A synoptic view of mantle plume shapes enabled by virtual reality

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Abstract

The shapes of mantle plumes are sensitive to mantle viscosity, density structure, and flow patterns. Increasingly, global tomographic models reveal broad plume conduits in the lower mantle and highly-tilting conduits in the mid and upper mantle. Previous studies mostly relied on 2D slices to analyze plume shapes, but fully investigating the complexity of 3D plume structures requires more effective visualization methods. Here, we use immersive virtual reality (VR) headsets to visualize the full-waveform global tomographic models SEMUCB-WM1 and GLAD-M25 (V_S). We develop criteria for the identification of plume conduits based on the relationship between the plume excess temperature and the V_S anomaly ([?]V_S). We are able to trace 20 major plume conduits, measure the offsets of the conduits in azimuth and distance with respect to the hotspots, calculate the tilt angle, and evaluate the [?]V_S along all traced conduits. The wavespeed variations along conduits traced from each tomographic model are slower than modeled or vertical conduits, regardless of which tomographic model they are evaluated in. The shapes of traced conduits tend to differ greatly from modeled conduits. Plume ponding and the emergence of secondary plumes, which could result from a combination of different plume compositions, phase transitions, small-scale convection, and variations in viscosity and density of the ambient mantle, can contribute to the complex observed plume shapes.

A synoptic view of mantle plume shapes enabled by virtual reality

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5 Key Points:

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6	•	The variation of shear velocity anomaly along the traced conduits and complex
7		plume shapes suggest a thermochemical origin of many plumes.
8	•	We identify complex plume shapes (ponding, branching, and merging) that sug-
9		gest complex rheological structure of the lower mantle.
10	•	We provide systematic and quantitative observations of plume shapes that can ben-
11		efit numerical modeling and geochemical studies of plumes.

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12 Abstract

The shapes of mantle plumes are sensitive to mantle viscosity, density structure, and flow 13 patterns. Increasingly, global tomographic models reveal broad plume conduits in the 14 lower mantle and highly-tilting conduits in the mid and upper mantle. Previous stud-15 ies mostly relied on 2D slices to analyze plume shapes, but fully investigating the com-16 plexity of 3D plume structures requires more effective visualization methods. Here, we 17 use immersive headset-based virtual reality (VR) to visualize the full-waveform global 18 tomographic models SEMUCB-WM1 and GLAD-M25. We develop criteria for the iden-19 tification of plume conduits based on the relationship between the plume excess temper-20 ature and the V_S anomaly (δV_S). We trace 20 major plume conduits, measure the off-21 sets of the conduits in azimuth and distance with respect to the hotspots, calculate the 22 tilt angle, and evaluate the δV_S along all traced conduits. We compare our traced con-23 duits with the conduits predicted by global mantle convection models and vertical con-24 duits. The wavespeed variations along conduits traced from each tomographic model are 25 slower than modeled or vertical conduits, regardless of which tomographic model they 26 are evaluated in. The shapes of traced conduits tend to differ greatly from modeled con-27 duits. Plume ponding and the emergence of secondary plumes, which could result from 28 a combination of compositional variations, phase transitions, small-scale convection, and 29 variations in viscosity, can contribute to the complex observed plume shapes. The vari-30 ation of δV_S along the traced conduits and complex plume shapes suggest a thermochem-31 ical origin of many plumes. 32

1 Introduction

Deep mantle plumes originating from the Core Mantle Boundary (CMB) are thought 34 to have a broad head, which generates Large Igneous Provinces (LIPs), and a narrower 35 tail, which forms long-lived hotspots (e.g. Richards et al., 1989). The geochemical di-36 versity of hotspot lavas, which are also known as Ocean Island Basalts (OIBs), reflects 37 the entrainment and transport of different mantle materials by ascending plumes. Hence, 38 understanding the shapes of mantle plumes is important for linking the rock record with 39 deep mantle structures, including the Large Low Shear Velocity Provinces (LLSVPs) and 40 Ultra Low Velocity Zones (ULVZs). Plume shape is influenced by the global pattern of 41 mantle circulation as well as the intrinsic buoyancy and viscosity variations within as-42 cending plumes and the ambient mantle. Seismic tomography is the only geophysical method 43 that currently resolves plume-scale features at all mantle depths. Tomographic models 44 shape our understanding of mantle plumes and naturally become a constraint on numer-45 ical models that aim to understand their structure and evolution. These comparisons 46 bridge our theoretical models to tomographic images of mantle plumes and help advance 47 our understanding of the physical and chemical properties of mantle plumes. Here we 48 analyze the shapes of mantle plumes using immersive 3D visualization based on two re-49 cent global tomographic models and consider the implications of plume shape for the pat-50 tern of global mantle circulation and the variation of mantle viscosity. 51

Mantle plumes that rise to the surface have previously been described conceptu-52 ally as primary and secondary plumes (Courtillot et al., 2003) on the basis of their buoy-53 ancy fluxes, upper mantle seismic signature, and the isotopic variations in OIBs. Pri-54 mary plumes rise directly from the CMB, whereas secondary plumes rise from the su-55 perswells or broad primary plumes that pond below the upper mantle. State-of-art global 56 tomographic models show patterns of slow shear velocity (Vs) resembling both types of 57 plumes, although the plume shapes revealed by tomographic models have more complex-58 ities than what is proposed by the schematic plume model of Courtillot et al. (2003). 59

There has been considerable debate about whether hotspots are preferentially lo cated at the edges of the Pacific and African LLSVPs (Torsvik et al., 2006; Steinberger
 & Torsvik, 2012) or whether they are associated with the LLSVP edges and interiors (Austermann

et al., 2014; Davies et al., 2015; Doubrovine et al., 2016). These two hypotheses have dif-

⁶⁴ ferent geodynamics implications: whether plumes rise from the edge of the pile-like LLSVPs

(Tan et al., 2011; Hassan et al., 2015), or the LLSVPs are cluster of plumes (Davaille &

66 Romanowicz, 2020).

Two complementary approaches have been taken to understand the evolution of 67 mantle plumes. First, some numerical models of thermal and thermochemical plume as-68 cent focus on idealized plumes and incorporate a high degree of physical realism at the 69 expense of describing the geologic context of specific plumes within Earth's mantle (Dannberg 70 71 & Sobolev, 2015; H. Liu & Leng, 2020). A second class of numerical models focuses on the influence of the global mantle flow associated with Earth's tectonic history on plume 72 conduits at the expense of a complete treatment of mantle rheology, phase transitions, 73 and plume buoyancy (e.g., Steinberger & O'Connell, 1998). For the first class of stud-74 ies, the comparison between the shape of the observed and the modeled plume conduits 75 is only qualitative because idealized models do not attempt to reproduce the detailed 76 dynamics of specific plumes. The second class of models does make testable predictions 77 of plume shape that can be qualitatively and quantitatively compared with plumes re-78 solved in tomographic models but only in terms of the wavespeed variations (Boschi et 79 al., 2007). 80

Plume shapes depend on both the inherent properties of a plume and the surround-81 ing mantle conditions, so they provide information about the composition and dynam-82 ics of plume and mantle. For example, the amount and direction of shear of plume con-83 duits reflect the large-scale mantle flow pattern. Changes in the conduit radius could in-84 dicate the viscosity variations across the mantle. The stagnation of plumes helps to re-85 veal the influence of the pressure-induced phase transitions on mantle convection. It is 86 crucial to measure the shapes of plume conduits quantitatively to make more appropri-87 ate and meaningful connections between numerical models and tomographic observations. 88

Measuring plume shapes from tomographic models requires effective visualization 89 of what are three-dimensional (3D) datasets, but most approaches to their visualization 90 have involved two-dimensional (2D) slicing or the rendering of isosurfaces (surfaces de-91 fined by a constant value) on a 2D medium such as a computer screen or a paper (French 92 & Romanowicz, 2015; Tsekhmistrenko et al., 2021; Celli et al., 2021). The understand-93 ing and insight gained from 2D visualizations of 3D data may be different than that gained 94 through immersive 3D visualization. For example, the 2D cross-section of a plume clus-95 ter associated with the Pacific LLSVP seems to imply that the conduits of plume Samoa, 96 and Tahiti are not resolved above 660 km depth (Figure 1a). However, the conduits of 97 these plumes extend out of the vertical cross-section plane, as shown in Figure 1b. Se-98 lecting an isosurface with a specific negative δV_S to represent the boundary of a plume 99 reveals plume shapes better than 2D cross sections and allows us to "see through" the 100 non-negative δV_S that obscures our view. However, these approaches may fail if the shape 101 of a plume is best represented by different isosurface values at different depths or when 102 many plumes are clustered. In the first case, visualizing plumes requires observing the 103 structures of many different δV_S isosurfaces simultaneously. In the second case, the iso-104 surfaces representing boundaries of conduits usually obscure each other, making it tricky 105 to identify an individual conduit if the observer is outside the cluster. This is the sce-106 nario for the plumes feeding Pitcairn, Macdonald, Marquesas, Tahiti, Samoa, and Easter, 107 which are located close together within the Pacific LLSVP (Figure 2). 108

Visualizing seismic tomographic models in a virtual reality (VR) environment can help to overcome these barriers. Immersive visualization allows an observer to explore mantle structures from within and view them quickly from arbitrary vantage points. Immersive 3D visualization is not new in geoscience research but has not seen widespread adoption due to the lack of commodity VR hardware and related software. Previously, the usage of VR environments centered on large, immobile, and expensive "cave" environments (e.g., Billen et al., 2008). As VR headset devices have become more prevalent, immersive 3D visualization is becoming more accessible due to its lower cost andgreater portability, presenting the potential to enable new discoveries.

The remainder of the paper is structured as follows. We establish a quantitative 118 procedure to define mantle plume conduits and discuss the advantages and limitations 119 of our conduit-choosing criteria. We present our traced conduits for well-resolved plumes 120 in SEMUCB-WM1 (French & Romanowicz, 2014) and GLAD-M25 (V_S) (Lei et al., 2020) 121 and the quantitative measurement of these conduits. We demonstrate that our traced 122 conduits are more consistent with the distributions of slow seismic velocities than geo-123 124 dynamic model predictions. We discuss the implications and potential applications of this study. 125

126 2 Methods

The two tomographic models analyzed in this study, SEMUCB-WM1 and GLAD-127 M25, are state-of-art global tomographic models based on full waveform inversion (FWI). 128 SEMUCB-WM1 inverts for 3-D variations in Voigt-average isotropic V_S and radial anisotropy 129 parameter ξ and parameterizes them radially using (continuous) cubic b-splines and lat-130 erally using spherical splines. Its starting model is SEMum2 (French et al., 2013) above 131 800 km and SAW24B16 (Mégnin & Romanowicz, 2000) below. The crust is approximated 132 by a smooth anisotropic layer to account for the crustal effects on wave propagation and 133 dispersion. GLAD-M25 inverts for the bulk sound speed and vertically and horizontally 134 polarized V_S in the mantle above 660 km. Its starting model is S362ANI (Kustowski et 135 al., 2008) for the mantle and Crust2.0 (Bassin et al., 2000) for the crust. As in the start-136 ing model S362ANI, GLAD-M25 uses a parameterization that includes first- and second-137 order discontinuities in the radial direction, permitting abrupt changes in the pattern 138 of heterogeneity across the mantle transition zone (MTZ). Both of the global tomographic 139 models resolve broad plumes rising from the CMB to the upper mantle beneath many 140 hotspots (French & Romanowicz, 2015; Lei et al., 2020). These enforced vertical discon-141 tinuities in GLAD-M25 could introduce artifacts to the resolved plume shapes around 142 the MTZ, but plume structures resolved in the lower mantle should remain robust, dis-143 cussed later. 144

¹⁴⁵ We define plume conduits based on three considerations. *First*, we require plume ¹⁴⁶ conduits to be continuous pathways from the lithosphere to the CMB. *Second*, we require ¹⁴⁷ that plume conduits be slower than average across all mantle depths (i.e., having a neg-¹⁴⁸ ative δV_S). *Third*, we seek plume conduits for which the temperature anomaly implied ¹⁴⁹ by wave speed variations is consistent with petrological constraints on plume excess tem-¹⁵⁰ perature. The third criterion may not always be satisfiable due to limitations in tomo-¹⁵¹ graphic modeling, discussed later.

Following our criteria, we manually traced the conduits of 20 plumes (listed in Ta-152 ble S1), of which the buoyancy flux is larger than 1000 kg/s (Jackson et al., 2021) and 153 are well-resolved in both SEMUCB-WM1 and GLAD-M25. We exclude the Yellowstone 154 plume as it is only well-resolved in GLAD-M25. We include the Canary and St. Helena 155 plumes, of which the buoyancy flux is only 800 and 500 kg/s, respectively, because sim-156 ilar plume shapes are clearly resolved in both tomographic models. Moreover, the OIBs 157 associated with both hotspots display isotopic signatures supporting a deep mantle ori-158 gin. 159

The plume conduits are traced in a headset-based immersive 3D visualization environment. We use the Valve Index VR headset and controllers and the Paraview 5.10.0 (Ahrens et al., 2005) visualization software. The identification of plume conduits was carried out using the following steps:

164	1. The traced conduit (TC) of each plume can be divided into an upper-mantle, a
165	mid-mantle, and a lower-mantle part. We first identify candidate conduits (CCs)
166	- conduit-like vertical negative δV_S structures - that extend vertically across the
167	mid mantle near each surface hotspot. There may be multiple candidate conduits
168	for each hotspot, and we seek conduits that are closer to the hotspot's surface ex-
169	pression.
170	2. We use pipelines (control points connected by line segments) to represent the path-
171	way of the traced conduit, where the control points are assigned every 200 km from
172	250 to 2450 km depth. We seek an upper-mantle TC, which connects the surface
173	hotspot with the upper-end of the mid-mantle TC, and a lower-mantle TC, which
174	starts from the lower-end of the mid-mantle TC. Where there is ambiguity, we pre-
175	fer more vertical plume conduits.
176	3. After tracing the plume conduits, we validate our TCs according to two criteria.
177	First, the δV_S along a TC should not be positive. Second, we use the plume and
178	ambient mantle potential temperature calculated from olivine-liquid equilibria (Putirka,
179	2008) to estimate the excess temperature of plumes. We then calculate the pro-
180	file of $d(\ln V_S)/dT$ (Figure S1) assuming that the plume has a pyrolitic compo-
181	sition and use the profile of $d(\ln V_S)/dT$ to calculate δV_S corresponding to the petrologically
182	estimated excess temperature at all depths for each plume that has an estimation.
183	δV_S along the TC should be comparable to δV_S converted from the petrologically-
184	estimated excess temperature at some depths above 1250 km. The second crite-
185	rion is not hardwired because the variable resolution, parameterization, and reg-
186	ularization of global tomographic models can all contribute to modeled V_S vari-
187	ations.

188 **3 Results**

We describe the general properties of the traced plume conduits (Figure 2), starting from describing the slowness of the traced conduits. We then describe overall trends in the amount of offset from the surface location, the tilt (measured in degrees away from the vertical) of plume conduits, and the depths at which large offsets or tilts occur. We describe the shapes of individual plume conduits in greater detail later.

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3.1 Slowness along plume conduits

The δV_S along conduits traced from SEMUCB-WM1 and GLAD-M25 is generally 195 between 0% and -2%, comparable with each other (Figure 3-4). We find that plumes orig-196 inating from the African LLSVP are faster than plumes stemming from the Pacific LLSVP 197 above ~ 1250 km depth in SEMUCB-WM1 and at all depths in GLAD-M25 (Figure 5b, 198 c, g, h). We also evaluate the average δV_S of conduits traced from SEMUCB-WM1 in 199 GLAD-M25 as well as conduits traced from GLAD-M25 in SEMUCB-WM1 (Figure 5d, 200 e, i, j). When plumes traced in one tomographic model are evaluated in the other to-201 mographic model, the average δV_S along TCs around the Pacific LLSVP remains neg-202 ative at all depths, while it is negative only in the lower mantle for TCs around the African 203 LLSVP. 204

3.2

3.2 Observed morphology

Tilt angles along the traced conduits generally remain smaller in the lower mantle (usually $< 60^{\circ}$) than in the upper mantle with a few exceptions (Figure 6). For example, the Louisville and Azores plumes have a tilt angle $(60 - 70^{\circ})$ below 2000 km in SEMUCB-WM1. A comparison of the tilt angles of plumes (Figure 6) and the offsets of plume conduits (azimuth and distance, shown in Figure 7) shows that large tilt angles are associated with abrupt changes in offset distances and/or azimuths of TCs. Changes in offset azimuths and distances are small where the tilt is closer to vertical. The azimuth

of a conduit is measured by assuming its hotspot as the origin, 0 degree at the north, 213 and counting clock-wise. Due to the manual process of conduit tracing, the uncertainty 214 in tilt of TCs is at least 5°. Hence TCs with tilt less than this should be interpreted as 215 nearly vertical. We do not report the average tilt angle of each conduit because these 216 values do not accurately describe the shape of conduits. For example, in SEMUCB-WM1, 217 the TC of Samoa has a similar average tilt angle (16.9°) to the TC of Pitcairn (16.1°) . 218 However, the TC of Samoa appears to be ponded and deflected at 660 and 410 km depth, 219 while the TC of Pitcairn tilts gently across the whole mantle. 220

Plume conduits traced in SEMUCB-WM1 and GLAD-M25 usually root at locations offset from their surface hotspots by $5 - 10^{\circ}$ and most of the offset occurs in the upper mantle. A few plume conduits show larger offsets. The TCs of Galapagos, San Felix, and Tahiti root at locations offset from their surface hotspots by more than 10° in both tomographic models (Figure 2 and 7). The offsets of conduits traced from SEMUCB-WM1 in the upper mantle can easily exceed 5 degrees (Figure 7), which converts to > 500 km offsets, while those of conduits traced from GLAD-M25 appear to be much smaller.

3.2.1 Paired plumes

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In SEMUCB-WM1, the MacDonald and Pitcairn plumes seem to branch from the same conduit in the lower mantle and the Macdonald plume is significantly deflected at ~ 1250 km depth (Figure 8a). The Canary and Cape Verde plumes also appear to share the same conduit from the CMB to at least ~ 1250 km depth and branch into two conduits separated by $\sim 15^{\circ}$ in the upper mantle (Figure 8b).

In GLAD-M25, we identify CC with a similar shape as what is observed in SEMUCB-234 WM1 below the Canary and Cape Verde hotspots. We interpret Canary and Cape Verde 235 as two adjacent plumes rising parallel to each other though this CC could be interpreted 236 as either two separate conduits or one broad plume branching into two secondary plumes 237 as it crosses the 660 km discontinuity. CCs of the Pitcairn and Macdonald plumes look 238 less like those in SEMUCB-WM1. These two plumes seem to emerge from different lo-239 cations at the CMB and merge into a broad plume conduit between 660 and 2000 km 240 depth and branch again above 660 km depth. 241

The San Felix and Juan Fernandez plumes are another potential paired plumes. These two plumes generally share the same CC in the mid-mantle in both tomographic models (Figure S2). We interpret it as two adjacent plumes rising parallel to each other and trace their conduits based on this interpretation. The conduit of San Felix is not resolved between 1250 and 660 km in SEMUCB-WM1 and above 660 km in GLAD-M25. The conduit of Juan Fernandez is generally well resolved at all depths in both tomographic models.

3.2.2 Iceland

The Iceland plume is generally vertical in both tomographic models, but the de-250 tailed shape of the plume is different. Starting from the surface hotspot, the traced con-251 duit from SEMUCB-WM1 is offset towards the northeast above ~ 350 km and then off-252 set back towards the hotspot at ~ 660 km. The conduit remains generally vertical be-253 low 660 km and slightly tilts towards the east below ~ 2000 km (Figure 6.7, and 8c). 254 Its TC from GLAD-M25 is vertical above 660 km, tilts first towards the east between 255 660 and 1000 km depth then towards the west between ~ 1250 and 1500 km depth, and 256 remains vertical below 1500 km. 257

258 3.2.3 Hawaii

The Hawaii plume appears to be mostly vertical in SEMUCB-WM1, while it appears to largely tilt towards the southeast in GLAD-M25. Its conduit is well resolved in SEMUCB-WM1 but not well resolved between 410 and 660 km depth in GLAD-M25 (Figure 8d). Although the TCs from SEMUCB-WM1 and GLAD-M25 are not consistent, both tomographic models resolve a similar CC between 660 and 1250 km depth below the surface hotspot location and a similar CC location at the CMB (Figure 8d).

3.2.4 Samoa, St Helena, Reunion, and Caroline

Similar CCs are identified in both tomographic models for the Samoa, St Helena, Reunion, and Caroline plumes. These plumes remain nearly vertical or slightly tilt in the lower mantle and tilt more heavily in the upper mantle (Figure 9a-c). We noticed that amplitudes of negative δV_S along these TCs from SEMUCB-WM1 vary smoothly and reach a maximum near 660 km. Amplitudes of the negative δV_S along these TCs from GLAD-M25, however, decrease abruptly above the 660 km discontinuity. These negative δV_S amplitudes are larger (slower) than those of conduits traced from SEMUCB-WM1 by 0.5-1.0 % δV_S below ~ 2000 km (Figure 3 and 4).

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3.2.5 Azores, Easter, Galapagos, Kerguelen, Marquesas, and Tahiti

²⁷⁵ We notice that for the Azores, Easter, Galapagos, Kerguelen, Marquesas, and Tahiti ²⁷⁶ plumes, similar CCs are resolved in the two tomographic models but different TCs are ²⁷⁷ identified (Figure 9d and S3-5). One of the main causes is the poor inter-model agree-²⁷⁸ ment above 660 km and below 2000 km. The other main cause is that the δV_S of CCs ²⁷⁹ with similar shapes can amplify at different depths in different tomographic models. It ²⁸⁰ can result in very different interpretations of the most-reasonable conduit path.

$_{281}$ 4 Discussion

We first demonstrate the reliability of our traced conduits to justify that our TCs represent seismically slow paths through the mantle. We then compare our TCs with modeled conduits and discuss the reasons for their differences. Next, we discuss the implications for mantle and plume dynamics from our observed plume shapes and slowness along conduits. We conclude our discussion by proposing some applications of our TCs in future studies of plume dynamics.

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4.1 Reliability of traced conduits

Seismic tomography is a mixed-determined inverse problem, and there exist many 289 possible Earth structures that are equally compatible with seismic observables. The shapes 290 of plumes could vary between different regional and global tomographic models due to 291 different parameterization/regularization choices and different earthquake events used 292 to constrain the tomographic models (French & Romanowicz, 2015; Wamba et al., 2021, 293 2023). Hence, one might question the veracity of mantle plume shapes determined on 294 the basis of seismic tomography. Several lines of evidence suggest that the imaged and 295 traced plume conduits are likely representative of real mantle structures. First, the slow 296 V_S structures near many hotspots are similar between the two models, suggesting that 297 the imaged features are robust. Second, the average slowness along TCs is much greater 298 than the average slowness along modeled or vertical conduits (Figure 5a-c, f-h). To fur-200 ther assess the robustness of the traced plume conduits, we evaluate the slowness along 300 Pacific TCs obtained from SEMUCB-WM1 and GLAD-M25 in other P- and S- veloc-301 ity tomographic models. We find that our Pacific TCs traced from GLAD-M25 are slower 302 than the MCs and vertical conduits (VCs) in the lower mantle (below $\sim 660-1000$ km 303

depth) when they are evaluated in most of the other models (Figure 5i and S2 g-k). Our Pacific TCs traced from SEMUCB-WM1 are slower than the MCs and vertical conduits (VCs) but in a more restricted depth range between ~ 1250 and 2100 km depth (Figure 5d and S2 a-d). (See Text S2 in the Supporting Information for more details.) This suggests that both sets of traced conduits, especially TCs from GLAD-M25, are more compatible with many other tomographic models than the modeled and vertical conduits in the mid to lower mantle.

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4.2 Comparison between traced and modeled conduits

Simplified numerical models of mantle plume shapes have been used widely in geo-312 dynamics to understand the mobility of deep mantle hotspots and to establish the mov-313 ing hotspot reference frames necessary for absolute plate reconstructions (e.g., Matthews 314 et al., 2016). We compare modeled conduits (MCs) from (Steinberger & Antretter, 2006) 315 with our traced conduits. These numerical models of plume dynamics start with a man-316 the buoyancy structure based on a tomographic model filtered to long wavelength. The 317 buoyancy structure is reconstructed backwards in time through the reversal of buoyancy 318 forces and the application of time-reversed plate reconstructions at the surface while ig-319 noring the effects of thermal diffusion, which cannot be time-reversed due to non-uniqueness. 320 321 This yields a model of *long-wavelength* (much longer wavelength than the widths of plumes) mantle flow in space and time. Then, initially vertical plume conduits are advected by 322 the flow field forward in time. Previous studies demonstrated that the shapes of MCs 323 are not very sensitive to the tomographic model used to compute the mantle flow field, 324 the details of the plate reconstructions used, or the detailed mantle viscosity structure 325 (Steinberger & O'Connell, 1998; Steinberger, 2000; Steinberger & Antretter, 2006; Williams 326 et al., 2019). 327

The tilt angles and offsets of MCs show that most of MCs slightly tilt (tilt angle 328 $< 30^{\circ}$) below 660 km. This is likely because the deformation rate is slow due to the high 329 viscosity of the lower mantle. Larger tilt angles (up to $> 90^{\circ}$) of MCs observed above 330 660 km (Figure 6) are mainly due to the oscillations of the tightly spacing conduit el-331 ements in the lower-viscosity upper mantle. The offsets of modeled conduits (shown in 332 Figure 7) show that MCs in fact tilt gently at these depths. Our TCs suggest that plumes 333 generally slightly tilt in the lower mantle, but large tilt angles in the mid-mantle below 334 660 km are observed for many TCs from both tomographic models (e.g., Macdonald, Samoa, 335 St Helena, and Tristan) (Figure 6). TCs generally have more complex shapes than MCs, 336 especially in the mid-mantle. 337

Although the paths of TCs and MCs are generally not in very good agreement (Fig-338 ure 2, Table S1), there are a couple of exceptions. TCs of plumes located at the edge of 339 LLSVPs (Canary, Juan Fernandez, San Felix, St Helena, and Reunion)(Figure 7) seem 340 to agree with their MCs better than TCs of plumes located near the center of LLSVPs. 341 TCs of these plumes share similar offset directions with their MCs, while the MCs have 342 $5-10^{\circ}$ more total offset distances than the TCs. These plumes have relatively simple 343 plume shapes, that is, the offset direction of a TC does not change with depth. TCs of 344 plumes located around the center of LLSVPs are usually vertical in the lower mantle but 345 meander in the middle and upper mantle. Because of the physics included in the mod-346 els, all MCs only have simple plume shapes (without stagnation or meandering). They 347 are always smooth curves extending from the LLSVPs to the surface hotspots. We dis-348 cuss this difference more in the next section. 349

The average seismic velocities of the TCs, MCs, and VCs are slower than the ambient mantle at all depths. However, TCs from SEMUCB-WM1 are up to 6 times slower than MCs and 3.7 times slower than VCs in the upper mantle, while they are 1.2-3 times slower than MCs and VCs in the lower mantle. TCs from GLAD-M25 are 1.1-3 times slower than MCs and VCs across the mantle. The average velocities of MCs are slower

than the those along VCs only in the lower mantle (Figure 5a, f), which is consistent with 355 the analysis of MCs and VCs done using older tomographic models (Boschi et al., 2007). 356 The δV_S along MCs is often close to 0% or even positive in the upper mantle (Figure 3) 357 and 4), while the δV_S along TCs is negative in most cases. There are a few exceptions 358 in SEMUCB-WM1 (Cape Verde and San Felix) and GLAD-M25 (Azores, Canary, Hawaii, 359 San Felix, Tahiti, and Tristan). In these cases, no CC can be identified at some depths 360 in the upper mantle. This may indicate that the global tomographic model does not re-361 solve the plume conduit at these depths. It is expected that plume radius can significantly 362 decrease as a plume rising from the more viscous lower mantle to the less viscous upper 363 mantle (Leng & Gurnis, 2012). 364

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4.3 Implications of the slowness along plume conduits

The excess temperature of a purely thermal plume conduit is not expected to change 366 significantly with depth since plumes rise rapidly relative to the thermal diffusion timescale 367 and mantle heat production is negligible on the timescale of material ascent through a 368 plume conduit. For example, the exothermic phase transition (olivine to wadsleyite) at 369 410 km depth, and shear heating may be able to increase the temperature of a plume, 370 but they are secondary effects compared with the plume's inherent excess temperature. 371 This implies that if a mantle plume is purely thermal, the amplitude of its δV_S should 372 generally vary following the thermodynamically determined $d(\ln V_S)/dT$ profile with depth. 373 Our observations from both tomographic models, however, show that the variation of 374 δV_S along plume conduits almost never strictly follow the $d(\ln V_S)/dT$ profile, which sug-375 gests that non-thermal variations are present in plume conduits. 376

Non-thermal variations in mantle plumes include differences in intrinsic composi-377 tion, water content, grain size, and melt fraction. At the 410 km discontinuity, the phase 378 transition from wadsleyite to olivine may result in water release when plume materials 379 rise and cross this boundary because wadsleyite has a higher water-bearing ability than 380 olivine (W. Wang et al., 2019). Increasing water content can reduce V_S (C. Liu et al., 381 2023) and may cause partial melting in this region, further reducing V_S (Chantel et al., 382 2016). Isotopic measurements of OIBs and numerical models suggest that LLSVPs may 383 be composed of a variety of different materials, ranging from primordial materials that 384 get preserved at the CMB since the differentiation in early Earth's evolution (Labrosse 385 et al., 2007; Deschamps et al., 2012) to piles of recycled oceanic crusts (Olson & Kin-386 caid, 1991; Brandenburg & van Keken, 2007). For many of the traced conduits, we find 387 that δV_S in the lowermost mantle is slower than expected on the basis of $d(\ln V_S)/dT$. 388 The incorporation of compositionally-distinct material within the lowermost mantle is 389 one possible explanation for the slower than expected velocities (Figure 3 and 4). 390

The systematically faster plumes (in the upper- and mid-mantle) originating from 391 the African LLSVP than those originating from the Pacific LLSVP (Figure 5b, c, g, h) 392 are consistent with previous estimates of plume excess temperature based on upper man-393 tle wavespeed variations (Bao et al., 2022). Y. Wang and Wen (2007) and He and Wen 394 (2009) also show that the two LLSVPs have different shape and topology. They may in-395 dicate that the two LLSVPs have different origins, but we cannot rule out the possibil-396 ity that the faster plumes from the African LLSVP are caused by different seismic data 397 coverage between the Pacific and the Atlantic regions. 398

399

4.4 Implications of diverse plume shapes

The shape of a plume conduit depends on both the plume's properties and its interaction with its surrounding mantle. Buoyancy, which is determined by $\Delta \rho$, the difference between the effective density of a plume and the density of its surrounding mantle ($\Delta \rho = \rho_{plume} - \rho_{mantle}$), controls the behaviours of a plume as it rises. The buoyant ascent of plume material and its interaction with the large-scale mantle flow will result in different plume conduit shapes. The composition of the plume, the pressure induced phase transitions, and the excess temperature (temperature difference between the potential temperature of a plume and the ambient mantle) together determine $\Delta \rho$. When a plume has a positive buoyancy ($\Delta \rho < 0$), it will rise, and it will start sinking when it has a negative buoyancy. When $\Delta \rho$ is close to or slightly smaller than 0, a plume could be ponded or develop a variety of complex shapes (Kumagai et al., 2008; Xiang et al., 2021).

The mantle viscosity structure and flow patterns of the ambient mantle also affect plume shapes. The mobility of a plume, that is how easily it gets deformed, is expected to be smaller in a more viscous than in a less viscous region (H. Liu & Leng, 2020). Largescale mantle flows driven by thermal convection, surface plate motion, and subduction could shear plume conduits or largely deflect the secondary plume stemming from a ponding primary plume (Steinberger, 2000; Farnetani & Samuel, 2005).

The more complex shapes of our TCs than the MCs suggest that the mantle convection models used to determine MCs may not consider all major factors affecting plume shapes, especially in the mid-mantle across and below the MTZ, where plume ponding and large tilt angles are only observed in TCs.

First, the mid-mantle below the MTZ could have significant viscosity variations (Marquardt 422 & Miyagi, 2015; Rudolph et al., 2015; Shim et al., 2017), which indicates a more com-423 plex rheology than the numerical models' assumption that only a few deformations oc-424 cur and diffusion creep is predominant at these depths (Ferreira et al., 2019). Further-425 more, the transition from ringwoodite to bridgmanite at 660 km, which can lead to plume 426 ponding at this depth, is not considered neither. In return, the numerical models lack 427 the ability to produce plumes that are ponded and deflected at different depths due to 428 their simplified physics, which does not consider the composition variations, phase tran-429 sitions, nor a temperature-dependent or strain-rate-dependent viscosity. 430

Second, the mantle flow field converted from the global tomographic model (Steinberger 431 & O'Connell, 1998) may not be accurate at a smaller scale due to our current incom-432 plete understanding of mantle dynamics. MCs are determined based on the assumption 433 that a plume rose to the surface vertically within a short time and left a vertical 100-434 kilometer-radius conduit that gets passively advected by the large-scale mantle flows later. 435 However, this assumption is only valid if mantle plumes are purely thermal. Recent seis-436 mic tomographic models have imaged plume conduits with a radius of ~ 500 km (French 437 & Romanowicz, 2015) and much more complex morphology (Tsekhmistrenko et al., 2021; 438 Celli et al., 2021; Wamba et al., 2023). Such broad plumes may not only be passively 439 advected, but also influence the mantle flow field. Plumes with such large radius would 440 have buoyancy fluxes that are much higher than previous estimations (Sleep, 1990; King 441 442 & Adam, 2014). Together with the complex plume shapes, they suggest that many, if not all, mantle plumes are thermochemical rather than purely thermal. For example, a 443 plume that incorporates an eclogitic component has a lower buoyancy flux and a larger 444 radius than a purely thermal plume, which is more consistent with observations (Dannberg 445 & Sobolev, 2015). 446

At ~ 410 km depth, previous numerical models suggest that plumes with some eclogitic component will have a buoyancy barrier due to the different phase transitions that occur in pyrolitic and eclogitic materials. This buoyancy barrier can result in plume ponding and the emergence of a secondary plume (Farnetani & Samuel, 2005; Dannberg & Sobolev, 2015). It can potentially explain the ponding of Samoa, a large tilt angle, and a large change in offset distance observed in SEMUCB-WM1 at this depth (Figure 6,9a).

Large tilt angles at 660 km depth mostly reflect plume ponding, which could be caused by the combined effect of the ~ 30-fold viscosity increase from above to below 660 km suggested by many geophysical studies (Hager, 1984; Mitrovica & Forte, 1997)

as well as the endothermic phase transition from ringwoodite to bridgmanite (Faccenda 456 & Dal Zilio, 2017). The phase transition can cause plume ponding as the hotter plume 457 materials undergo this phase transition at a shallower depth, hindering ascent. Several 458 scenarios may happen after a primary plume is ponded at this depth. First, the primary 459 plume could penetrate the 660-discontinuity broadly while some plume materials are ponded. 460 These ponding materials become so hot that there is a significant viscosity reduction, 461 allowing the conduit to be laterally deflected by hundreds of kilometers (Tosi & Yuen, 462 2011). This scenario is observed for St. Helena and Tristan in both tomographic mod-463 els (Figure 6, 7, 9b and S6). 464

When the primary plume cannot penetrate the 660-discontinuity in the first place, 465 significant amount of plume materials will accumulate at this depth. The ponding ma-466 terials will spread like a pancake and secondary plumes can develop from anywhere above 467 the ponding zone. As a result, the offset distance between an upper-mantle secondary 468 plume and a lower-mantle primary plume is not large, while the offset azimuth can be 469 irrelevant to the flow patterns (Caroline in GLAD-M25, Azores, Iceland, Reunion in both 470 tomographic models) (Figure 6, 7, 8c, 9c, S3 c and d). They may resemble the "plume-471 tree" model proposed in Liu and Leng (2020), which requires a thin low-viscosity layer 472 beneath the 660 km ponding depth and a low-viscosity upper mantle to allow secondary 473 plume(s) develop from any part of the ponding materials. 474

At a greater depth ~ 1250 km, large tilt angles observed of Tahiti in both tomo-475 graphic models, Hawaii in GLAD-M25, and Kerguelen in SEMUCB-WM1 (Figure 6) could 476 arise if the viscosity is higher around this depth than in the mantle above and below it. 477 Owing to the higher viscosity, conduits tilt less around this depth, so the conduit above 478 this depth could be preferentially deflected by mantle flow. Some inversions of geophys-479 ical data suggest that there exists a viscosity hump, a one-to-two-order of magnitude vis-480 cosity increase, between 800 and 1200 km depth (King & Masters, 1992; Mitrovica & Forte, 481 1997; Rudolph et al., 2015). Studies on mineral physics also suggest that the increasing 482 strength of ferropericlase (Marquardt & Miyagi, 2015; Deng & Lee, 2017) and decreas-483 ing the iron-enrichment in bridgmanite (Shim et al., 2017) at the mid-mantle depth can 484 both result in this mid-mantle viscosity hump. 485

Another mechanism that may produce large tilt angles at $\sim 1000-1250$ km (Ca-486 nary and MacDonald in SEMUCB-WM1) is plume ponding and secondary plumes emerg-487 ing. This mechanism is proposed by Wamba et al. (2023) to explain alternating verti-488 cal conduits and horizontal ponding zone observed for the Reunion and Comores plumes 489 from ~ 1000 km depth to the top of the asthenosphere in the latest tomographic mod-490 els. There is no known endothermic phase transition, which could cause plume pond-491 ing, at these depths. However, a denser mantle below ~ 1000 km depth due to its higher 492 basalt content (Ballmer et al., 2015) could cause plume ponding at this depth if the ther-493 mal expansion effect is not strong enough to reduce the plume effective density to be smaller 494 than the mantle density above ~ 1000 km (Xiang et al., 2021). Seismic observations im-495 ply a not-global discontinuity presenting at 1000 km depth (Zhang et al., 2023), which 496 may indicate a compositional layered mantle. 497

Other than these various behaviours of a single plume conduit, plume merging may 498 further complicate the observed plume shapes. For example, we identify two CCs for Gala-499 pagos in the mid-mantle that merge into one CC with $< 1\% \delta V_S$ above 660 km in SEMUCB-500 WM1. It may represent that two adjacent conduits are ponded at 660 km and the pond-501 ing zones of them merge into one conduit or these two resolved CCs are caused by a lack 502 of resolution in SEMUCB-WM1 as they are only observed in SEMUCB-WM1. The TCs 503 504 of Macdonald and Pitcairn from GLAD-M25 suggest these two plumes merge in the midmantle and branch above 660 km. Merging of two adjacent plumes has been demonstrated 505 by both lab experiment (Moses et al., 1991) and numerical models (e.g., Lewis-Merrill 506 et al., 2022; Brunet & Yuen, 2000), and the branching of the merged conduit could be 507 explained by secondary plumes emerging from a ponding plume. 508

Given all these uncertainties in our interpretations of plume dynamics from observed 509 plume shapes, our TCs are useful for future numerical modeling. For example, idealized 510 plume models can explore under which geodynamics setting, the observed plume shapes 511 can be reproduced. Our TCs can also provide a better schematic model for future stud-512 ies to interpret the geochemical heterogeneity of OIBs from different hotspots. For ex-513 ample, previous studies have tried to interpret the heterogeneous isotopic signals of OIBs 514 from neighbouring hotspots by correlating them with the vertical projection of the hotspots 515 onto the CMB (Huang et al., 2011; Harpp & Weis, 2020) or interpreting these isotopic 516 signals under simplified schematic plume models (Williams et al., 2019; Cordier et al., 517 2021). Our TCs can provide information about potential inter-plume interactions and 518 the ascent history of plumes, which can be critical to the interpretation of geochemical 519 observations. 520

521 5 Conclusion

Broad plumes clustering around LLSVPs have been recognized from the latest global 522 tomographic models. Our study presents a systematic analysis of the pathways of these 523 plume conduits. We carried out an analysis of the shapes of plume conduits in an im-524 mersive headset-based virtual reality (VR) environment. The wavespeed variations along 525 the traced conduits from SEMUCB-WM1 and GLAD-M25 generally appear to be slower 526 than the conduits predicted by geodynamic models and vertical conduits in the mid to 527 lower mantle depth regardless of which tomographic models they are evaluated in. The 528 traced conduits are 1.1 - 3 times slower than either modeled or vertical conduits. This 529 suggests that our manually-traced conduits are more consistent with the locus of slow 530 seismic velocities within the mantle than either the vertical conduits that some authors 531 have assumed when relating surface observables to deep mantle structures or the shapes 532 of plume conduits predicted using physically simplified geodynamic models. Moreover, 533 our traced conduits are more consistent with the petrologically-determined excess tem-534 perature than either of the other types of conduits. 535

In our manually traced conduits, the total amount of offset from the surface to the 536 deep mantle is comparable between many traced and modeled conduits (usually smaller 537 than 10°), while the offset direction of traced and modeled conduits usually differ. Some 538 traced conduits of plumes stemming from the edge of the LLSVPs (Canary, Juan Fer-530 nando, Reunion, San Felix, and St Helena) tend to be $5-10^{\circ}$ less offset than their mod-540 eled conduits, but the traced and modeled conduits share similar offset directions. Our 541 traced conduits reveal a tendency for plumes to stagnate or to be offset at mid-mantle 542 depths (660 - 1250 km), a behavior that is not captured in modeled conduits. Previous 543 geophysical studies, mineral physics studies, and geodynamics modeling provide multi-544 ple mechanisms that could contribute to plume ponding or deflection, including the buoy-545 ancy barrier induced by phase transitions and the viscous decoupling of conduits. The 546 large variations of V_S anomaly along plume conduits and the complex observed plume 547 shapes together suggest that many plumes are thermochemical. Our analysis of plume 548 conduit shapes provides a dataset that can be of value across multiple disciplines includ-549 ing geodynamic modeling, geochemistry, and mineral physics. 550

551 6 Figures



Figure 1. (a) Cross section of Pacific plumes in SEMUCB-WM1 and the location of the crosssection on the map, and (b) the 3D image of -2%, -1.2%, and -0.75% δV_S isosurfaces taken from the same region.



Figure 2. Traced and modeled (Steinberger & Antretter, 2006) plume conduits in SEMUCB-WM1 (top) and in GLAD-M25 (bottom). The colorful dots represent modeled conduits, while black-white dots represent traced conduits. The green circles represent the location of hotspots. The background shows δV_S at 2850 km depth. Plate motions in the spreading-aligned mantle reference frame of Becker et al. (2015) are shown with gray arrows.



Figure 3. The depth profile of δV_S along 20 plume conduits in SEMUCB-WM1. Red represents the traced conduits. Blue represents the conduits modeled in Steinberger and Antretter (2006). Yellow represents the vertical conduits. The gray solid line is the corresponding δV_S of the petrologically estimated excess temperature from Putirka, 2008. The blue shade is the reference profile for expecting δV_S along a conduit given excess temperatures between 200 and 500 K calculated from the $d(\ln V_S)/dT$ profile (Figure. S1). The tomographically-resolved slowness along plume conduits can likely be interpreted as a lower bound on the true slowness.



Figure 4. The depth profile of δV_S along 20 plume conduits in GLAD-M25 similar to Figure 3.



Figure 5. Average δV_S along traced, model-predicted, and vertical plume conduits in two tomographic models. Pacific plumes, which are plumes locate around the Pacific LLSVP, include Caroline, Easter, Galapagos, Hawaii, Macdonald, Marquesas, Pitcairn, Samoa, and Tahiti. African plumes, which are plumes locate around the African LLSVP, include Azores, Canary, Cape Verde, Iceland, Reunion, St. Helena, and Tristan. The dotted lines indicate the depth range where the traced plume conduits from SEMUCB-WM1 (GLAD-M25) outperform either the model-predicted or vertical plume conduits in GLAD-M25 (SEMUCB-WM1).



Figure 6. The depth profile of tilt angle along 20 plume conduits. Blue represents the conduits modeled in Steinberger and Antretter (2006). Red represents the traced conduits in SEMUCB-WM1. Yellow represents the traced conduits in GLAD-M25. The gray line marks the 60° angle.



Figure 7. Azimuth and offset distance of model-predicted conduits and conduits traced in SEMUCB-WM1 and GLAD-M25 with respect to hotspots. Blue represents the azimuth of a conduit at different depths. Green represents the angular offset between a conduit and its hotspot.



Figure 8. Cross section and map view of the traced conduits of a) Macdonald and Pitcairn, b) Cape Verde and Canary, c) Iceland, d) Hawaii in SEMUCB-WM1 and GLAD-M25. From top to bottom, the dash lines represent 410, 660, and 1250 km depth.



Figure 9. Cross section and map view of the traced conduits of a) Samoa, b) St Helena, c) Reunion, d) Easter similar to Figure 8.

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779 Open Research Section

The data and computer code necessary to reproduce all figures is available on Zenodo (doi: 10.5281/zenodo.10668212). 3D-visualization is done using the Paraview 5.10.0 (Ahrens et al., 2005) visualization software.

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Supporting Information for "A synoptic view of mantle plume shapes enabled by virtual reality"

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Contents of this file

- 1. Text S1 to S3 $\,$
- 2. Figures S1 to S7
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Introduction In Text S1, we describe how we construct the reference $d \ln V_S/dT$ profile along depth in more details. In Text S2, we evaluate the slowness of our two sets of traced conduits in multiple other global tomographic models and discuss where the mutual consistency and disagreement are. In Text S3, we provides more examples of how to trace conduit of plumes that have multiple possible candidate conduits or the traced conduits do not strictly follow our criteria. We also provide more cross sections of plumes that we traced in this study (Figure S2-6) and a table of the locations, buoyancy flux, and information about whether the traced conduits agree with the modeled conduits of all traced plumes.

Text S1. $d \ln V_S / dT$ profile

The $d \ln V_S/dT$ profile (Figure S1) beneath 800 km is calculated in Burnman (Cottaar et

al., 2014; Myhill et al., 2021) assuming the phases at these depths are 82% perovskite $[(Mg_{0.9}Fe_{0.1})SiO_3]$ and 18% ferropericlase $[(Mg_{0.8}Fe_{0.2})O]$. The profile above 800 km depth is adapted from Cammarano, Goes, Vacher, and Giardini (2003). Although the mantle composition used in Burnman are not in mass conversation with the mantle composition used in Cammarano et al. (2003), it is a reasonable composition of a pyrolitic lower mantle. We believe that the $d \ln V_S/dT$ profile we calculate is accurate enough for our purpose of use.

Text S2. Slowness of trace plume conduits in other tomographic models.

To evaluate the robustness of our traced conduits, we evaluate the slowness, which is measured as the velocity anomaly, of our two sets of traced conduits traced from SEMUCB-WM1 and GLAD-M25 (V_S) in other global tomographic models, both S-velocity models (GLAD-M25 (V_S)/SEMUCB-WM1 TX2019slab (V_S) and SPiRaL (V_S)) and P-velocity models (GLAD-M25 (V_P), TX2019slab (V_P), SPiRaL (V_P), DETOX-P3, and UU-P07). Here, GLAD-M25 (Lei et al., 2020), TX2019slab (Lu et al., 2019), and SPiRaL (Simmons et al., 2021) are jointly inverted P and S velocity models. DETOX-P3 (Hosseini et al., 2020) and UU-P07 (Amaru, 2007) are purely P-velocity models, where SEMUCB-WM1 is a purely S-velocity model. Among all these tomographic models, only SEMUCB-WM1 and GLAD-M25 are full-waveform models, while the others are body wave travel-time models based on race tracing theory. Only SEMUCB-WM1, GLAD-M25, and DETOX-P3 claim to resolve plumes in the original publications (French & Romanowicz, 2015; Hosseini et al., 2020; Lei et al., 2020), while the others do not make any statement about resolving plumes in their original publications.

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conduits (MCs) and vertical conduits (VCs) below 660 - 1200 km in all tomographic model except UU-P07 (Figure 5i Figure S2 h-n). The slowness along this set of TCs is generally greater or comparable to the slowness along MCs and TCs. In TX2019slab (V_P and V_S), no MC is slower than TCs at any depth. In SPiRaL (V_P and V_S), the average slowness of TCs is less than the slowness of MCs at about 1500 km (Figure S2 h, k), which is mainly caused by Samoa plume.

The Pacific TCs from SEMUCB-WM1 are slower than MCs and VCS in a more restricted depth range (between ~ 1250 and 2100 km) in GLAD-M25 (V_P), TX2019slab (V_P and V_S), SPiRaL (V_S), and DETOX-P3, but are comparable to MCs and VCs in SPiRaL (V_P) and UU-P07 (Figure 5d Figure S2 a-g). TCs of Easter, Galapagos, and Macdonald plumes are the main contributor of slowness in TX2019slab (V_P and V_S). In SPiRaL (V_P), the average slowness of TCs is indistinguishable to the average slowness of MCs and VCs mostly because TCs of Macdonald, Marquesas, San Felix, and especially Samoa plumes are faster than their MCs and VC in the mid-mantle.

In UU-P07, the average slowness of two sets of TCs, MCs and VCs are comparable to each other and remain close 0% at all depths. This result is not surprising because first, P-velocity is less sensitive to thermal anomaly; second, the resolution of UU-P07 is generally poorer below the ocean (Amaru, 2007), where most of the traced plumes locate. The resolution of TX2019slab (V_P) and DETOX-P3, in which the average slowness of two sets of TCs is greater than the average slowness of MCs and VCs in the mid to lower mantle, has a poor resolution in the upper mantle in the Pacific region but a good resolution in the mid and lower mantle (Lu et al., 2019; Hosseini et al., 2020).

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In summary, both sets of traced conduits, especially TCs from GLAD-M25, are more compatible with many other tomographic models than the modeled and vertical conduits in the mid to lower mantle. Our traced conduits should be a better representation of plume shapes than the modeled and vertical conduits.

Text S3. Procedures to trace plume conduits with ambiguity.

Here, we provide some examples of how we decide the traced conduit of a plume over multiple candidate traced conduits of a plume. For example, the traced conduits of Galapagos from SEMUCB-WM1 and GLAD-M25 almost do not have any overlaps but we find that CCs resolved in the two models have overlaps (Figure S4a-b). We traced the most straightforward conduit path below 660 km for Galapagos that connects the CC resolved above 660 km depth in SEMUCB-WM1 (box in Figure S4a) to the CC right beneath this anomaly. If we decide that the upper-mantle CC is connected to the lower-mantle CC resolved in both tomographic models, the conduit traced from SEMUCB-WM1 will have much more overlaps with the conduit traced from GLAD-M25. Similarly for Easter, strongly sheared CC is observed between 660 and \sim 2000 km depth (Figure 9d). The CC resolved in GLAD-M25 below \sim 2000 km favors a conduit sheared towards the northeast, while the CC resolved in SEMUCB-WM1 could be interpreted as either vertical or sheared conduit.

The Tristan plume is thought to form the Tristan-Gough hotspot track and the Parana-Etendeka flood basalts (Richards et al., 1989). The isotopic observations of basalt from the Tristan-Gough hotspot track suggest that they are EM1 and HIMU types, which usually indicates a mantle plume origin. Because of these observations, we include the

conduit of Tristan, although a continuous conduit is only clearly resolved in SEMUCB-WM1 but not in GLAD-M25 (Figure S6). The conduit of Tristan is resolved only below 660 km depth in GLAD-M25. For plume Azores, the CC with large-amplitude negative δV_S between 660 and 1250 km depth in SEMUCB-WM1 makes us decide the conduit to pass through this region while this CSS is not significant in GLAD-M25 (Figure S3c).

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Figure S1. Sensitivity of shear velocity anomaly (left) and the reference δVs (right) with a bulk composition of pyrolite. The reference δVs profile (the blue shaded region) is calculated from the $\delta lnVs/dT$ profile assuming a purely thermal plume with excessive temperatures between 200 and 500 K along depths.



Figure S2. Average δV_S along 12 Pacific traced, model-predicted, and vertical plume conduits (same as Figure 5) in S-velocity models TX2019slab (V_S) (a, h), SPiRaL (V_S) (b, i), and Pvelocity models GLAD-M25 (V_P) (c, j), TX2019slab (V_P) (d, k), SPiRaL (V_P) (e, l), DETOX-P3 (f, m), UU-P07 (g, n). The top row is the result of the set of traced conduits from SEMUCB-WM1; the bottom row is the result of the set of traced conduits from GLAD-M25 (V_S). The dotted lines indicate the depth range where the traced plume conduits outperform either the model-predicted or vertical plume conduits.



Figure S3. Cross section and map view of the traced conduits of San Felix and Juan Fernandez similar to Figure 8.



Figure S4. Cross section and map view of the traced conduits of a) Caroline, b) Louisville, and c,d) Azores similar to Figure 8.

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Figure S5. Cross section and map view of the traced conduits of a,b) Galapagos and c,d) Kerguelen similar to Figure 8.



Figure S6. Cross section and map view of the traced conduits of a,b) Marquesas and c,d) Tahiti similar to Figure 8.



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Figure S7. Cross section and map view of the traced conduits of Tristan similar to Figure 8.

Table S1. List of plumes traced in this study. The buoyancy flux is obtained from Jackson et al. (2021), the hot spot locations are obtained from Steinberger (2000), and the excess temperature is the petrological estimated excess temperature obtained from Putirka (2008).

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Plume	Lat	Lon	Buoyancy Flux	$T_{ex}(K)$	Agree with	n MC?
			$(10^3 kg s^{-1})$		SEMUCB	GLAD
Azores	38.5°	-28.4°	1.1	124	No	No
Canary	28.0°	-18.0°	0.8	164	Yes	Yes
Cape Verde	15.0°	-24.0°	1.1	114	Maybe	Maybe
Caroline	5.0°	164.0°	1.2	150	No	No
Easter	-27.1°	-109.3°	1.6	N/A	No	No
Galapagos	-0.4°	-91.5°	1.4	130	No	No
Hawaii	19.4°	-155.3°	6.3	290	No	Yes
Iceland	65.0°	-19.0°	5.5	186	Maybe	Maybe
Juan Fernandez	-34.0°	-82.0°	1.7	185	Yes	Yes
Kerguelen	-49.0°	69.0°	1.1	209	Maybe	Yes
Louisville	-51.0°	-138.0°	1.5	200	No	No
Macdonald	-29.0°	-140.2°	3.3	N/A	No	No
Marquesas	-11.0°	-138.0°	3.1	167	Maybe	No
Pitcairn	-25.0°	-129.0°	2.1	189	No	No
Reunion	-21.2°	55.7°	1.4	176	Yes	Yes
Samoa	-15.0°	-168.0°	1.7	223	No	No
San Felix	-26.0°	-80.0°	2.0	N/A	Yes	Yes
St Helena	-17.0°	-10.0°	0.5	164	Yes	Yes
Tahiti	-17.9°	-148.1°	3.7	185	No	No
Tristan	-38.0°	-11.0°	1.0	176	No	No