number (Ra) is defined as $a = (\rho_0 g \alpha_0 \Delta T h^3)/(\eta_0 \kappa_0)$, where ρ_0 , g , α_0 , η_0 and κ_0 are the background mantle reference density, the gravitational acceleration, the reference thermal expansivity, the reference

viscosity, and the reference thermal diffusivity, respectively, and h is the thickness of the mantle. The reference values are listed in [Extended Data Table 1](#). The viscosity depends only on composition for most models, but models with additional temperature dependence of viscosity have also been performed. We employ a model input Rayleigh number of $Ra = 1 \times 10^6$ for all cases, but mantle viscosity is varied case by case which leads to a wide range of effective Rayleigh number and vigor of convection.

Shortly after the initial condition, the pile materials are pushed by cold downwellings into a thermochemical pile and we focus on the maximum height that a pile can reach ([Fig. 2](#)). The height of the thermochemical pile refers to the vertical distance from the bottom of the model to depths where the lateral extent of the pile falls below 5% width of the base of the pile. The average height is calculated for each calculation when the model reached statistically steady-state. Additional details about model setup are in the Materials and Methods. [Supplementary Data 1](#) lists the parameters for all models used in this study.

We define a reference case which has a buoyancy number of 0.8 and a viscosity of 2×10^{20} Pa s for the pile materials that initially occupy the lowermost 7% of the model domain. The background mantle viscosity for the reference case is 2×10^{22} Pa s. We first explored the effect of initial volume of pile materials on the height of pile. The snapshots of three different models are shown in [Fig. 2](#), in which the intrinsically dense pile materials occupy the lowermost 4% ([Fig. 2a-2d](#)), 7% ([Fig. 2b-2e](#)) and 11% ([Fig. 2c-2f](#)) of the model domain, respectively, for each model, whereas other parameters are the same as in the reference case. Interestingly, the thermochemical piles in all 3 models reach similar maximum heights ([Figs. 2d-2f](#)). [Fig. 3A](#) compares the pile height for 9 cases in which the initial pile volume ranges from 3% to 11% of the model domain. We find that the pile height is not significantly affected by the volume of pile materials. Adding more pile material to the model domain only increases the lateral extent of the pile rather than its vertical elevation ([Fig. 2d-2f](#)). We do not consider cases in which the pile material occupies more than 11% of the model domain, because then the pile material forms a global layer which is different from the LLSVPs that are spatially isolated structures. In models where the initial volume of pile material is less than 3% of the model domain, the pile becomes very unstable and is quickly entrained into the ambient mantle, even after we double the model resolution.

We investigated the impact of buoyancy number B on the pile height. We find that when B is smaller than 0.45 the pile material becomes unstable and is mixed into the background mantle quickly, and when B is larger than 1.25, the pile material forms a stable, global layer at the bottom. Three snapshots of three cases with buoyancy number 0.5, 0.7 and 1.1 are shown in Figs. 2g-2i. As expected, the pile height decreases accordingly with increasing buoyancy number. Fig. 3B shows the pile height for 16 cases with B ranging from 0.5 to 1.25 while other parameters are kept the same as in the reference case. We find that the decrease of pile height with increasing buoyancy number can be described by $h' = (0.137 \pm 0.013) \times B^{-1.29 \pm 0.03}$, where h' is the non-dimensional height normalized by mantle thickness, or $h = (394 \pm 37) \times B^{-1.29 \pm 0.03}$, with h the dimensional height.

We investigated the influence of background mantle viscosity, η_{bg} , on the height of the pile. We gradually increased the mantle viscosity from 2×10^{22} Pa s to 5×10^{23} Pa s in 26 models, while other parameters are kept the same as in the reference case. The lower row in Figs. 2j-2l shows snapshots of three cases with $\eta_{bg} = 1 \times 10^{23}$, 2×10^{23} , and 4×10^{23} Pa s, respectively. Clearly, the pile height increases moderately with increasing background mantle viscosity. In Fig. 3c, the results of 26 cases also show that the height of the pile increases with η_{bg} . The pile height increases more rapidly from ~400 km to ~750 km in the η_{bg} interval between 1×10^{22} Pa s and 10×10^{22} Pa s. However, the increase of pile height with η_{bg} becomes slower when η_{bg} is larger than 10×10^{22} Pa s. The increases of pile height with η_{bg} as shown in Fig. 3c is best fitted by a power law $h' = (0.175 \pm 0.024) \times \eta'_{bg}^{0.25 \pm 0.04}$, where η'_{bg} is the viscosity normalized by reference viscosity of 2×10^{22} Pa s, or $h = (503 \pm 70) \times \eta_{bg}^{0.25 \pm 0.04}$, with h and η_{bg} the dimensional height and viscosity, respectively.

We also explored how the viscosity of pile material affects pile height. We vary pile viscosity from 1.4×10^{19} Pa s to 2×10^{25} Pa s for 32 cases with the background mantle viscosity fixed at 2×10^{22} Pa s, and other parameters the same as in the reference case. We found that the height of the piles is ~500 km for most cases while the height increases moderately (<150 km) if the pile viscosity is at least hundreds of times higher than ambient mantle. Hence, the pile viscosity is not a main factor controlling pile height (Fig. 3d).

The results shown and discussed above demonstrate that the height of a stable thermochemical pile is mainly controlled by two factors: the background mantle viscosity and

the buoyancy number of the pile material. We next investigated the pile height for different combinations of these two parameters. We systematically vary the buoyancy number from 0.4 to 1.25, and the background mantle viscosity from 2×10^{22} Pa s to 5×10^{23} Pa s. A total number of 450 models (defined here as individual models) were run for all combinations of the two parameters with the above ranges ([Supplementary Data 1](#)).

To avoid the influence of the minor mantle temperature differences between models on our results, we also performed a reference case and allowed the temperature field to reach quasi-steady state. We then restarted the case but changed the buoyancy number and the background mantle viscosity. This gives us a second group of 450 models (defined here as re-run models; [Supplementary Data 1](#)). We compute pile height when it reaches a new quasi-steady state, but before there is any noticeable temperature changes (>95% similarity) in the mantle. This approach thus allows all the calculations to have nearly the same temperature-controlled part of the buoyancy fields and effective Rayleigh number.

[Fig. 4](#) shows pile height as a function of buoyancy number and background mantle viscosity for the 450 re-run models, whose results are nearly the same as the individual models ([Extended Data Fig. 4](#)). The white stars (green triangles) mark the height of the pile at 500-700 km (1500-1800 km), corresponding to the maximum height of the Pacific LLSVP (African LLSVP). We found that the height of the Pacific LLSVP can be explained by a very wide range of background mantle viscosity and pile buoyancy number, and there is a clear trade-off between the two parameters. However, the height of the African LLSVP can only be explained by a pile buoyancy number in a narrow range of 0.45-0.50. In addition, for a pile buoyancy number of 0.50, the background mantle viscosity required to explain the height of the African LLSVP is more than 3×10^{23} Pa s, which is unrealistically high^{22,23}. Even if the pile buoyancy number is 0.45, the background mantle viscosity needs to be larger than 1.2×10^{23} Pa s, which is near at the maximum estimations of lower mantle viscosity^{22,23}. The thermochemical pile can become taller as its buoyancy number further decreases; however, for a pile buoyancy number lower than 0.45, the pile becomes unstable (gray inverse triangles in [Fig. 4](#)), with more than half of its volume mixed into the background mantle after ~4.6 Gyr. This occurs even when the pile viscosity is more than several hundred times higher than the background mantle.

In summary, given the assumption that the LLSVPs are caused by thermochemical piles, [Fig. 4](#) shows that, for the same background mantle viscosity, the African LLSVP needs to be at

least 0.5% intrinsically lighter than the Pacific LLSVP. The 1,500-1,800 km height of the African LLSVP cannot not be explained solely by increasing the background mantle viscosity but requires a relatively low pile buoyancy number, but a low buoyancy number also makes the pile unstable.

We also performed cases with an aspect ratio of 6:1 for the model domain and found that it only leads to minor changes of pile height (Extended Data Fig. 5). Cases with temperature dependence of viscosity are also performed (Supplementary Data 1). In these cases, the background mantle viscosity generally increases with the distance from the thermochemical piles due to the decrease of temperature, and therefore, including temperature-dependent viscosity reduces the height of piles. Interestingly, we find that for a case with temperature-dependent viscosity to have similar pile height as a case with the same parameters but without temperature-dependence of viscosity, the average background mantle viscosity in regions within ~50 km from the edges of thermochemical piles needs to be similar (Extended Data Fig. 6), indicating that the viscosity in regions close to the pile edges plays a controlling role for the pile height, which is consistent with previous laboratory experiments^{20,25,26}. As the degree of temperature-dependence of viscosity increases, the viscosity at the pile margins decreases, and pile height is further reduced (Extended Data Fig. 6). Therefore, it is even more difficult for a pile to reach the height of African LLSVP when temperature-dependence of viscosity is considered. We here intentionally used the simplest 2D Cartesian models to identify the most important parameters that control the height of piles. More complexities such as 3D spherical geometry, phase transition at 660 km, subduction history, and long wavelength convection would likely affect the pile height, but it is unclear how they could cause the large (~1,000 km) height difference between the two LLSVPs because they likely affect the heights of two thermochemical piles of the Earth in the same way.

One idea is that the seismically-observed LLSVPs may contain an upper layer of thermal mantle plumes or basaltic material²⁷ with thickness comparable to or larger than the basal thermochemical layer. In these scenarios, the maximum height of the LLSVPs we measured in Fig. 1 is larger than the maximum height of the thermochemical piles. However, mantle plumes or basaltic materials should occur on both LLSVPs, and this possibility still does not explain the difference in height for the two LLSVPs. In addition, the seismic observations by²⁸ provide

evidence that the thermochemical section of the African LLSVP reaches more than 1,500 km above the CMB, which poses questions about this possibility.

It was proposed by Tan and Gurnis (2005)⁷ that if the pile material has larger bulk modulus or is less compressible than the background mantle, metastable piles will form with steep edges. However, the height of the piles in the metastable models of Tan and Gurnis (2005)⁷ is mostly less than ~1,000 km, much lower than the maximum height of the African LLSVP which is ~1,500-1,800 km (Fig. 1). One of their metastable cases has height above ~1500 km, but it requires a very large bulk modulus of pile material (8% higher than ambient mantle). We also performed a series of calculations in which the buoyancy number of pile material decreases with depth with similar parameterization to (7), and we find the pile can have a height similar to African LLSVP but only when the pile buoyancy number is relatively small to make it unstable (Extended Data Fig. 7). Nevertheless, this scenario does not explain the different height of the two LLSVPs, unless they have different compositions and bulk moduli. Importantly, a recent study of LLSVP density using Earth's tides found a higher density for the bottom two-thirds of the LLSVPs²⁹, in contrast to the assumption of Tan and Gurnis (2005)⁷ in which the intrinsic density of piles decreases with depth.

Laboratory experiments by Davaille (1999)⁵ found that for a narrow range of pile buoyancy number (~0.15-0.35), thermochemical piles that are ~10-10,000 times more viscous than the background mantle oscillate between phases of growth and collapse, which may explain different heights of the two LLSVPs if they are in different phases of oscillation. However, in their experiments the pile materials cover more than half the depth of the tank, and a continuous global layer is always covering the bottom of the tank during the oscillatory processes, which is different from the two LLSVPs being spatially isolated. It remains unclear if such an oscillatory mode will still occur if the volume of pile materials is only several volume percent of the mantle⁸. The oscillating behavior of piles in this model means that they are not stable structures.

For a viscosity in the lower mantle of $\sim 1 \times 10^{23}$ Pa s²³, our experiments clearly show the large height of the African LLSVP requires it to have low intrinsic density anomaly to make the LLSVP unstable (Fig. 4). This is consistent with the studies by Tan and Gurnis (2005)⁷ and Davaille (1999)⁵ which hinted that the African LLSVP is not stable. Our results (Fig. 4) show that the African LLSVP may be in a more stable regime if the background viscosity is much higher, but even though, the African LLSVP may be currently less intrinsically dense than the

Pacific LLSVP. If the two LLSVPs were originally made of the same primordial materials, their density difference may be caused by long-term dynamic interactions with the surrounding mantle which may entrain different amounts of background mantle materials and subducted materials (which may have different intrinsic densities) into the LLSVPs. This is corroborated by a most recent study of systematic radiogenic isotopes (lead, neodymium and strontium) on plume-induced basalts above the two LLSVPs, showing the African LLSVP is enriched by subducted upper continental materials (less dense) during Pangaea supercontinent cycle but no such feature in the Pacific LLSVP³⁰.

Main References

1. Garnero, E. J., McNamara, A. K. & Shim, S. H. Continent-sized anomalous zones with low seismic velocity at the base of Earth's mantle. *Nat. Geosci.* **9**, 481–489 (2016).
2. Grand, S. P. Mantle shear-wave tomography and the fate of subducted slabs. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **360**, 2475–2491 (2002).
3. Li, X. & Romanowicz, B. Global mantle shear velocity model developed using nonlinear asymptotic coupling theory and Barbara. *J. Geophys. Res. Solid Earth* **101**, 22245–22272 (1996).
4. Ritsema, J., Heijst, H. J. Van & Woodhouse, J. H. Global transition zone tomography. *J. Geophys. Res.* **109**, B02302 (2004).
5. Davaille, A. Simultaneous generation of hotspots and superwells by convection in a heterogeneous planetary mantle. *Nature* **402**, 756–760 (1999).
6. Li, M., Zhong, S. & Olson, P. Linking lowermost mantle structure, core-mantle boundary heat flux and mantle plume formation. *Phys. Earth Planet. Inter.* **277**, 10–29 (2018).
7. Tan, E. & Gurnis, M. Metastable superplumes and mantle compressibility. *Geophys. Res. Lett.* **32**, 1–4 (2005).
8. Cottaar, S. & Lekic, V. Morphology of seismically slow lower-mantle structures. *Geophys. J. Int.* **207**, 1122–1136 (2016).
9. He, Y. & Wen, L. Structural features and shear-velocity structure of the 'Pacific Anomaly'. *J. Geophys. Res. Solid Earth* **114**, 1–17 (2009).
10. Lekic, V., Cottaar, S., Dziewonski, A. & Romanowicz, B. Cluster analysis of global lower mantle tomography : A new class of structure and implications for chemical heterogeneity.

- 244 *Earth Planet. Sci. Lett.* **357–358**, 68–77 (2012).
- 245 11. Ni, S. & Helmberger, D. V. Ridge-like lower mantle structure beneath South Africa. *J.*
246 *Geophys. Res.* **108**, 2094 (2003).
- 247 12. Wang, Y. & Wen, L. Geometry and P and S velocity structure of the ‘African Anomaly’. *J.*
248 *Geophys. Res. Solid Earth* **112**, 1–26 (2007).
- 249 13. Li, M. & Zhong, S. The source location of mantle plumes from 3D spherical models of
250 mantle convection. *Earth Planet. Sci. Lett.* **478**, 47–57 (2017).
- 251 14. Tackley, P. J. Three-Dimensional Simulations of Mantle Convection with a Thermo-
252 Chemical Basal Boundary Layer : D ”? *AGU Geophys. Mongraph C. ed. M. Gurnis* 1–18
253 (1998).
- 254 15. McNamara, A. K. & Zhong, S. Thermochemical structures beneath Africa and the Pacific
255 Ocean. *Nature* **437**, 1136–1139 (2005).
- 256 16. Zhang, N., Zhong, S., Leng, W. & Li, Z. X. A model for the evolution of the Earth’s
257 mantle structure since the Early Paleozoic. *J. Geophys. Res. Solid Earth* **115**, 1–22 (2010).
- 258 17. Davaille, A., Bars, M. Le & Carbonne, C. Thermal convection in a heterogeneous mantle
259 Convection thermique dans un manteau hétérogène. *Comptes Rendus Geosci.* **335**, 141–
260 156 (2003).
- 261 18. Jellinek, A. M. & Manga, M. Links between long-lived hot spots, mantle plumes, D”, and
262 plate tectonics. *Rev. Geophys.* **42**, 1–35 (2004).
- 263 19. Kumagai, I., Davaille, A. & Kurita, K. On the fate of thermally buoyant mantle plumes at
264 density interfaces. *Earth Planet. Sci. Lett.* **254**, 180–193 (2007).
- 265 20. Le Bars, M. & Davaille, A. Whole layer convection in a heterogeneous planetary mantle.
266 *J. Geophys. Res.* **109**, 1–23 (2004).
- 267 21. Solomatov, V. S. & Moresi, L. N. Numerical Investigation of 2d Convection with
268 Extremely Large Viscosity Variations. *Phys. Fluids* **7**, 2154–2162 (1995).
- 269 22. Mitrovica, J. X. & Forte, A. M. A new inference of mantle viscosity based upon joint
270 inversion of convection and glacial isostatic adjustment data. **225**, 177–189 (2004).
- 271 23. Steinberger, B. & Calderwood, A. R. Models of large-scale viscous flow in the Earth’s
272 mantle with constraints from mineral physics and surface observations. *Geophys. J. Int.*
273 **167**, 1461–1481 (2006).
- 274 24. Seton, M. *et al.* Global continental and ocean basin reconstructions since 200Ma. *Earth-*

- 275 *Science Rev.* **113**, 212–270 (2012).
- 276 25. Davaille, A. & Jaupart, C. Transient High-Rayleigh-Number Thermal Convection With
277 Large Viscosity Variations. *J. Fluid Mech.* **253**, 141–166 (1993).
- 278 26. Le Bars, M. & Davaille, A. Large interface deformation in two-layer thermal convection
279 of miscible viscous fluids. *J. Fluid Mech.* **499**, 75–110 (2004).
- 280 27. Ballmer, M. D., Schumacher, L., Lekic, V., Thomas, C. & Ito, G. Geochemistry,
281 Geophysics, Geosystems. *Geochemistry, Geophys. Geosystems* **17**, 4517–4533 (2016).
- 282 28. Simmons, N. A., Forte, A. M. & Grand, S. P. Thermochemical structure and dynamics of
283 the African superplume. *Geophys. Res. Lett.* **34**, 1–5 (2007).
- 284 29. Lau, H. C. P. *et al.* Tidal tomography constrains Earth’s deep-mantle buoyancy. *Nature*
285 **551**, 321–326 (2017).
- 286 30. Doucet, L. S. *et al.* Distinct formation history for deep-mantle domains reflected in
287 geochemical differences. *Nat. Geosci.* **13**, (2020).
- 288 31. Ritsema, J., Deuss, A., Van Heijst, H. J. & Woodhouse, J. H. S40RTS: A degree-40 shear-
289 velocity model for the mantle from new Rayleigh wave dispersion, teleseismic traveltimes
290 and normal-mode splitting function measurements. *Geophys. J. Int.* **184**, 1223–1236
291 (2011).
- 292 32. Farrell, K. A. O. & Lowman, J. P. Emulating the thermal structure of spherical shell
293 convection in plane-layer geometry mantle convection models. *Phys. Earth Planet. Inter.*
294 **182**, 73–84 (2010).
- 295 33. Tackley, P. J. & King, S. D. Testing the tracer ratio method for modeling active
296 compositional fields in mantle convection simulations. *Geochemistry, Geophys.*
297 *Geosystems* **4**, 1–15 (2003).
- 298 34. Hosseini, K. *et al.* SubMachine: Web-Based Tools for Exploring Seismic Tomography
299 and Other Models of Earth’s Deep Interior. *Geochemistry, Geophys. Geosystems* **19**,
300 1464–1483 (2018).
- 301 35. Simmons, N. A., Forte, A. M., Boschi, L. & Grand, S. P. GyPSuM: A joint tomographic
302 model of mantle density and seismic wave speeds. *J. Geophys. Res. Solid Earth* **115**, 1–24
303 (2010).
- 304 36. Houser, C., Masters, G., Shearer, P. & Laske, G. Shear and compressional velocity models
305 of the mantle from cluster analysis of long-period waveforms. *Geophys. J. Int.* **174**, 195–

212 (2008).

37. Montelli, R., Nolet, G., Dahlen, F. A. & Masters, G. A catalogue of deep mantle plumes: New results from finite frequency tomography. *Geochemistry, Geophys. Geosystems* **7**, (2006).
38. Koelemeijer, P., Ritsema, J., Deuss, A. & van Heijst, H. J. SP12RTS: A degree-12 model of shear- and compressional-wave velocity for Earth's mantle. *Geophys. J. Int.* **204**, 1024–1039 (2016).
39. Tesoniero, A., Auer, L., Boschi, L. & Cammarano, F. Journal of Geophysical Research : Solid Earth Hydration of marginal basins and compositional variations within the continental lithospheric mantle inferred from a new global model of shear and compressional velocity. *J. Geophys. Res.* 7789–7813 (2015). doi:10.1002/2015JB012026.Received
40. Ritsema, J., Van Heijst, H. J. & Woodhouse, J. H. Complex shear wave velocity structure imaged beneath Africa and Iceland. *Science (80-.).* **286**, 1925–1931 (1999).
41. Moulik, P. & Ekström, G. An anisotropic shear velocity model of the Earth's mantle using normal modes, body waves, surface waves and long-period waveforms. *Geophys. J. Int.* **199**, 1713–1738 (2014).
42. Auer, L., Boschi, L., Becker, T. W. & Giardini, D. Journal of Geophysical Research : Solid Earth Savani : A variable resolution whole-mantle model of anisotropic shear velocity variations based. 3006–3034 (2014). doi:10.1002/2013JB010773.Received
43. Panning, M. P., Lekić, V. & Romanowicz, B. A. Importance of crustal corrections in the development of a new global model of radial anisotropy. *J. Geophys. Res. Solid Earth* **115**, 1–18 (2010).
44. French, S. W. & Romanowicz, B. A. Whole-mantle radially anisotropic shear velocity structure from spectral-element waveform tomography. *Geophys. J. Int.* **199**, 1303–1327 (2014).
45. Lekić, V. & Romanowicz, B. Inferring upper-mantle structure by full waveform tomography with the spectral element method. *Geophys. J. Int.* **185**, 799–831 (2011).
46. Chang, S. J., Ferreira, A. M. G., Ritsema, J., Van Heijst, H. J. & Woodhouse, J. H. Joint inversion for global isotropic and radially anisotropic mantle structure including crustal thickness perturbations. *J. Geophys. Res. Solid Earth* **120**, 4278–4300 (2015).

47. Lu, C. & Grand, S. P. The effect of subducting slabs in global shear wave tomography. *Geophys. J. Int.* **205**, 1074–1085 (2016).
48. Durand, S., Debayle, E., Ricard, Y. & Lambotte, S. Seismic evidence for a change in the large-scale tomographic pattern across the D'' layer. *Geophys. Res. Lett.* **43**, 7928–7936 (2016).
49. Durand, S., Debayle, E., Ricard, Y., Zaroli, C. & Lambotte, S. Confirmation of a change in the global shear velocity pattern at around 1000km depth. *Geophys. J. Int.* **211**, 1628–1639 (2017).

Figures

Figure 1 | Depth profiles of the averaged V_s anomaly at 4 vertical cross-section locations through the LLSVPs. a. the yellow colors highlight 30% of the CMB area at 2800 km depth with the lowest V_s from the seismic tomography model S40RTS³¹. The thick, solid curves mark the locations of vertical cross-section for which the horizontally averaged V_s anomalies of 17

379 tomography models as a function of depth, or the depth- V_s profile, are shown in panels b-c. **b.**
380 the horizontally averaged V_s anomalies of 17 models as a function of depth for the 4 vertical
381 cross-sections as shown in panel a. **c.** similar to panel b, but only the negative values of V_s are
382 used when calculating the horizontal average.
383

Figure 2 | The effects of volume of pile materials, buoyancy number and mantle viscosity on the height of piles. The first row (a-c) and second row (d-f), respectively, show the snapshots of temperature and compositional fields (red shows pile materials, black shows background mantle materials, and green shows a mixture between the two) for 3 cases with the volume of pile

materials occupying 4% (a, d), 7% (b, e) and 12% (c, f) of the model domain. The white dotted lines in (d-f) show the initial height of the pile materials before the calculation starts, and the h shows the height of the pile. g-i, snapshots of the compositional fields for 3 cases in which the buoyancy numbers of pile materials are 0.5 (g), 0.7 (h) and 1.1 (i). j-l, snapshots of viscosity fields for 3 cases in which the background mantle viscosity is 1×10^{23} Pa s (j), 2×10^{23} Pa s (k), and 4×10^{23} Pa s (l).

Figure 3 | The effects of model parameters on the height of piles. Model parameters tested here include the volume percentage of pile materials with respect to the model domain (a), the buoyancy number of pile materials (b), the viscosity of the background mantle materials (c), and the viscosity of the pile materials (d). The blue dots show the average height after the model reaches statistically steady state, with the error bars showing the standard deviation. One model parameter is modified for each case, with the other parameters the same as the reference case which uses a buoyancy number of 0.8 and pile viscosity of 2×10^{20} Pa s. The controls of pile

buoyancy number and viscosity of the background mantle on the pile height are best fitted by the orange dashed curves in panels **b** and **c**, respectively, with the dimensional fitting equations included in each panel.

Figure 4 | The height of piles as a function of pile buoyancy number and background mantle viscosity. The height of piles for different combinations of buoyancy number of pile materials and the viscosity of the background mantle. White stars show cases in which the height of piles is 500 – 700 km, and green triangle shows cases in which the pile height is 1,500 – 1,800 km. The gray triangles show cases in which the thermochemical piles are not stable.

Methods

Governing equations

We perform geodynamic calculations by solving the following non-dimensional equations of conservation of mass, momentum and energy under the Boussinesq approximation:

$$\nabla \cdot \vec{u} = 0 \quad (1)$$

$$-\nabla P + \nabla \cdot (\eta \epsilon) = Ra(T - BC)\vec{z} \quad (2)$$

$$\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla)T = \nabla^2 T + Q \quad (3)$$

where $\vec{u}$ is the velocity, P is the dynamic pressure, η is the viscosity, ϵ is the strain rate, Ra is the Rayleigh number, T is the temperature, B and C are the buoyancy number and composition, respectively. $\vec{z}$ is the unit vector in the vertical direction, t is the time, Q is the internal heating rate. α and κ are thermal expansivity and thermal diffusivity, respectively.

The advection of the composition C is given by:

$$\frac{\partial C}{\partial t} + (\mathbf{u} \cdot \nabla)C = 0 \quad (4)$$

Most cases are computed in 2- D Cartesian geometry with aspect ratio of 1 with exception for a few models with aspect ratio of 6 cases, which were found to have little difference compared with square geometry. To solve the conservation equations, we use a modified version of the convection code, Citcom²¹, that includes thermochemical convection and composition-dependent rheology. We exclude internal heating for all models in this study, which is more appropriate for our 2D Cartesian models³². The initial temperature is 0.5 everywhere with small perturbations. The top and the bottom surface are isothermal with $T=0$ and $T=1$, respectively. All boundaries are free-slip. The side boundaries are reflective and insulating.

A ratio tracer method³³ with eight million tracers was used for the advection of the compositional field. On average, each element has 20 randomly distributed tracers which are advected with mantle flow. Initially, a global layer of pile material was introduced to the lowermost mantle, which was later pushed by cold downwellings into a thermochemical pile to the side boundaries of the model domain.

Pile materials are consistently entrained up and mixed into the background mantle, affecting the density of the background mantle. We therefore change pile materials into background mantle materials once they are entrained to the upper mantle. Some background mantle materials are mixed into the thermochemical piles as well, but they do not significantly affect the intrinsic density of the piles. For example, the intrinsic density of the thermochemical pile in the reference case changes by less than 0.3% after ~4.6 Gyr.

The parameters for all cases used in this study are listed in Supplementary Data 1.

Methods References

32. Farrell, K. A. O. & Lowman, J. P. Emulating the thermal structure of spherical shell convection in plane-layer geometry mantle convection models. *Phys. Earth Planet. Inter.* **182**, 73–84 (2010).
33. Tackley, P. J. & King, S. D. Testing the tracer ratio method for modeling active compositional fields in mantle convection simulations. *Geochemistry, Geophys. Geosystems* **4**, 1–15 (2003).

Data Availability

All data and parameters are available in the main text or the supplementary materials.

Code availability

Request about the modified 2D Citcom code using in this paper is available from the corresponding author upon request.

Acknowledgement

We are grateful to the extensive discussions with Ed Garnero. We also thank Kasra Hosseini for SubMachine datasets processing and Yongming Wang and Shule Yu for valuable comments. The numerical models are performed on the Agave cluster at Arizona State University. Funding: This work is supported by National Science Foundation grant of EAR-1849949 and EAR-1855624.

Author Contributions

Author contributions: M.M.L conceived the project and Q.Y performed all experiments. Both analyzed the data and wrote the manuscript.

Competing Interests

The authors declare no competing interests.

Additional Information

Additional data related to this paper should be sent to Q.Y.

Extended Data Figure Legends

Extended Data Figure 1 | Cross-section locations through two LLSVPs used for depth profiles of the averaged V_s anomaly. A1-A10 and B1-B5 are for African LLSVP while C1-C3 and D1-D13 performed for Pacific LLSVP. A4, B4 and C1, D6 are the four cross-sections that were found bear the maximum height for African and Pacific LLSVP, respectively. They are respectively named as Aa, Bb and Cc, Dd in the main text. All section data were downloaded from the SubMachine website³⁴. The 17 global S-wave models are GyPSuM-S³⁵, HMSL-S06³⁶, PRI-S05³⁷, SP12RTS-S³⁸, SPani-S³⁹, S20RTS⁴⁰, S362ANI+M⁴¹, S40RTS³¹, SAVANI⁴², SAW642ANb⁴³, SEMUCB-WM1⁴⁴, SEMum⁴⁵, SGLOBE-rani⁴⁶, TX2011², TX2015⁴⁷, SEISGLOB1⁴⁸, SEISGLOB2⁴⁹.

Extended Data Figure 2 | Depth profiles of the averaged V_s anomaly at 15 vertical cross-section locations through the African LLSVP. **a**, the horizontally averaged V_s anomaly as a function of depth for the 10 vertical cross-sections as shown in Extended Data Fig. 1. **b**, similar to panel **a**, but only the negative values of V_s are used when calculating the horizontal average. **c**, the horizontally averaged V_s anomaly as a function of depth for the 5 vertical cross-sections as shown in Extended Data Fig. 1. **d**, similar to panel **c**, but only the negative values of V_s are used when calculating the horizontal average. The gray rectangles mark the turning point we defined as the maximum height in main text.

Extended Data Figure 3 | Depth profiles of the averaged V_s anomaly at 16 vertical cross-section locations through the Pacific LLSVP. a, the horizontally averaged V_s anomaly as a function of depth for the 3 vertical cross-sections as shown in Extended Data Fig. 1. **b**, similar to panel **a**, but only the negative values of V_s are used when calculating the horizontal average. **c**, the horizontally averaged V_s anomaly as a function of depth for the 13 vertical cross-sections as shown in Extended Data Fig. 1. **d**, similar to panel **c**, but only the negative values of V_s are used when calculating the horizontal average. The gray rectangles mark the turning point we defined as the maximum height in main text.

Extended Data Figure 4 | Pile height as a function of pile buoyancy number and background mantle viscosity for 450 individual models.

Extended Data Figure 5 | The effect of different geometry on pile height. a and b show the composition and temperature fields respectively for a model of same parameters with the reference case but with aspect ratio of 6. c, Blue solid circles show the height of pile from models with aspect ratio of 1, and orange solid circles show the height of pile from models with aspect ratio of 6.

Extended Data Figure 6 | Effects of temperature-dependent viscosity on pile height. (a-c) are the composition, temperature, and viscosity fields, respectively, for case 67 without temperature dependent viscosity. The viscosity of pile for case 67 is 2×10^{21} Pa s and other parameters are same to the reference case. (d-f) show composition, temperature, and viscosity fields, respectively, for case 998 in which the viscosity is temperature-dependent in the lower mantle with a non-dimensional activation coefficient of $A = 7.0$ that leads to slightly more than 10^3 x of viscosity change as the temperature varies from 0 to 1. (g-i) are also the composition, temperature, and viscosity fields for case 999 with $A=9.21$ corresponding to 10^4 x of viscosity change due to temperature in lower mantle. The dashed lines in **f**, **i** mark the boundary between pile materials and background mantle.

Extended Data Figure 7 | Pile height for cases in which the intrinsic density anomaly of pile material decreases with depth. The left (a, d) and middle column (b, e) show the snapshots of temperature and compositional fields, respectively, for 2 cases in which the intrinsic density anomaly of pile materials decreases linearly with depth from 1.38 to 0.23 for the top case (c), and from 0.84 to 0.28 for the bottom case (f), as shown in the right column. A non-dimensional activation coefficient of $A = 4.61$ is used, like that in (Tan and Gurnis, 2005) (7). The thermochemical pile of the bottom case can temporally reach similar height to African LLSVP, but it is also very unstable.

556

557 **Extended Data Table 1** | Physical and model parameters.

Parameter	Symbol	Value
Input Rayleigh number	Ra	1×10^6
Mantle thickness	R	6371 km
Core-mantle boundary radius	r	3503 km
Mantle thickness	h	2868 km
Thermal expansivity	α_0	$1 \times 10^{-5}/\text{K}$
Thermal diffusivity	κ_0	$1 \times 10^{-6} \text{ m}^2/\text{s}$
Gravitational acceleration	g_0	9.8 m/s^2
Temperature difference between surface and core-mantle boundary	ΔT	2500 K
Background mantle reference density	ρ_0	4000 kg/m^3
Reference viscosity	η_0	$2 \times 10^{22} \text{ Pa s}$

558

559 **Supplementary Information**

560 Supplementary Data 1. Physical parameters and results for all cases in this study.

Figures

Figure 1

Depth profiles of the averaged Vs anomaly at 4 vertical cross-section locations through the LLSVPs. a. the yellow colors highlight 30% of the CMB area at 2800 km depth with the lowest Vs from the seismic tomography model S40RTS31. The thick, solid curves mark the locations of vertical cross-section for

which the horizontally averaged Vs anomalies of 17 tomography models as a function of depth, or the depth- Vs profile, are shown in panels b-c. b. the horizontally averaged Vs anomalies of 17 models as a function of depth for the 4 vertical cross-sections as shown in panel a. c. similar to panel b, but only the negative values of Vs are used when calculating the horizontal average. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 2

The effects of volume of pile materials, buoyancy number and mantle viscosity on the height of piles. The first row (a-c) and second row (d-f), respectively, show the snapshots of temperature and compositional fields (red shows pile materials, black shows background mantle materials, and green shows a mixture between the two) for 3 cases with the volume of pile materials occupying 4% (a, d), 7% (b, e) and 12% (c, f) of the model domain. The white dotted lines in (d-f) show the initial height of the pile

materials before the calculation starts, and the h shows the height of the pile. g-i, snapshots of the compositional fields for 3 cases in which the buoyancy numbers of pile materials are 0.5 (g), 0.7 (h) and 1.1 (i). j-l, snapshots of viscosity fields for 3 cases in which the background mantle viscosity is 1×10^{23} Pa s (j), 2×10^{23} Pa s (k), and 4×10^{23} Pa s (l).

Figure 3

The effects of model parameters on the height of piles. Model parameters tested here include the volume percentage of pile materials with respect to the model domain (a), the buoyancy number of pile materials (b), the viscosity of the background mantle materials (c), and the viscosity of the pile materials (d). The blue dots show the average height after the model reaches statistically steady state, with the error bars showing the standard deviation. One model parameter is modified for each case, with the other parameters the same as the reference case which uses a buoyancy number of 0.8 and pile viscosity of 2×10^{20} Pa s. The controls of pile buoyancy number and viscosity of the background mantle on the pile height are best fitted by the orange dashed curves in panels b and c, respectively, with the dimensional fitting equations included in each panel.

Figure 4

The height of piles as a function of pile buoyancy number and background mantle viscosity. The height of piles for different combinations of buoyancy number of pile materials and the viscosity of the background mantle. White stars show cases in which the height of piles is 500 – 700 km, and green triangle shows cases in which the pile height is 1,500 – 1,800 km. The gray triangles show cases in which the thermochemical piles are not stable.

Figure 5

Cross-section locations through two LLSVPs used for depth profiles of the averaged V_s anomaly. A1-A10 and B1-B5 are for African LLSVP while C1-C3 and D1-D13 performed for Pacific LLSVP. A4, B4 and C1, D6 are the four cross-sections that were found bear the maximum height for African and Pacific LLSVP, respectively. They are respectively named as Aa, Bb and Cc, Dd in the main text. All section data were downloaded from the SubMachine website³⁴. The 17 global S-wave models are GyPSuM-S35, HMSL-S0636, PRI-S0537, SP12RTS-S38, SPani-S39, S20RTS40, S362ANI+M41, S40RTS31, SAVANI42, SAW642ANb43, SEMUCB-WM144, SEMum45, SGLOBE-rani46, TX20112, TX201547, SEISGLOB148, SEISGLOB249. Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

Figure 6

Depth profiles of the averaged Vs anomaly at 15 vertical cross-section locations through the African LLSVP. a, the horizontally averaged Vs anomaly as a function of depth for the 10 vertical cross-sections as shown in Extended Data Fig. 1. b, similar to panel a, but only the negative values of Vs are used when calculating the horizontal average. c, the horizontally averaged Vs anomaly as a function of depth for the 5 vertical cross-sections as shown in Extended Data Fig. 1. d, similar to panel c, but only the negative values of Vs are used when calculating the horizontal average. The gray rectangles mark the turning point we defined as the maximum height in main text.

Figure 7

Depth profiles of the averaged Vs anomaly at 16 vertical cross-section locations through the Pacific LLSVP. a, the horizontally averaged Vs anomaly as a function of depth for the 3 vertical cross-sections as shown in Extended Data Fig. 1. b, similar to panel a, but only the negative values of Vs are used when calculating the horizontal average. c, the horizontally averaged Vs anomaly as a function of depth for the 13 vertical cross-sections as shown in Extended Data Fig. 1. d, similar to panel c, but only the negative values of Vs are used when calculating the horizontal average. The gray rectangles mark the turning point we defined as the maximum height in main text.

Figure 8

Pile height as a function of pile buoyancy number and background mantle viscosity for 450 individual models.

Figure 9

The effect of different geometry on pile height. a and b show the composition and temperature fields respectively for a model of same parameters with the reference case but with aspect ratio of 6. c, Blue solid circles show the height of pile from models with aspect ratio of 1, and orange solid circles show the height of pile from models with aspect ratio of 6.

Figure 10

Effects of temperature-dependent viscosity on pile height. (a-c) are the composition, temperature, and viscosity fields, respectively, for case 67 without temperature dependent viscosity. The viscosity of pile for case 67 is 2×10^{21} Pa s and other parameters are same to the reference case. (d-f) show composition, temperature, and viscosity fields, respectively, for case 998 in which the viscosity is temperature-dependent in the lower mantle with a non-dimensional activation coefficient of $A = 7.0$ that leads to slightly more than 103x of viscosity change as the temperature varies from 0 to 1. (g-i) are also the composition, temperature, and viscosity fields for case 999 with $A=9.21$ corresponding to 104x of viscosity change due to temperature in lower mantle. The dashed lines in f, i mark the boundary between pile materials and background mantle.

Figure 11

Pile height for cases in which the intrinsic density anomaly of pile material decreases with depth. The left (a, d) and middle column (b, e) show the snapshots of temperature and compositional fields, respectively, for 2 cases in which the intrinsic density anomaly of pile materials decreases linearly with depth from 1.38 to 0.23 for the top case (c), and from 0.84 to 0.28 for the bottom case (f), as shown in the right column. A non-dimensional activation coefficient of $A = 4.61$ is used, like that in (Tan and Gurnis, 2005) (7). The thermochemical pile of the bottom case can temporally reach similar height to African LLSVP, but it is also very unstable.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [SupplementaryData1.xlsx](#)