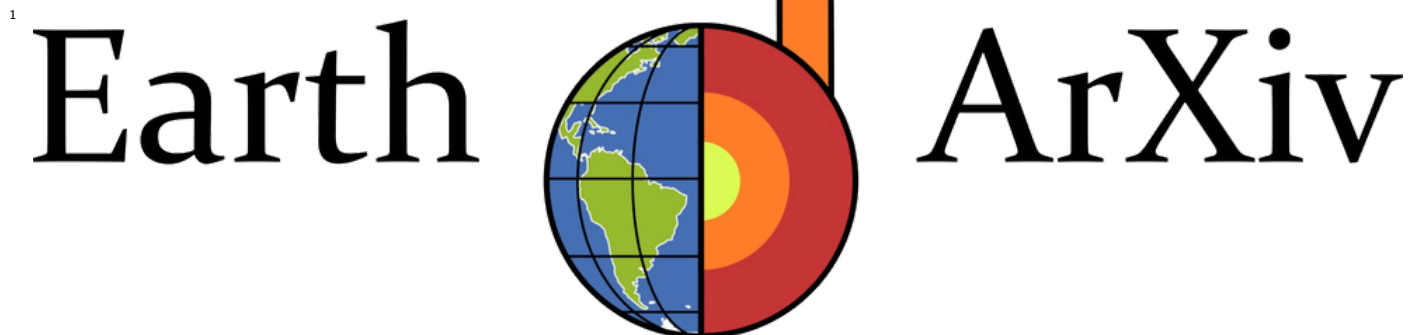




This is a non-peer-reviewed preprint submitted to EarthArXiv.

This manuscript has been submitted for publication in NATURE GEOSCIENCE. Please note the manuscript has yet to be formally accepted for publication. Subsequent versions of this manuscript may have slightly different content. If accepted, the final version of this manuscript will be available via the 'Peer-reviewed Publication DOI' link on the right-hand side of this webpage. Please feel free to contact any of the authors; we welcome feedback.

Corresponding author: Katrina Harris,
katrina.harris.19@ucl.ac.uk,
<https://orcid.org/0000-0001-7159-0536>

Azores–Canaries mantle plume interactions revealed by seismic imaging

Katrina M Harris(1), Ana MG Ferreira(1), Michael Witek(2), Maxim Ballmer(1), Sung-Joon Chang(3),
Miguel Miranda(4)

1 Department of Earth Sciences, Faculty of Mathematical Physical Sciences, University College
London, London, UK

2 Los Alamos National Laboratory, Los Alamos, USA

3 Division of Geology and Geophysics, Kangwon National University, Chuncheon, South Korea

4 Instituto Português do Mar e da Atmosfera, Atlantic International Research Centre

Azores–Canaries mantle plume interactions revealed by seismic imaging

Katrina M Harris¹, Ana MG Ferreira¹, Michael Witek², Maxim Ballmer¹, Sung-Joon Chang³,
Miguel Miranda⁴

¹ Department of Earth Sciences, Faculty of Mathematical Physical Sciences, University College
London, London, UK

² Los Alamos National Laboratory, Los Alamos, USA

³ Division of Geology and Geophysics, Kangwon National University, Chuncheon, South Korea,

⁴ Instituto Português do Mar e da Atmosfera, Atlantic International Research Centre

Mantle plumes transport heat and material from the deep Earth towards the surface, yet how neighbouring plumes interact and influence mantle flow remains poorly understood. The Azores–Madeira–Canaries region, which hosts several closely spaced mantle upwellings, provides a unique opportunity to investigate these processes. Here we use data from the UPFLOW experiment, an unprecedented ocean-bottom seismometer deployment across the region, to image two mantle upwellings across the upper mantle and transition zone using multimode waveform tomography. We find widespread lateral spreading of low-velocity anomalies between ~230 and 400 km depth, accompanied by pronounced radial anisotropy variations. These observations are consistent with large-scale ponding and lateral flow of eclogitic material predicted by geodynamic models of thermochemical plumes. Where the lateral spreading associated with the two upwellings converges, fast-SV radial anisotropy indicates localised downwelling. Our observations provide evidence that neighbouring mantle plumes can interact dynamically, with their lateral spreading possibly driving localised downwelling that returns material to greater depths. This provides a rare observational window into the three-dimensional flow and interaction of thermochemical plumes in the upper mantle.

Recent studies of oceanic volcanism have begun to link large-scale mantle convection with plume behaviour¹. However, the processes governing mantle plume evolution, how they traverse the upper mantle and their ability to influence other plumes remain poorly understood. The classical plume model describes a broad, thermally buoyant head followed by a narrow tail rising from the core–mantle boundary to feed hotspot volcanism². Seismic observations, however, reveal a greater diversity of plume morphologies than this simple model predicts^{3,4}. Geodynamic models show that phase transitions and viscosity contrasts can cause plumes to pond and spread at different depths, including around the 660- and 410-km discontinuities, and can promote the formation of secondary plumelets rising from these reservoirs^{5,6}. Such behaviour is particularly important for thermochemical plumes containing dense eclogitic material derived from recycled oceanic crust^{7,8}. Because eclogite is denser than surrounding peridotite through much of the upper mantle, it can reduce plume buoyancy and promote ponding and lateral spreading rather than direct ascent^{5,8}, evidence for which has been found, for example, in Hawaii⁹. Yet the extent of such spreading, the fate of ponded material and its influence on surrounding mantle flow remain poorly constrained observationally.

An additional largely unexplored aspect of plume dynamics is the interaction between neighbouring upwellings. Geodynamic models indicate that adjacent plumes can interact and merge, altering their trajectories and morphology¹⁰, while plume–plume interaction has also been invoked to explain changes in hotspot geometry and

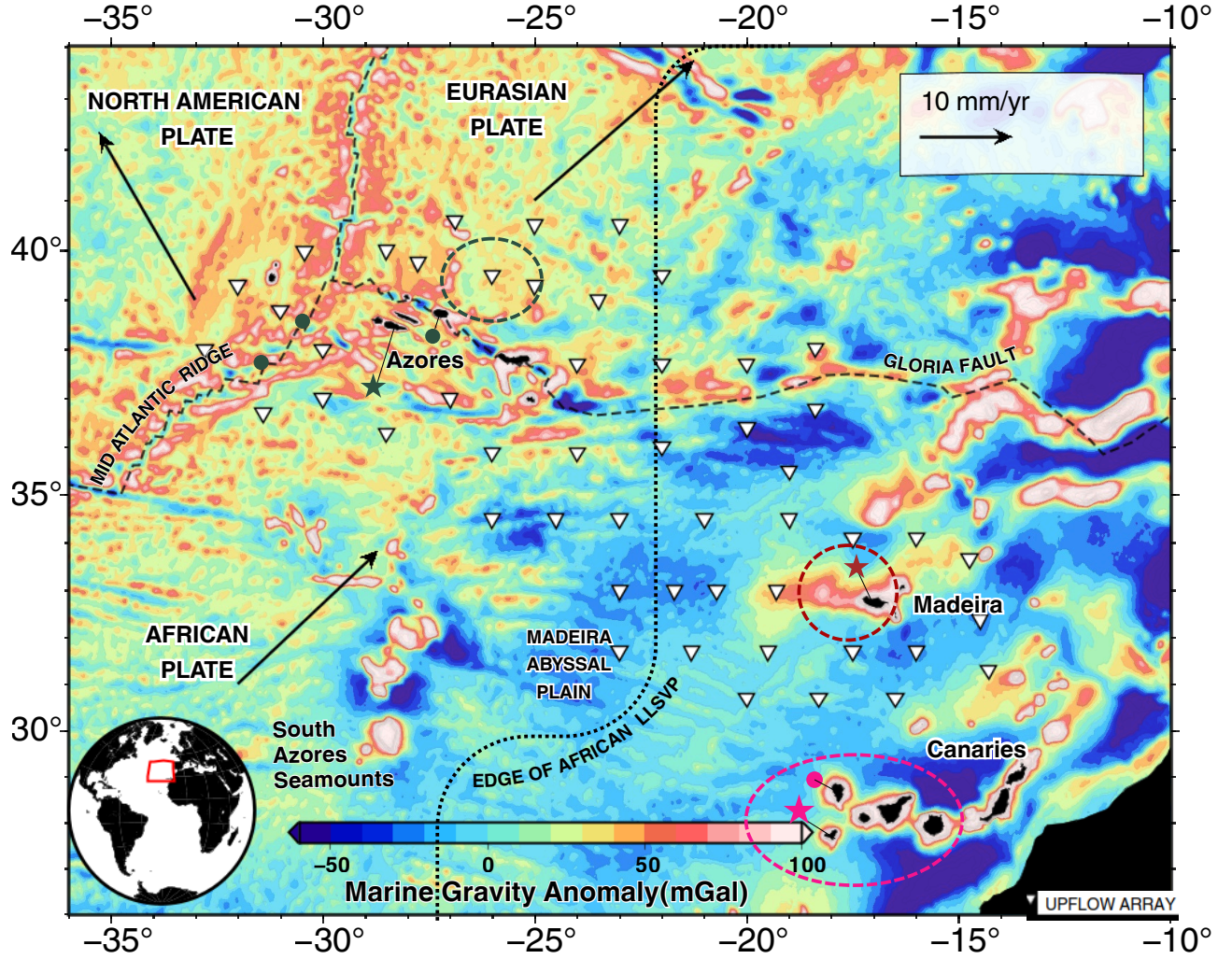


Figure 1: **UPFLOW ocean-bottom seismic array and regional setting.** Marine gravity anomalies of the Azores–Madeira–Canaries region from Sandwell et al.¹³. White triangles denote location of UPFLOW ocean–bottom–seismometer (OBS) stations. The dark green circle denotes the location of a low velocity anomaly at 375 km depth from Yang et al.¹⁴. The brown circle indicates a region of depressed 410 km and normal 660 km discontinuities from Bonatto et al.¹⁵. The pink ellipse indicates a region of depressed 410 km and elevated 660 km from Bonatto et al.¹⁵. Stars indicate youngest islands of the three archipelagos¹⁶: El Hierro (pink), Madeira (brown) and Pico (dark green). Dots indicate locations of samples found with primitive helium isotope signatures; La Palma in the Canaries (Pink)¹⁷ and Terceira island¹⁸ and Mid-Atlantic Ridge¹⁹ in the Azores (green). Black arrows indicate plate motion²⁰. Black dashed lines indicate plate boundaries. Black dotted line indicates the approximate edge of the African Large–Low–Shear–Velocity–Province (LLSVP) from Chang et al.²¹.

volcanism¹¹. Models of thermochemical plumes further show that interaction with the mantle transition zone can promote lateral spreading, stagnation and secondary upwellings¹². These results suggest that plumes are not necessarily isolated conduits, but dynamic systems capable of reorganizing mantle flow around and between them. However, direct observational constraints on the interaction and associated mantle flow of neighbouring oceanic plumes remain scarce. In particular, it remains unclear how lateral spreading of adjacent plumes interacts at depth, and whether their interaction can induce return flow into the surrounding mantle.

The Azores–Madeira–Canaries region of the Central–East Atlantic (Fig. 1) provides an exceptional natural laboratory for investigating these processes. The region hosts several closely spaced volcanic systems with evidence for

anomalous mantle beneath them, including positive residual topography, lower-mantle geochemical signatures and low seismic velocities^{14,22–26}. A thinned mantle transition zone beneath Madeira and the Canaries is also consistent with thermal upwelling^{15,27}. Nevertheless, particularly beneath the Azores, the origin of the anomalous mantle remains debated, with proposed explanations including a deep mantle plume, ridge-related melting, underplating and fertile mantle heterogeneity^{28–34}. The close spatial association of these systems therefore offers an opportunity to investigate not only their individual origins, but also whether they are dynamically connected.

Resolving these questions requires imaging the upper mantle and transition zone across the region rather than beneath individual volcanic centres. The UPFLOW ocean-bottom seismometer experiment provides a unique opportunity, with 50 instruments deployed across an approximately $1,000 \times 2,000$ km broad region, providing unprecedented seismic coverage between the Azores, Madeira and Canaries³⁵. This geometry allows multiple upwellings to be imaged simultaneously, together with the mantle between them. Here we combine this unique dataset with advanced 3-D isotropic and anisotropic waveform tomography to investigate the structure and mantle flow associated with two neighbouring upwellings. Inverting for anisotropy is key to constraining mantle flow, allowing us to resolve their lateral extent and changes in flow where the upwellings approach one another. By resolving the relationship between adjacent upwellings, our observations provide a test of models in which thermochemical plumes spread and interact within the upper mantle, and constrain how deep-mantle material is redistributed during ascent.

Mantle plume observations: upper-mantle plume ponding

Geochemical evidence indicates deep mantle sources for Azores and Canary volcanism, while global and regional seismic models consistently image low-velocity anomalies beneath these archipelagos^{3,36}. Resolving the morphology of the related upwellings and their interaction, however, requires substantially denser seismic coverage. Here, we combine ocean-bottom seismometer observations from the UPFLOW array with regional land stations to overcome sparse onshore coverage and obtain a new radially anisotropic S-wave model of the upper mantle.

We apply the partitioned waveform inversion tomography method³⁷ to 6,961 three-component waveforms recorded by the UPFLOW array (43 stations) together with 418 land stations across the surrounding region (Supplementary Fig. S1). The waveforms are divided into time-frequency windows spanning periods of T~20–210s, providing complementary sensitivity from the crust to the uppermost lower mantle (Supplementary Fig S2; see Methods). The resulting 20,456 measurements provide dense coverage of the study region (Supplementary Figs. S3). The high quality of the UPFLOW observations³⁵, together with stringent data-selection criteria³⁷, enables inversion for both isotropic structure and radial anisotropy, the latter providing an additional constraint on mantle flow³⁸. We assess resolution using conventional checkerboard tests (Supplementary Figs. S5 – S8) and synthetic inversions incorporating realistic structures, including columnar anomalies representing plume-like upwellings (Supplementary Figs. S9 – S12) and synthetic data generated from our recovered model with added noise (Supplementary Fig. S13). These tests show that both isotropic V_S and radial anisotropy are well recovered beneath the UPFLOW array. Beneath the Canaries, recovery remains robust, although anomaly amplitudes are somewhat decreased. We additionally explore a broad range of regularisation parameters (Supplementary Figs. S14 – S16) and restrict our interpretation to features that remain stable across these choices.

Our shear-wave velocity (V_S) model (Figs. 2 and 3a) reveals shallow low-velocity anomalies above 80 km depth, primarily associated with the Mid-Atlantic Ridge (MAR) and the Azores, Madeira and Canary archipelagos. From 80 to ~200 km depth, low-velocity anomalies form two approximately north–south-trending structures: the L1 anomaly in the western part of the study region, and the L3 anomaly in the eastern part (Fig. 2b; Fig. 3a). At 150 km depth, these anomalies reach amplitudes below -2.5% beneath Madeira, the Canaries, and the Azores.

Between ~200 and ~350 km depth, broad low- V_S anomalies span the region, with the strongest perturbations beneath the Azores and Canaries and within a north-south-trending corridor beneath the Madeira Abyssal Plain (L2

anomaly in Fig. 2c, Fig. 3a). Within this corridor, low velocities persist weakly to the 410-km seismic discontinuity (Fig. 3a C-C', L2 anomaly), whereas beneath the Azores and Canaries two discrete anomalies continue through the mantle transition zone (Figs. 2d,e and Supplementary Fig. S18d-f). The north-south low-velocity structure remains evident within the transition zone, although its lateral extent is more restricted than at 200–350 km depth (L4 anomaly in Fig. 2e, Fig. 3a). At the base of the transition zone, a strong low- V_S anomaly is evident beneath the central Azores, as well as a weaker anomaly beneath the eastern Canary Islands, and additional low velocity anomalies occur south of the Azores (Fig. 2f).

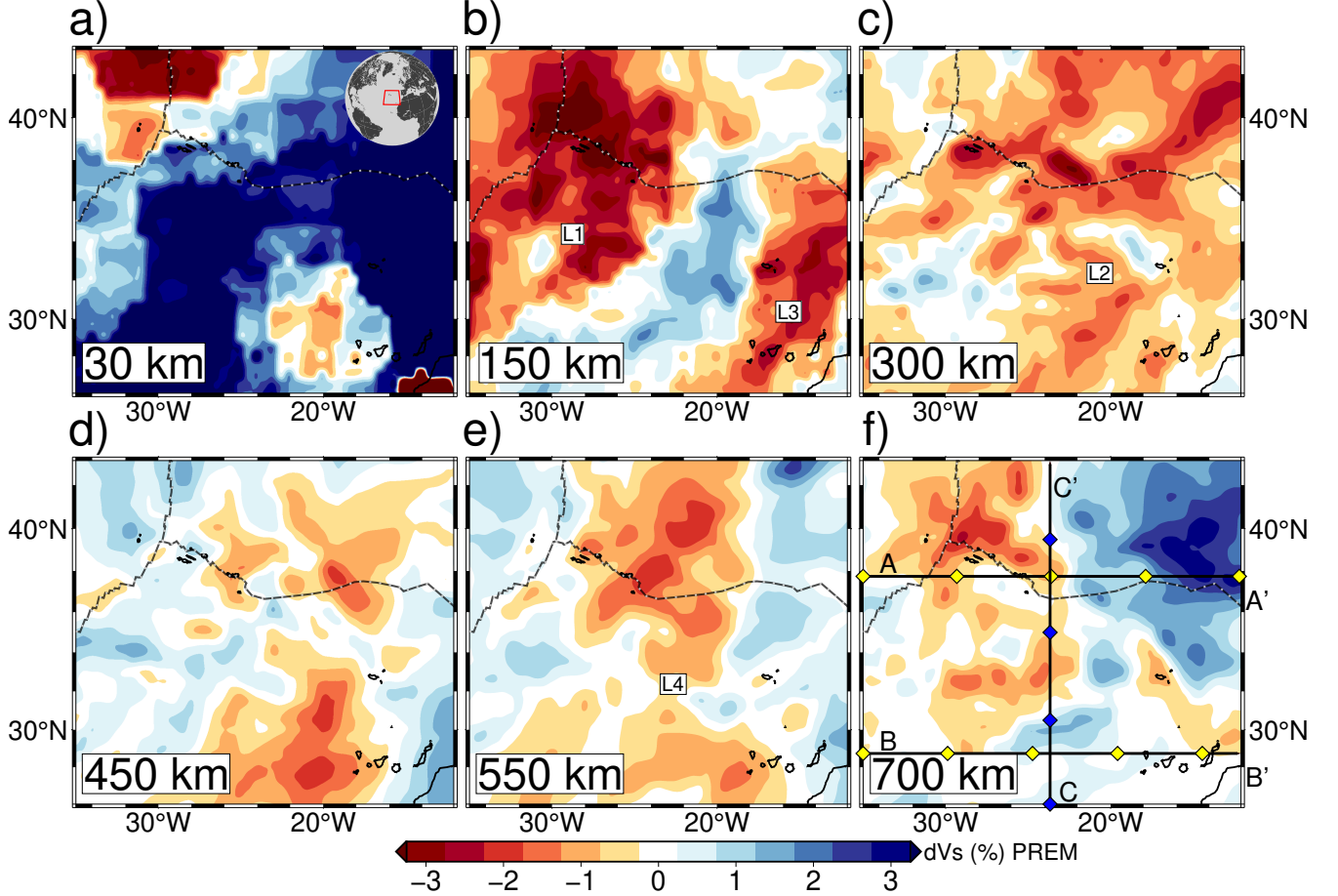


Figure 2: **Depth slices of Isotropic V_S model.** Horizontal depth slices of our isotropic V_S model, plotted in perturbations with respect to PREM. Cross sections on panel (f) are plotted in Fig. 3a. The L1–L4 annotations are referenced in the main text.

We interpret these coherent low-velocity structures as two plume-like upwellings rising through a laterally extensive slow velocity layer centered at ~550 km depth. The northern upwelling, associated with the Azores, lies east of the islands between ~300 and 550 km depth, consistent with previous regional P-wave observations¹⁴ and global shear-wave models e.g., ref.²¹. The southern upwelling is larger and connects the Madeira and Canary systems, lying slightly west of their youngest surface expressions and south of Madeira within the upper transition zone. Both structures rise into the upper mantle before spreading laterally at ~300 km depth, producing the broad low-velocity structure at these depths. Their coherent geometry and common depth extent suggest that the Azores and Canary upwellings are dynamically related rather than being entirely independent features.

Observations of mantle anisotropy and flow interpretation

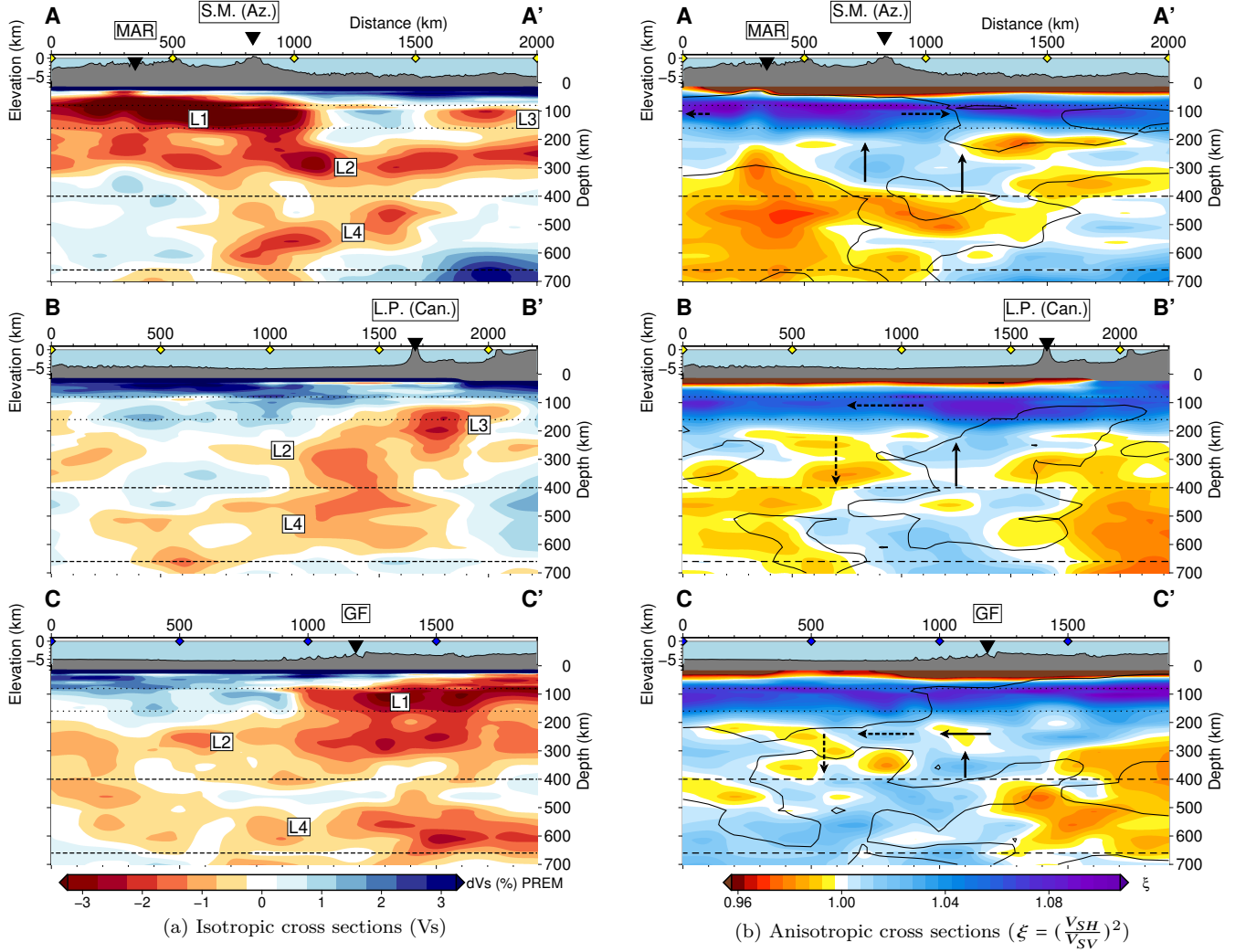


Figure 3: Vertical cross sections through tomographic model. Cross sections of isotropic (a) and anisotropic (b) structure along transects in Fig 2 f). Isotropic V_s is plotted in perturbations from PREM. Anisotropy is plotted in $\xi = (\frac{V_{SH}}{V_{SV}})^2$. Black contours plotted on (b) are the -0.5% V_s perturbations along the same transects. Dashed lines indicate 80, 170, 400 and 660 km depths. Grey topography is plotted atop tomography cross sections on a larger scale. S.M.=São Miguel Island, L.P.=La Palma Island, MAR=Mid-Atlantic Ridge, GF=Gloria Fault. The L1–L4 annotations in (a) and the black arrows in (b) (solid and dashed lines correspond to assuming C-type and A-type olivine fabric, respectively) aid with the description in the main text. A C-type olivine fabric is assumed near the plume-like upwellings because they are likely water-rich³³.

Our radial anisotropy model reveals fast-SV anomalies in the crust ($V_{SH} < V_{SV}$, where V_{SH} and V_{SV} denote horizontally and vertically polarized shear-wave speeds, respectively), transitioning to fast-SH anomalies between 50 and 200 km depth. Both layers are perturbed beneath the MAR (Fig. 3b, A-A'). Particularly strong fast-SH anomalies between 80 and 150 km depth occur beneath the central Azores and northwest of the Canaries. Between 200 and 400 km depth, fast-SH perturbations occur west of the low-velocity structure beneath the Canaries and overlap the low-velocity anomaly beneath the Azores. In contrast, a strong fast-SV anomaly occurs beneath the MAR between 250 and 400 km depth, consistent with previous regional anisotropic tomography³⁹. A further fast-SV anomaly is resolved midway between the two hotspot systems, approximately equidistant from the Azores and Canaries, extending from ~250 to 400 km depth (Fig. 3b, C-C', Supplementary Fig. S17 e),f)).

Because radial anisotropy is less well resolved than isotropic V_S structure²¹, we performed additional tests to establish the robustness of these features. We evaluated trade-offs between isotropic and anisotropic structure and found that the anisotropic anomalies do not arise from leakage of isotropic structure (Supplementary Figs. S6 and S10). Conversely, Figs. S8 and S12 show that anisotropy does not contaminate the recovered isotropic V_S structure. Including anisotropy in the inversions substantially improves the fit to the observations, as demonstrated by the reduced waveform misfit distributions shown in Supplementary Fig. S4b.

The anisotropic signature of the MAR resembles that observed beneath other oceanic ridges in tomographic studies (e.g. French et al.⁴⁰) and predicted by geodynamic models⁴¹. Assuming the simplest A-type olivine fabric, the anomalies observed at ~40–200 km depth ($V_{SH} > V_{SV}$) are consistent with horizontal flow (e.g., Karato et al.³⁸; Fig. 3b, A-A', dashed arrows showing mantle flow assuming A-type olivine). The plume-like upwellings are likely water-rich³³, favouring development of a C-type fabric during ascent. Under this fabric, the fast-SH anomalies at 270 – ~400 km depth (Fig. 3b A-A', B-B', with solid arrows showing mantle flow assuming C-type olivine) are consistent with predominantly vertical flow beneath the Azores and west of the Canaries³⁸. At depths of partial melting, plume dehydration should promote a transition towards A- or E-type fabrics. The strong fast-SH anomalies above ~180 km are consistent with this transition and with lateral spreading of plume material beneath the lithosphere. Conversely, the fast-SV anomaly between the hotspots suggests localized downwelling (as mechanisms for dry upwelling, such as small scale convection, are not imaged in the region) (Fig. 3b B-B', C-C', with dashed arrows showing mantle flow assuming A-type olivine), which may reflect return flow driven by the lateral spreading of plume material beneath the lithosphere and its interaction between the two plumes.

A ~300 km-deep eclogitic pool fed by the Azores and Canaries mantle plumes

The broad low- V_S structure centered at ~300 km depth suggests that the two upwellings spread laterally within a relatively shallow reservoir (Fig. 3a, L2 anomaly). Geodynamic models^{5,8} predict that eclogitic plume material can pond at these depths because its buoyancy decreases following the wadsleyite-to-olivine phase transition at ~410 km depth. Continued influx of hot material from below can dynamically support the negatively buoyant eclogitic component, allowing it to accumulate and spread laterally. Independent evidence for accumulation of eclogite-rich mantle in this region comes from the detection of the coesite-stishovite discontinuity beneath the Canaries¹⁵.

In the models of Ballmer et al.⁵, the hot eclogitic material is surrounded by warm pyrolite that continues to rise around the pond. Our observations show a geometry consistent with this prediction: upwellings around the principal ~300 km deep low-velocity structure (L2) occur predominantly to its east (L3) and west (L1) (Fig. 3a A-A'). Surface hotspot activity, however, is expressed primarily to the west at higher latitudes, towards the Azores, potentially reflecting the influence of the nearby MAR on lithospheric structure. A similar L1-L2-L3 configuration occurs at the latitude of Madeira (Supplementary Figs. S19 F-F', S20 F-F'), where present-day hotspot expression is concentrated in the east. The western arm beneath the South Azores Seamount Chain may have influenced the distribution of volcanism and provides a minimum age of ~85 Ma for this large-scale ponding structure⁴².

At the latitude of the Canaries, upwelling from (or around) the ~300 km deep reservoir is preferentially directed south-eastwards beneath the islands (L3).

The eclogitic component is expected to accumulate beneath the coesite-stishovite transition at ~300 km depth⁴³, above which it becomes positively buoyant^{5,8}. However, the upper limit of the pond in our model is offset to a depth of ~250 km. This offset may result from vertical smearing effects of the low velocity pond (Supplementary Fig. S5), or it may reflect the presence of a thermal boundary layer. Alternatively, water and aluminium may be present in the silica system, which can result in a shallower transition depth by ~50 km⁴⁴. Importantly, independent receiver-function observations place the coesite-stishovite transition at 253–316 km depth beneath the Canaries¹⁵, overlapping with the depth range of the reservoir imaged here. Receiver-functions from Hawaii found the same transition between 290 and 350 km⁹, indicating eclogitic ponding may be present below other plumes.

Civiero et al.⁴⁵ proposed that the low-velocity Central-East Atlantic anomaly in the topmost lower mantle (~700–1,200 km depth) gives rise to ‘plumelets’ around the margins of a deep ponding barrier, potentially explaining the irregular hotspot tracks of the Canaries and Madeira. Our observations suggest that the ~300 km reservoir may provide a shallower analogue: by impeding and redirecting ascending material around its margins, it may reorganize plume trajectories and contribute to the irregular spatial distribution of volcanism across the region.

Dynamical interactions and associated mantle flow of neighbouring oceanic upwellings

Merle et al.⁴⁶ combined geochemical sampling and geochronology from hotspots across the Northern Central Atlantic to propose a common mechanism for widespread, long-lived volcanism in the region since the Cretaceous. Using GPlates reconstructions, they identified volcanic anomalies distributed between concentric circles of 1,000 and 2,500 km radius centred approximately beneath the present-day Madeira Abyssal Plain. Because the interior of this annulus is largely devoid of melting anomalies, they proposed that multiple plumes originate from the margins of a broad deep-seated anomaly. Our observations provide another possible mechanism for such a hotspot distribution: the imaged eclogitic reservoir, which has been deposited by the plumes themselves over time, may deflect ascending material around its margins. The longevity of deep eclogitic reservoirs and their ability to redirect buoyant upwellings, however, remain uncertain. Highly buoyant plumes should displace neutrally buoyant material and rise through such reservoirs, whereas converging eclogitic material may more effectively impede and redirect upwellings over geological timescales. Testing these mechanisms requires targeted geodynamic modelling that is beyond the scope of this study.

The volume of the low velocity anomaly between 400 and 250 km associated with the eclogitic pond is estimated to be $1.34 \times 10^{17} \text{ m}^3$. This accounts for mantle resolved to have a -1% V_S perturbation from PREM in the area 30°W to 12° W, and 26°N to 43°N. Assuming these plumes have been depositing eclogitic material over 85 Ma⁴², this results in a volumetric flux of $5 \text{ m}^3 \text{ s}^{-1}$. Taking an excess temperature of 198 °K⁴⁷, this results in a buoyancy flux Q_B of $0.98 \times 10^6 \text{ g s}^{-1}$ associated with the pond. This is comparable to the cumulative buoyancy flux estimated from swell volume for the Canaries ($0.93 \times 10^6 \text{ g s}^{-1}$), Azores ($0.85 \times 10^6 \text{ g s}^{-1}$) and Great Meteor seamounts ($0.37 \times 10^6 \text{ g s}^{-1}$)⁴⁸. The possible cooling and escaping of this material was not considered but may be significant, as may additional eclogitic rich material outside of our well resolved study region. Such a large pool may indicate considerable filtering of plume material between the mantle transition zone and the uppermost mantle, with a large volume of dense material not reaching the base of the lithosphere, and thus not sampled by hotspot melting. Thus, ocean-island basalt geochemistry in the region, and perhaps worldwide, may provide a biased view of (lower) mantle composition, undersampling recycled silica-rich heterogeneity.

The low-velocity anomalies at ~300 km depth are more laterally extensive and coherent than those within the mantle transition zone at ~550 km depth (Fig. 3a). In contrast, the deeper anomalies have a less coherent

199 geometry and become progressively shallower towards the south (Fig. 4). These contrasting geometries may reflect
 200 the different effects of mantle phase transitions on plume buoyancy. Immediately above the 660-km discontinuity,
 201 associated with the post-spinel transition, hot Mid-Ocean Ridge Basalt (MORB)-derived material ascending through
 202 pyrolitic mantle experiences a reduction in buoyancy relative to conditions below the transition. Given the modest
 203 buoyancy and temperature anomalies of the Canaries and Azores plumes⁴⁹, this reduction in buoyancy could
 204 promote lateral spreading at ~550 km depth. A weaker buoyancy reduction across the wadsleyite-ringwoodite
 205 transition at ~520 km depth is also expected⁵⁰, potentially explaining the less coherent geometry of the low-
 206 velocity anomalies at ~550 km compared with the shallower, more coherent eclogite reservoir. Alternatively, the
 207 low-velocity material may represent eclogite-rich plume material that has cooled sufficiently (even though not
 208 completely) to sink, escape the ~300 km reservoir, and be intermittently trapped at, or at least slowed down near,
 209 the wadsleyite-ringwoodite transition.

210 The olivine fabric within an eclogitic reservoir has not previously been modelled, but its fabric may vary
 211 systematically with distance from the plume conduits. Water-rich conditions are expected close to the conduits
 212 and to decrease as the reservoir spreads into comparatively dry ambient mantle. Under this framework, the fast-SV
 213 anomaly observed between ~180 and 400 km depth near the plume conduits (e.g., Fig. 3b, A-A') is consistent
 214 with horizontal spreading of eclogitic material from the plumes under a C-type fabric, while fast-SH at the same
 215 depths and proximity is consistent with vertical flow within the reservoir. Farther from the plume centres, where
 216 A- or E-type fabrics may dominate, fast-SH is consistent with continued horizontal spreading into the surrounding
 217 mantle. With increasing distance from the conduits, eclogitic material cools and loses thermal buoyancy, while
 218 convergence between the spreading reservoirs may redirect ambient mantle flow and promote downwelling. Under
 219 A- or E-type fabrics, the fast-SV anomaly between the hotspots is therefore consistent with localized downwelling,
 220 potentially reflecting return flow induced by the interaction of the neighbouring, laterally spreading plumes.

221 Together, our seismic velocity and anisotropy observations reveal interacting but distinct Azores and Canaries
 222 upwellings, each feeding reservoirs at different depths while progressively losing material during ascent (Fig. 4).
 223 Localized return flow separates the two systems at multiple depths, indicating that their interaction is primarily dy-
 224 namic rather than involving direct material exchange. This progressive redistribution and loss of ascending material
 225 provides a framework for understanding how mantle flow can modify the geochemical expression of neighbouring
 226 plumes and ultimately shape the surface manifestation of long-lived Atlantic volcanism.

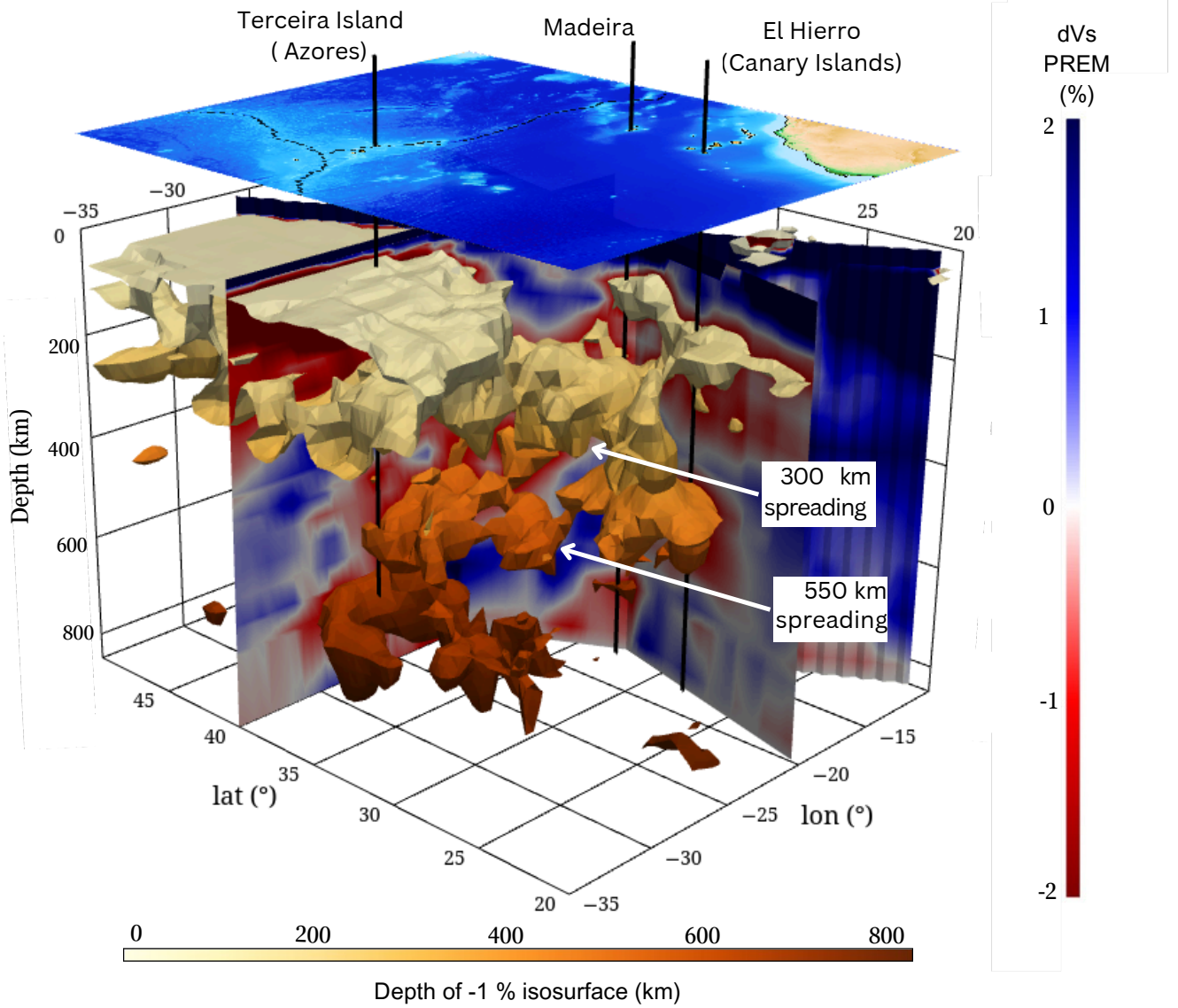


Figure 4: **Low velocity structure of isotropic V_S model.** Isosurface of -1% V_S perturbation from PREM of our V_S model, coloured by depth. Three vertical slices of our V_S model show both positive and negative velocity perturbations, with colour scale to the right. Black lines correspond to key island locations on the surface. The isosurface in the range 20°–30° latitude , -25°– -35° longitude was removed for visual clarity of the main structures.

References

- [1] Emerging insights on oceanic intraplate volcanism. *Nature Geoscience*, **19**:739–739, (2026).
- [2] Morgan, W. J. Convection plumes in the lower mantle. *Nature*, **230**:42–43, (1971).
- [3] French, S. W. and Romanowicz, B. Broad plumes rooted at the base of the Earth’s mantle beneath major hotspots. *Nature*, **525**:95–99, (2015).

- [4] Tsekhmistrenko, M., Sigloch, K., Hosseini, K., and Barruol, G. A tree of Indo-African mantle plumes imaged by seismic tomography. *Nature Geoscience*, **14**:612–619, (2021).
- [5] Ballmer, M. D., Ito, G., Wolfe, C. J., and Solomon, S. C. Double layering of a thermochemical plume in the upper mantle beneath Hawaii. *Earth and Planetary Science Letters*, **376**:155–164, (2013).
- [6] Li, Y., Wang, Y., Zhao, L., Chen, L., and Huang, J. The role of mantle viscosity heterogeneities on the development of secondary plumes in the upper mantle. *Geophysical Journal International*, **235**:2900–2915, (2023).
- [7] Sobolev, S. V. et al. Linking mantle plumes, large igneous provinces and environmental catastrophes. *Nature*, **477**:312–316, (2011).
- [8] Dannberg, J. and Sobolev, S. V. Low-buoyancy thermochemical plumes resolve controversy of classical mantle plume concept. *Nature Communications*, **6**, (2015).
- [9] Kemp, M., Jenkins, J., MacLennan, J., and Cottaar, S. X-discontinuity and transition zone structure beneath Hawaii suggests a heterogeneous plume. *Earth and Planetary Science Letters*, **527**:115781, (2019).
- [10] Arnould, M., Coltice, N., Flament, N., and Mallard, C. Plate tectonics and mantle controls on plume dynamics. *Earth and Planetary Science Letters*, **547**:116439, (2020).
- [11] Zhang, L. et al. An emerging plume head interacting with the Hawaiian plume tail. *The Innovation*, **4**(2): 100404, (2023).
- [12] Zhu, X., Balázs, A., Gerya, T., and Sun, Z. Secondary plumes formation controlled by interaction of thermochemical mantle plumes with the mantle transition zone. *Geophysical Research Letters*, **52**:e2025GL117079, (2025).
- [13] Sandwell, D. T., Müller, R. D., Smith, W. H., Garcia, E., and Francis, R. New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure. *Science*, **346**:65–67, (2014).
- [14] Yang, T., Shen, Y., van der Lee, S., Solomon, S. C., and Hung, S. H. Upper mantle structure beneath the Azores hotspot from finite-frequency seismic tomography. *Earth and Planetary Science Letters*, **250**:11–26, (2006).
- [15] Bonatto, L. et al. Unveiling the Distinct Structure of the Upper Mantle Beneath the Canary and Madeira Hotspots, as Depicted by the 660, 410, and X Discontinuities. *Journal of Geophysical Research: Solid Earth*, **129**:e2023JB028195, (2024).
- [16] Carracedo, J. C. and Troll, V. R. North-East Atlantic Islands: The Macaronesian Archipelagos. In Alderton, D. and Elias, S. A., editors, *Encyclopedia of Geology (Second Edition)*, pages 674–699. Academic Press, Oxford, (2021).
- [17] Hilton, D. R., MacPherson, C. G., and Elliott, T. R. Helium isotope ratios in mafic phenocrysts and geothermal fluids from La Palma, the Canary Islands (Spain): implications for HIMU mantle sources. *Geochimica et Cosmochimica Acta*, **64**:2119–2132, (2000).
- [18] Madureira, P. et al. Helium isotope systematics in the vicinity of the Azores triple junction: Constraints on the Azores geodynamics. *Chemical Geology*, **372**:62–71, (2014).
- [19] Moreira, M. and Allègre, C. J. Rare gas systematics on Mid Atlantic Ridge (37–40°N). *Earth and Planetary Science Letters*, **198**:401–416, (2002).

270 [20] Müller, R. D. et al. A Global Plate Model Including Lithospheric Deformation Along Major Rifts and Orogens
271 Since the Triassic. *Tectonics*, **38**:1884–1907, (2019).

272 [21] Chang, S. J., Ferreira, A. M. G., Ritsema, J., Heijst, H. J. V., and Woodhouse, J. H. Joint inversion for
273 global isotropic and radially anisotropic mantle structure including crustal thickness perturbations. *Journal of*
274 *Geophysical Research: Solid Earth*, **120**:4278–4300, (2015).

275 [22] Hoggard, M. J., Winterbourne, J., Czarnota, K., and White, N. Oceanic residual depth measurements, the
276 plate cooling model, and global dynamic topography. *Journal of Geophysical Research: Solid Earth*, **122**:
277 2328–2372, (2017).

278 [23] Geldmacher, J., Hoernle, K., Bogaard, P. V., Duggen, S., and Werner, R. New $^{40}\text{Ar} / ^{39}\text{Ar}$ age and geo-
279 chemical data from seamounts in the Canary and Madeira volcanic provinces: Support for the mantle plume
280 hypothesis. *Earth and Planetary Science Letters*, **237**:85–101, (2005).

281 [24] Beier, C., Haase, K. M., and Hansteen, T. H. Magma evolution of the Sete Cidades volcano, São Miguel,
282 Azores. *Journal of Petrology*, **47**:1375–1411, (2006).

283 [25] Civiero, C. et al. A common deep source for upper-mantle upwellings below the Ibero-western Maghreb region
284 from teleseismic P-wave travel-time tomography. *Earth and Planetary Science Letters*, **499**:157–172, (2018).

285 [26] Civiero, C. et al. Thermal Nature of Mantle Upwellings Below the Ibero-Western Maghreb Region Inferred
286 From Teleseismic Tomography. *Journal of Geophysical Research: Solid Earth*, **124**:1781–1801, (2019).

287 [27] Saki, M., Thomas, C., Nippres, S. E., and Lessing, S. Topography of upper mantle seismic discontinuities
288 beneath the North Atlantic: The Azores, Canary and Cape Verde plumes. *Earth and Planetary Science Letters*,
289 **409**:193–202, (2015).

290 [28] Adam, C. et al. Mantle dynamics and characteristics of the Azores plateau. *Earth and Planetary Science*
291 *Letters*, **362**:258–271, (2013).

292 [29] Beier, C., Haase, K. M., and Turner, S. P. Conditions of melting beneath the Azores. *Lithos*, **144-145**:1–11,
293 (2012).

294 [30] Bourdon, B., Turner, S. P., and Ribe, N. M. Partial melting and upwelling rates beneath the Azores from a
295 U-series isotope perspective. *Earth and Planetary Science Letters*, **239**:42–56, (2005).

296 [31] Luis, J. F. and Neves, M. C. The isostatic compensation of the Azores Plateau: A 3D admittance and coherence
297 analysis. *Journal of Volcanology and Geothermal Research*, **156**:10–22, (2006).

298 [32] Neves, M. C., Miranda, J. M., and Luis, J. F. The role of lithospheric processes on the development of linear
299 volcanic ridges in the Azores. *Tectonophysics*, **608**:376–388, (2013).

300 [33] Métrich, N. et al. Is the ‘Azores Hotspot’ a Wetspot? Insights from the Geochemistry of Fluid and Melt
301 Inclusions in Olivine of Pico Basalts. *Journal of Petrology*, **55**:377–393, (2014).

302 [34] Hildenbrand, A., Weis, D., Madureira, P., and Marques, F. O. Recent plate re-organization at the Azores Triple
303 Junction: Evidence from combined geochemical and geochronological data on Faial, S. Jorge and Terceira
304 volcanic islands. *Lithos*, **210-211**:27–39, (2014).

305 [35] Tsekhmistrenko, M. et al. Performance of the 2021-2022 UPFLOW large ocean bottom seismometer array in
306 the Azores-Madeira-Canary Islands region, Atlantic Ocean. *Seismica*, **5**, (2026).

- [36] Montelli, R., Nolet, G., Dahlen, F. A., and Masters, G. A catalogue of deep mantle plumes: New results from finitefrequency tomography. *Geochemistry, Geophysics, Geosystems*, **7**, (2006).
- [37] Witek, M., Lee, S.-M., Chang, S.-J., and Lee, S. V. D. Waveform inversion of large data sets for radially anisotropic Earth structure. *Geophysical Journal International*, **232**:1311–1339, (2022).
- [38] Karato, S.-I., Jung, H., Katayama, I., and Skemer, P. Geodynamic Significance of Seismic Anisotropy of the Upper Mantle: New Insights from Laboratory Studies. *Annual Review of Earth and Planetary Sciences*, **36**: 59–95, (2008).
- [39] Silveira, G. et al. Azores hotspot signature in the upper mantle. *Journal of Volcanology and Geothermal Research*, **156**:23–34, (2006).
- [40] French, S., Lekic, V., and Romanowicz, B. Waveform tomography reveals channeled flow at the base of the oceanic asthenosphere. *Science*, **342**:227–230, (2013).
- [41] Rappisi, F., Witek, M., Faccenda, M., Ferreira, A. M., and Chang, S. J. Artificial age-independent seismic anisotropy, slab thickening and shallowing due to limited resolving power of (an)isotropic tomography. *Geophysical Journal International*, **237**:217–234, (2024).
- [42] Ribeiro, L. P., Martins, S., Hildenbrand, A., Madureira, P., and ao Mata, J. The genetic link between the Azores Archipelago and the Southern Azores Seamount Chain (SASC): The elemental, isotopic and chronological evidences. *Lithos*, **294-295**:133–146, (2017).
- [43] Ono, S., Kikegawa, T., Higo, Y., and Tange, Y. Precise determination of the phase boundary between coesite and stishovite in SiO₂. *Physics of the Earth and Planetary Interiors*, **264**:1–6, (2017).
- [44] Koch-Müller, M. et al. The coesite-stishovite transition of hydrous, Al-bearing SiO₂ : an in situ synchrotron X-ray study. *Eur. J. Mineral*, **36**:1023–1036, (2024).
- [45] Civiero, C. et al. The Role of the Seismically Slow Central-East Atlantic Anomaly in the Genesis of the Canary and Madeira Volcanic Provinces. *Geophysical Research Letters*, **48**:e2021GL092874, (2021).
- [46] Merle, R. E., Jourdan, F., Chiaradia, M., Olierook, H. K., and Manatschal, G. Origin of widespread Cretaceous alkaline magmatism in the Central Atlantic: A single melting anomaly? *Lithos*, **342-343**:480–498, (2019).
- [47] Schilling, J. G. Fluxes and excess temperatures of mantle plumes inferred from their interaction with migrating mid-ocean ridges. *Nature*, **352**:397–403, (1991).
- [48] Hoggard, M. J., Parnell-Turner, R., and White, N. Hotspots and mantle plumes revisited: Towards reconciling the mantle heat transfer discrepancy. *Earth and Planetary Science Letters*, **542**:116317, (2020).
- [49] King, S. D. and Adam, C. Hotspot swells revisited. *Physics of the Earth and Planetary Interiors*, **235**:66–83, (2014).
- [50] Faccenda, M. and Zilio, L. D. The role of solid-solid phase transitions in mantle convection. (2016).

Methods

Partitioned waveform inversion tomography

Our partitioned waveform inversion tomography⁵¹ methodology follows Witek et al.³⁷, which has been demonstrated to recover radial anisotropy and isotropic variations in synthetic tests⁴¹, and has been applied to image subducting slabs and a mantle plume structure in the Coral Sea⁵².

Briefly, the method comprises two stages: retrieving a depth-dependent set of path-averaged model perturbations for each source–receiver pair through waveform fitting, followed by a regularised inversion for 3D structure. The first stage begins by isolating suitable fundamental-mode waveforms in time–frequency windows to fit against fundamental-mode synthetics, resulting in a best fit set of isotropic and anisotropic 1D model perturbations ($\boldsymbol{\gamma}$). This 1D model is used as a starting model to fit full waveform time–frequency windows against a synthetic summed over modes $n = 0$ to 20, from which a final set of 1D model perturbations is determined. If no suitable fundamental-mode time–frequency windows are found, the full waveform is fit using the original starting model (Fig. S21). Perturbations are calculated via a sensitivity kernel averaged from local sensitivity kernels along the ray path through the 3D starting model (SGLOBE-rani; Chang et al.²¹).

The misfit $F_i(\boldsymbol{\gamma})$ for each time–frequency window is defined as:

$$F_i(\boldsymbol{\gamma}) = \frac{\int_{t_i} w_i(t) [d(t) - u(\boldsymbol{\gamma}, t)]^2 dt}{\int_{t_i} w_i(t) d(t)^2 dt} \quad (1)$$

where $w_i(t)$ is a weighting term calculated per window to equalise the effect of high and low amplitude wave groups, and $u(\boldsymbol{\gamma}, t)$ and $d(t)$ are normalized synthetic and normalized data traces, respectively.

We seek a set of perturbations ($\boldsymbol{\gamma}$) of the model parameters:

$$V_S^2 = \frac{1}{2}(V_{SH}^2 + V_{SV}^2) \quad (2)$$

$$\zeta_S = \frac{V_{SH}^2 - V_{SV}^2}{2V_S^2} \quad (3)$$

We convert ζ_S to $\xi = (\frac{V_{SH}}{V_{SV}})^2$ for the purpose of plotting our anisotropic images. For each linearly independent combination of parameters derived from the path-averaged 1D models, we determine uncertainties by automatically selecting a waveform-misfit cut-off that defines a confidence region for that parameter combination. We do not invert for density ρ or isotropic P-wave velocity V_P , but fix them proportionally to V_S variations using the same scaling relationships as used by Chang et al.²¹:

$$\frac{d \ln \rho}{d \ln V_S} = 0.4 \quad (4)$$

$$\frac{d \ln V_P}{d \ln V_S} = 0.5 \quad (5)$$

We combine linearly independent combination of 1D model parameters from the first stage, down-weighted by their uncertainties, into a LSQR inversion to invert for a set of 3D model parameters $\boldsymbol{\mu}$. We include the additional cost terms $\lambda_D^2 |\boldsymbol{I}\boldsymbol{\mu}|^2$ and $\lambda_F^2 |\boldsymbol{F}\boldsymbol{\mu}|^2$, which regularise the 3D inversion by penalising the model norm and model gradient through tuning λ_D and λ_F , respectively. This is referred to as damping and flattening the inversion, respectively. $\boldsymbol{I}$ is the identity matrix and $\boldsymbol{F}$ is a horizontal gradient operator to flatten $\boldsymbol{\mu}$.

As the inversion is linearized, a robust 3D starting model is required; we use SGLOBE-rani²¹, which incorporates both anisotropic and isotropic structure and shows good isotropic V_S agreement with previous local and global studies²¹ (see Supplementary Figures S22–S26). Due to elevated noise levels of short period seismic data across

the Atlantic, the maximum overtone fitting frequency was lowered to 0.0625 Hz. The number of depth splines was also increased to 32 to better resolve shallow features at fine lateral scales. As one depth spline is at 0.0 km we allow inversion for crustal structure to avoid leakage effects.

Suitable regularisation parameters for the 3D inversion are determined through L-curve analysis, which balances model norm against variance reduction, followed by visual inspection of the damping and flattening parameter space (Supplementary Figures S14 -S16). Our preferred model uses a damping parameter of 0.02, with flattening parameters of 0.01 and 0.015 for the isotropic and anisotropic structure, respectively.

Data

Three-component data from 440 stations and 435 events are used, yielding 20,491 successfully fit fundamental time-frequency windows and 125,854 successfully fit full waveform windows (Supplementary Figure S2) from 6,959 ray paths (Supplementary Figure S1). Events were selected in the magnitude range $M_w \sim 5.5\text{--}8.0$ for epicentral distances of $45\text{--}65^\circ$. Smaller magnitude events (M_w 4.5–8.0) were additionally included for paths shorter than 45° to maximise ray coverage, and long paths of $65\text{--}100^\circ$ were also incorporated; both were quality-checked visually. Good ray coverage is achieved across the UPFLOW array⁵³ and around the Canary Islands (Supplementary Figure S3a), though azimuthal distribution is uneven, with ray paths predominantly trending from Central and South America to our study region (Supplementary Figures S3b)). To mitigate smearing effects, similar ray paths are clustered and down-weighted prior to the 3D inversion following Witek et al.³⁷.

Resolution tests

Checkerboard and realistic structure tests were performed using the data coverage of our preferred model to identify regions of robust retrieval. For the sparse checkerboard tests, a synthetic model was constructed comprising sinusoidal positive and negative anomalies of 2° lateral extent and 100 km thickness, with maximum amplitudes of $\pm 5\%$, placed at 50 km lateral spacing. Anomalies were specified as either purely isotropic or purely anisotropic. Synthetic data vectors were generated by multiplying the synthetic model by the sensitivity matrix of the preferred tomographic model, and Gaussian noise estimated from the uncorrelated uncertainties of the observed data vector was added prior to inversion. The resulting synthetic data were then inverted using identical regularisation to the preferred model. Isotropic checkerboard retrieval beneath the study region is shown in Supplementary Figure S5. Anomalies beneath the UPFLOW array are well recovered, with minimal streaking and strong amplitude retrieval. Beneath the Canaries, retrieval remains good with minimal streaking, though amplitude recovery is slightly reduced. Outside the main study region, streaking becomes apparent. Anisotropic retrieval shows the same spatial patterns of recovery (Supplementary Figure S7). Leakage between isotropic and anisotropic structure is minimal, not exceeding 1.55% (Supplementary Figures S6 and S8). Two additional plume-geometry tests were performed. The first placed columns of negative isotropic anomalies (maximum -5%, tapering radially with a Gaussian profile) beneath Madeira, the Canaries, and the Azores. The second placed positive ζ_S anomalies (+5%) in columns below 200 km depth and negative anomalies (-5%) in broader columns between 50 and 150 km depth. These tests demonstrate that plumes beneath the Canaries and Madeira can be retrieved as distinct structures with minimal smearing (Supplementary Figures S9 and S11). Spurious retrieval of anisotropic structure is very low (Supplementary Figure S10). The negative ζ_S columns are well recovered (Supplementary Figures S11), and while some smearing of the positive ζ_S layers is apparent, likely reflecting their large lateral extent, the primary feature is retrieved robustly and spurious amplitudes remain low. Leakage of isotropic structure is very low (Supplementary Figure S12). Finally, the preferred tomographic model itself was used as the input (with Gaussian noise added as explained above) for a more complex test (Supplementary Figure S13). The main features are well recovered, with only minor distortion of anomaly shape and amplitude.

Data availability. This study utilised UPFLOW data, which are deposited in the GFZ EIDA node⁵⁴ (network 8J, data embargoed until May 2028). We are grateful to all the institutions that contributed instruments to the UPFLOW experiment: 32 OBSs were rented from the DEPAS international pool of instruments maintained by the Alfred Wegener Institute (Bremerhaven), Germany (<https://www.awi.de/en/science/geosciences/geophysics/methods-and-tools/ocean-bottom-seismometer/depas.html>), while additional instruments were borrowed from other institutions, 7 from DIAS' iMARL OBS pool (<https://geohub.dias.ie/imarl/>), 4 from IDL, 3 from ROA-UCM, and 4 from GEOMAR. We are also grateful to IPMA (co-beneficiary of the UPFLOW project), who made the research vessel NI Mário Ruivo (<https://marioruivo.ipma.pt/en/home-page/>) available for the UPFLOW experiment. We also used data from other land and OBS stations around the UPFLOW study region: 3C, 9A, 9H, BL, C8, CM, CN, CU, DK, EI, ES, FR, GB, GE, IB, II, IP, IU, LX, N4, NA, NE, PM, PR, RA, RD, SS, TA, TR, UK, US, VE, VI, WC, WI, X8, Y6, YW and Z4.

Code availability. All the figures in this paper were produced with pyvista⁵⁵ and pyGMT⁵⁶. The computing codes and relevant scripts used in this study are available upon reasonable request from the corresponding author.

Supplementary Information Supplementary Information is available for this paper.

Corresponding author. Correspondence and requests for materials should be addressed to K.M.H. (katrina.harris.19@ucl.ac.uk).

Acknowledgments. This work was supported by the UPFLOW project, funded by the European Research Council under the European Union's Horizon 2020 research and innovation program (grant agreement No 101001601).

Competing interests. The authors declare no competing interests.

Author contributions. Conceptualisation: K.M.H., A.M.G.F., M.W., M.B., S.-J.C. and M.M. Methodology: K.M.H., A.M.G.F., M.W., M.B. and S.-J.C. Software: K.M.H., M.W. Validation: K.M.H., M.W., S.-J.C. Formal analysis: K.M.H. Investigation: K.M.H., A.M.G.F., M.W., M.B., S.-J.C. and M.M. Data curation: K.M.H., A.M.G.F. Writing original draft: K.M.H., A.M.G.F. Writing review and editing: K.M.H., A.M.G.F., M.W., M.B., S.-J.C. and M.M. Visualisation: K.M.H., M.W. Supervision: A.M.G.F. and M.B. Project administration: K.M.H. and A.M.G.F. Funding acquisition: A.M.G.F. and M.M.

References

- [51] Nolet, G. Partitioned waveform inversion and two-dimensional structure under the network of autonomously recording seismographs. *Journal of Geophysical Research: Solid Earth*, **95**:8499–8512, (1990).
- [52] Park, J. H. and Chang, S. J. Low-velocity anomaly in the Coral Sea associated with subducting slabs and the Woodlark rift. *Communications Earth & Environment* 2025 6:1, **6**:1–9, (2025).
- [53] Ferreira, A. M. G. et al. Charting the mantle. *Astronomy & Geophysics*, **67**:2.35–2.40, (2026).
- [54] Ferreira, A. M. G. Upward mantle flow from novel seismic observations (UPFLOW), *GFZ Data Services*, <https://doi.org/10.14470/3W055238>, (2024).
- [55] Sullivan, B. and Kaszynski, A. PyVista: 3D plotting and mesh analysis through a streamlined interface for the Visualization Toolkit (VTK). *Journal of Open Source Software*, **4**(37):1450, (2019).

456 [56] Tian, D. et al. PyGMT: Bridging python and the generic mapping tools for geospatial visualization and
457 analysis. *Geochemistry, Geophysics, Geosystems*, **27**:e2026GC013105, (2026).

Supplementary Information for "Azores–Canaries mantle plume
interactions revealed by seismic imaging"

Katrina M Harris, Ana MG Ferreira, Michael Witek, Maxim Ballmer, Sung-Joon Chang, Miguel Miranda

June 2025

1 Data and Coverage

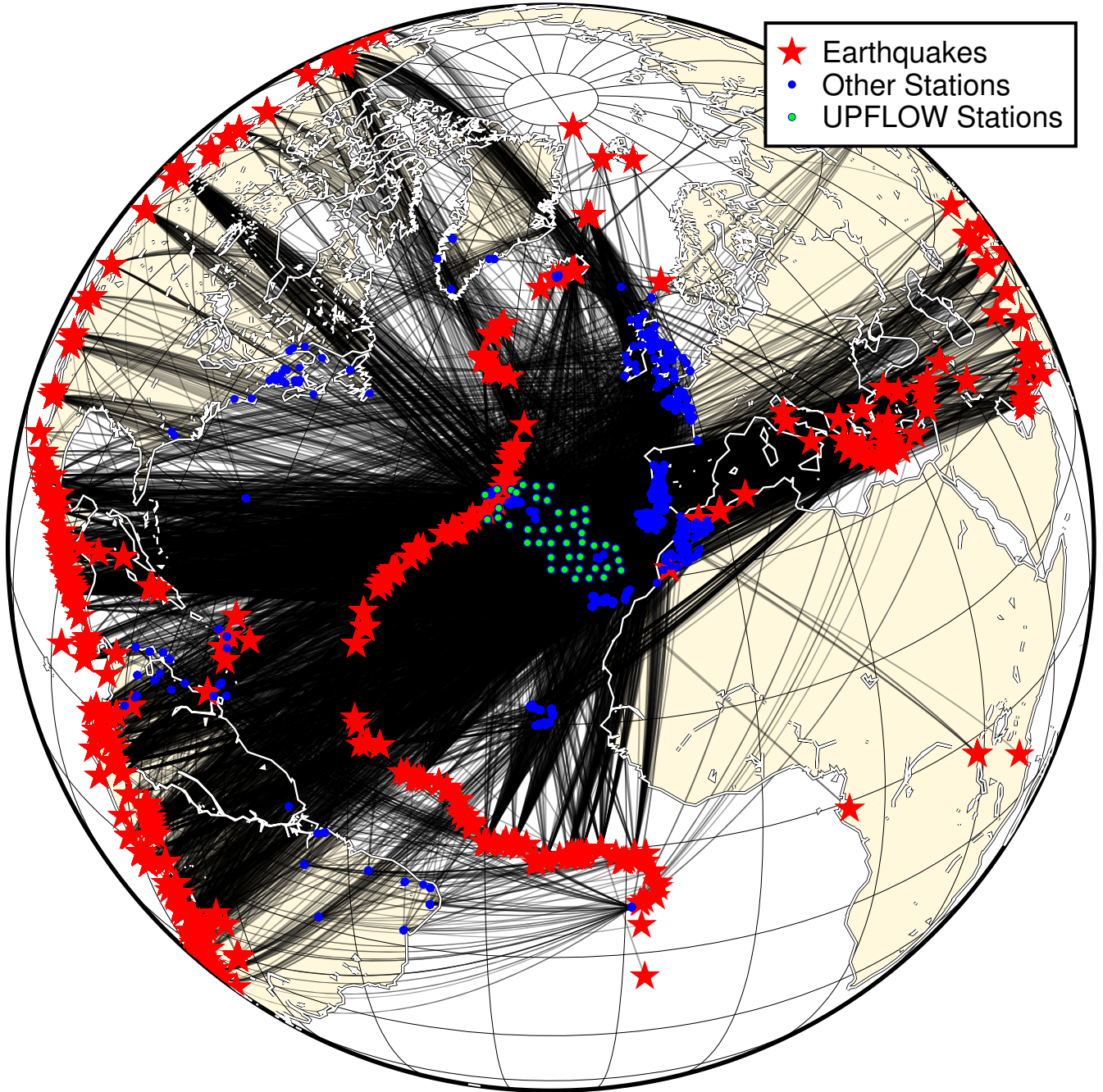


Figure S1: **Total ray coverage.** Ray paths (black lines), earthquakes (red stars) and stations used in the final inversion. The cyan circles correspond to UPFLOW stations while the dark blue circles correspond to land and OBS stations around the UPFLOW region with network codes 3C, 9A, 9H, BL, C8, CM, CN, CU, DK, EI, ES, FR, GB, GE, IB, IL, IP, IU, LX, N4, NA, NE, PM, PR, RA, RD, SS, TA, TR, UK, US, VE, VI, WC, WI, X8, Y6, YW and Z4.

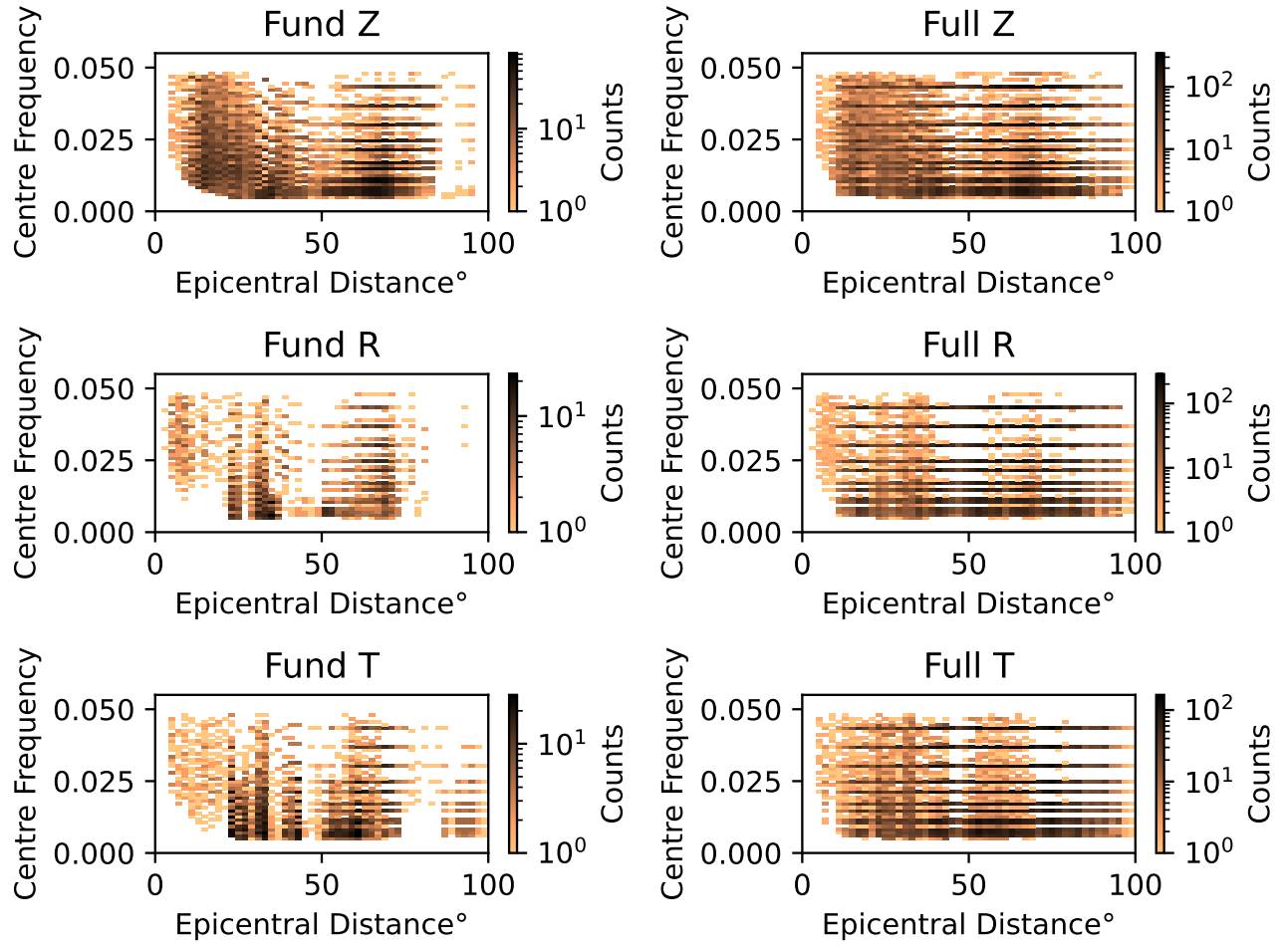
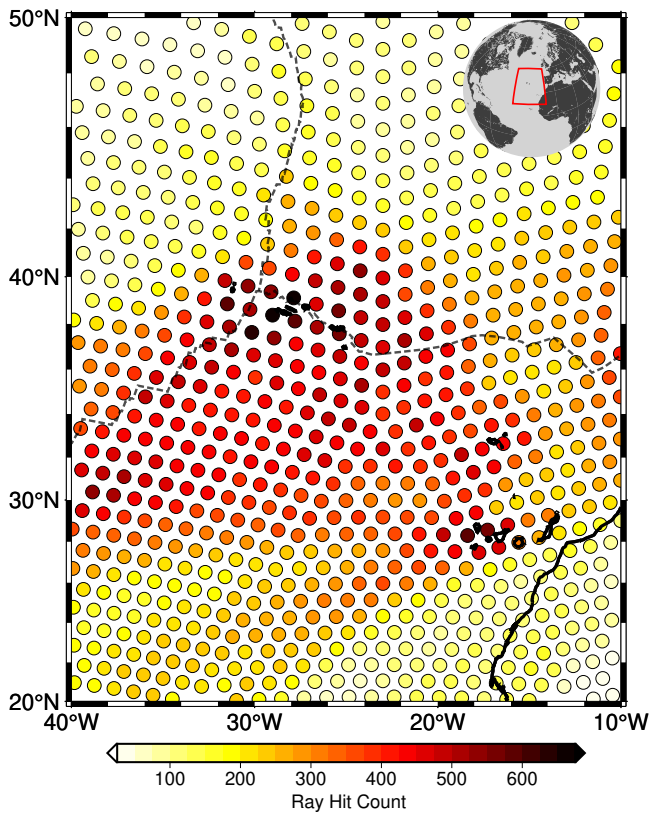


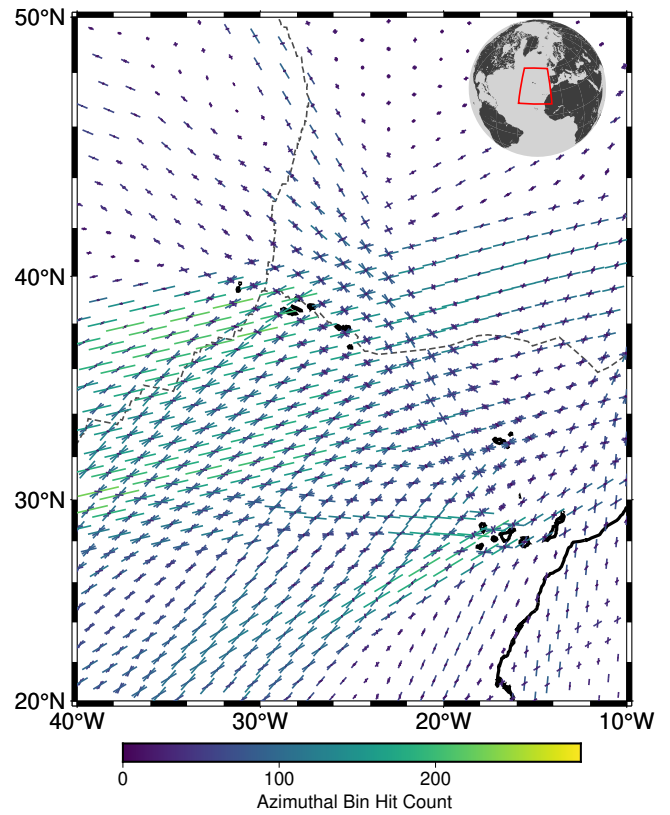
Figure S2: **Distribution of three-component time–frequency windows used in the final inversion.** Histograms of time–frequency windows plotted against epicentral distance, with fundamental-mode windows shown on the left and full-waveform time–frequency windows shown on the right.

Regional Ray Hit Count



(a) Ray-hit count at each grid point in the regional domain, showing the number of ray paths crossing each node.

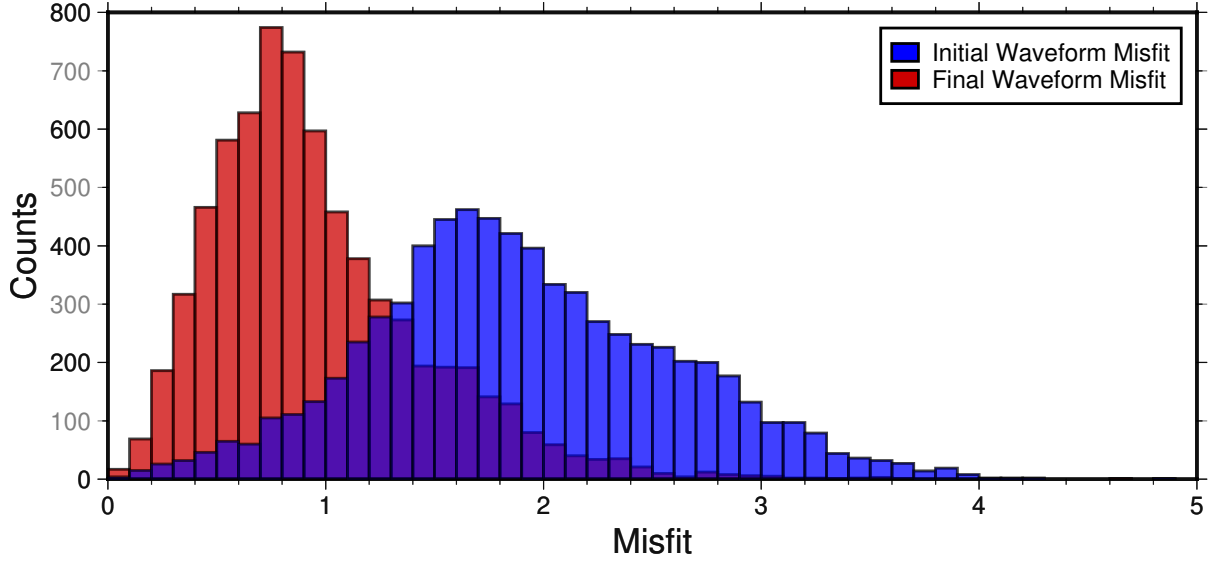
Regional Azimuthal Direction



(b) Azimuthal ray coverage at regional grid points. Each line represents an 18°-wide azimuthal bin, with line length and colour indicating the number of rays crossing that grid point within that bin.

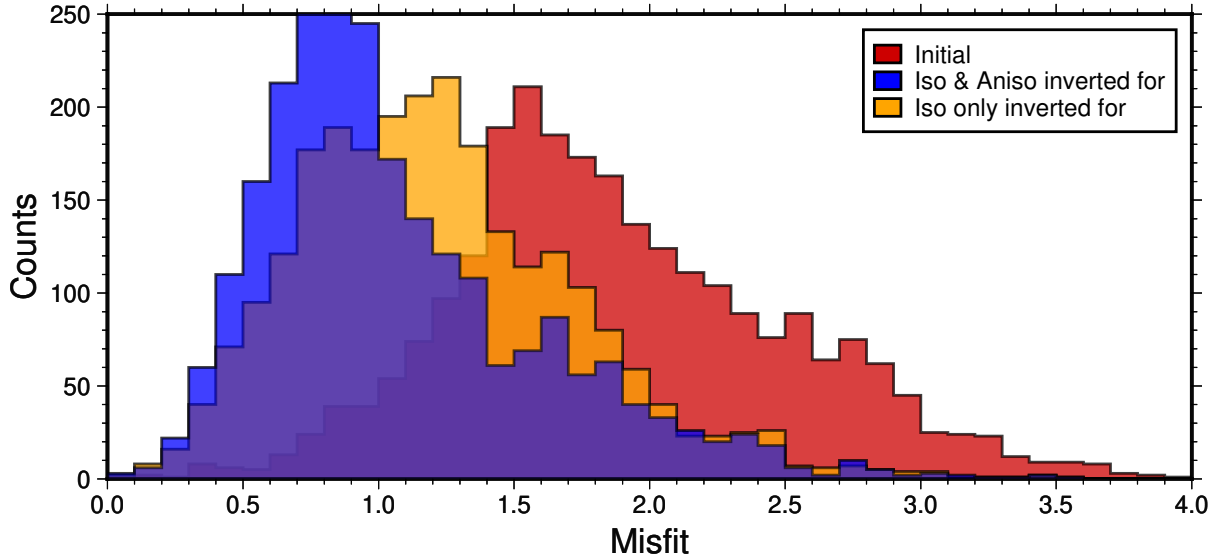
Figure S3: Regional ray coverage.

Waveform Misfit



(a) Improvement in waveform misfit before and after the 1D fitting process, for all paths used in the final inversion, inverting jointly for anisotropic and isotropic structure.

Anisotropic contribution to Waveform Misfit



(b) Comparison of waveform misfit improvement when inverting jointly for anisotropic and isotropic structure versus isotropic-only (V_S) structure. Only waveforms with both Rayleigh and Love wave information were included. Misfits are shown before and after the 1D fitting process.

Figure S4: **Histograms of waveform misfit.** Misfit is defined per path, using the retrieved best-fit model parameters γ , by $F(\gamma) = \frac{1}{2N_L} \sum_i F_i^L(\gamma) + \frac{1}{2N_R} \sum_i F_i^R(\gamma)$, where N_R and N_L are the number of Rayleigh and Love windows, respectively, included in the summation coefficients to equalise the contribution of Love and Rayleigh waves (if both are present in the 1D waveform fitting), and $F_i(\gamma)$ is defined as $F_i(\gamma) = \frac{\int_{t_i} w_i(t) [d(t) - u(\gamma, t)]^2 dt}{\int_{t_i} w_i(t) d(t)^2 dt}$, where $w_i(t)$ is a weighting term, calculated per window to equalise the effect of high- and low-amplitude wave groups, and $u(\gamma, t)$ and $d(t)$ are the normalized synthetic and data traces, respectively.

2 Resolution Tests

2.1 V_S Chequerboard Tests (2 Degrees)

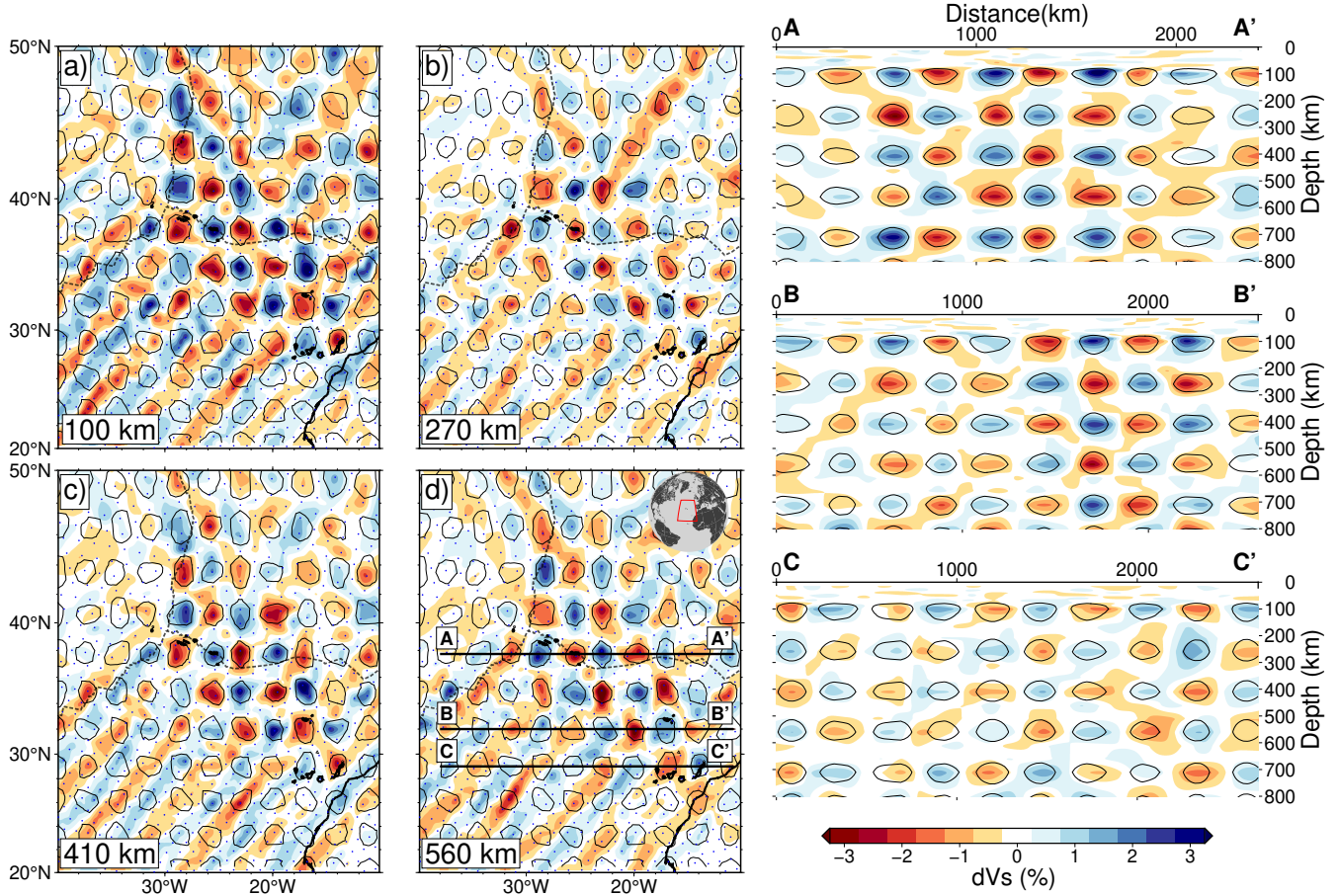


Figure S5: **Sparse chequerboard resolution test (Isotropic V_S)**. Recovered V_S from inversion of a synthetic input model containing a sparse chequerboard pattern of $\pm 5\%$ sinusoidal V_S anomalies. Black contour is of input $\pm 1\%$ V_S . Recovered isotropic V_S is shown in colour as a percent perturbation relative to the starting 3D model, SGLOBE-rani. Blue dots correspond to the surface locations of the inversion grid nodes.

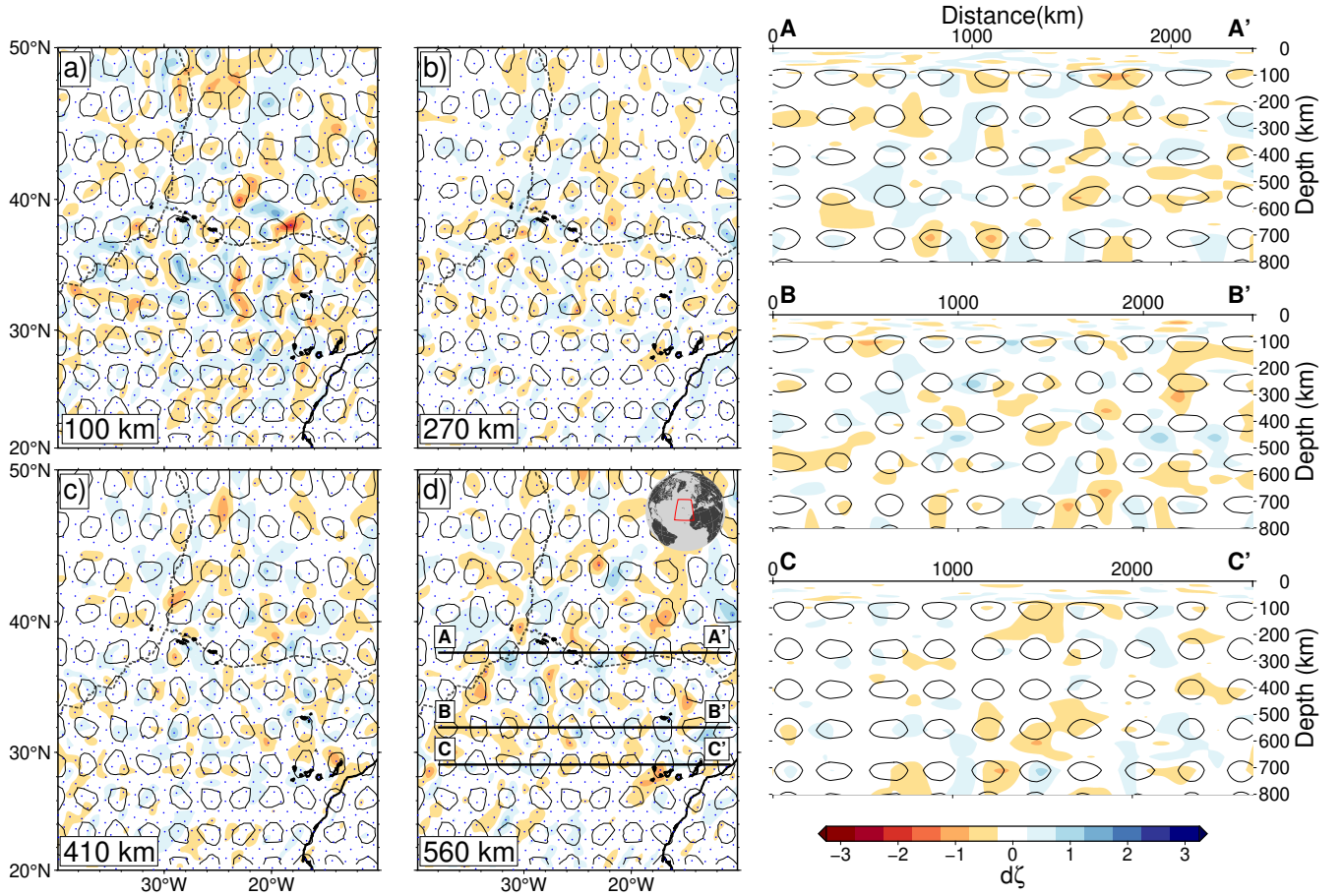


Figure S6: **Testing anisotropic leakage from sparse isotropic input chequerboard model.** Anisotropic ζ_S output from synthetic inversion using as input a sparse isotropic chequerboard model with $\pm 5\%$ sinusoidal V_S anomalies and with no input variations in anisotropy. Black contour is of input $\pm 1\%$ V_S . The retrieved anisotropic structure shown here is due to leakage from the input isotropic structure. The random and weak nature of the retrieved anomalies indicate negligible leakage. $\zeta_S = \frac{V_{SH}^2 - V_{SV}^2}{2V_S^2}$, and $d\zeta$ is shown as the perturbation relative to the starting 3D model, SGLOBE-rani. Blue dots correspond to the surface locations of the inversion grid nodes.

2.2 ζ Chequerboard Tests (2 Degrees)

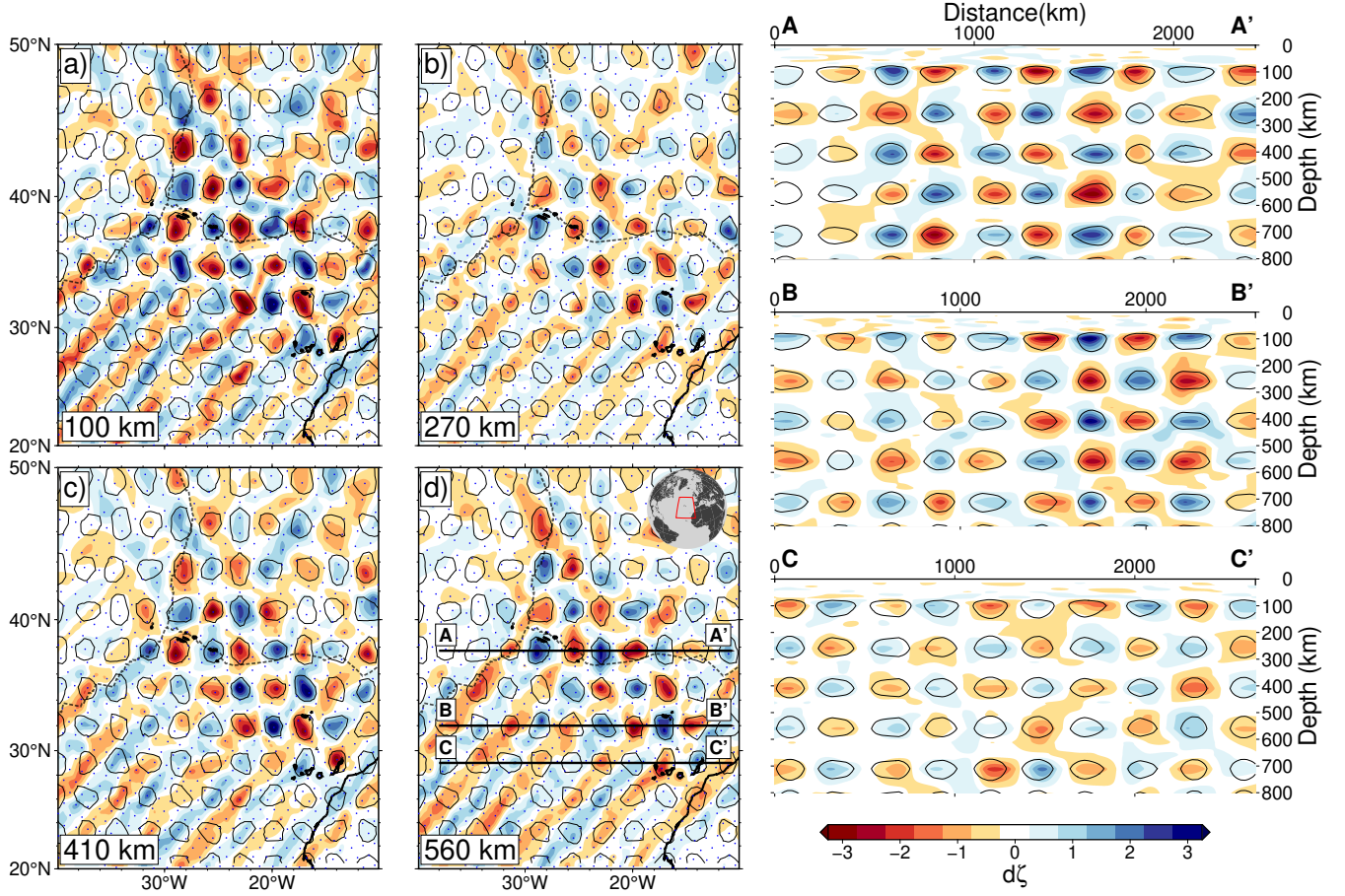


Figure S7: **Sparse chequerboard resolution test (Anisotropy ζ)**. Recovered ζ_S from inversion of a synthetic input model containing a sparse chequerboard pattern of ± 5 sinusoidal ζ_S anomalies. Black contour is of input $\pm 1\%$ ζ_S . $\zeta_S = \frac{V_{SH}^2 - V_{SV}^2}{2V_S^2}$, and $d\zeta$ is plotted with respect to SGLOBE-rani. Blue dots correspond to the surface locations of the inversion grid nodes.

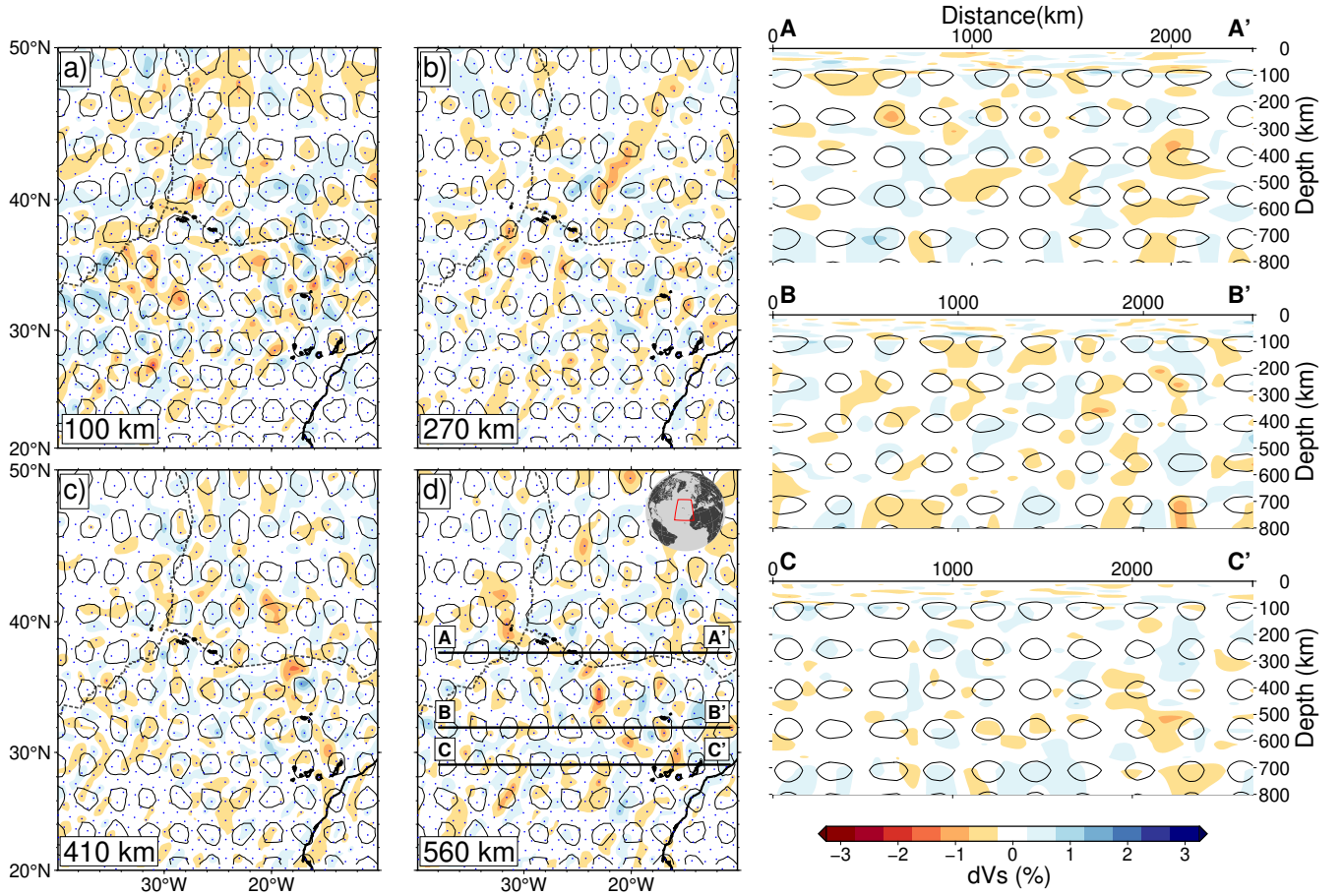


Figure S8: **Testing isotropic leakage from sparse anisotropic input chequerboard model.** Isotropic V_S output from synthetic inversion using as input a sparse anisotropic chequerboard model with $\pm 5\%$ sinusoidal ζ_S anomalies and with no input variations in isotropic V_S . Black contour is of input $\pm 1\%$ ζ_S . The retrieved isotropic structure shown here is due to leakage from the input anisotropic structure. The random and weak nature of the retrieved anomalies indicate negligible leakage. Isotropic V_S is plotted in perturbations from starting 3D model SGLOBE-rani. Blue dots correspond to the surface locations of the inversion grid nodes.

2.3 Simple mantle plume-like, column resolution tests

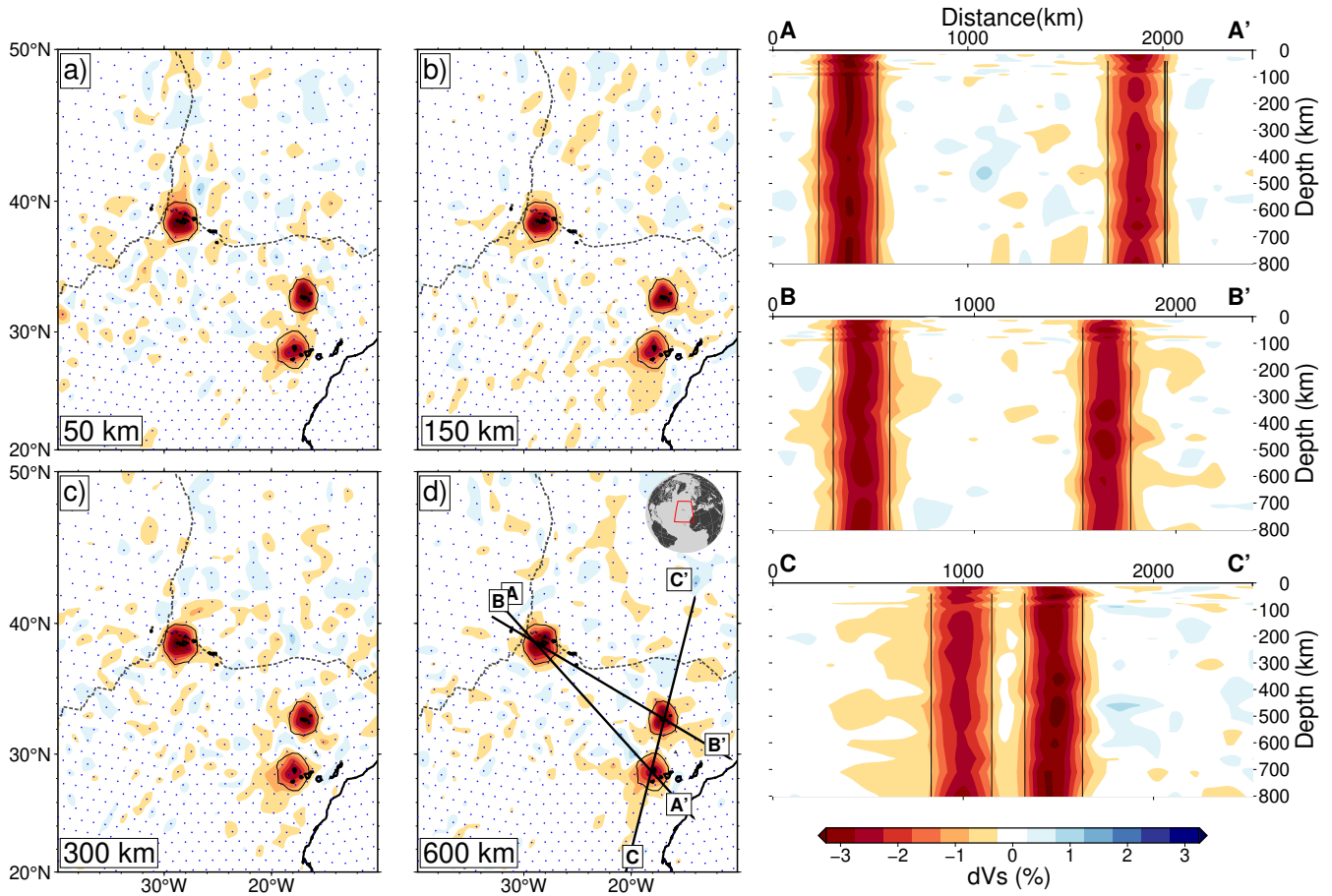


Figure S9: **Simple plume structure resolution test (Isotropic V_S).** V_S output of resolution test using as input three Gaussian columns underneath the Azores, Canaries and Madeira. Each column has a maximum amplitude of -5% in V_S and a rapid spatial decay. Black contour is of input -1% V_S , which captures the bulk of the input Gaussian column, effectively delineating the region where the perturbation remains appreciable. The retrieved isotropic V_S is plotted in perturbations from starting 3D model SGLOBE-rani. Blue dots correspond to the surface locations of the inversion grid nodes.

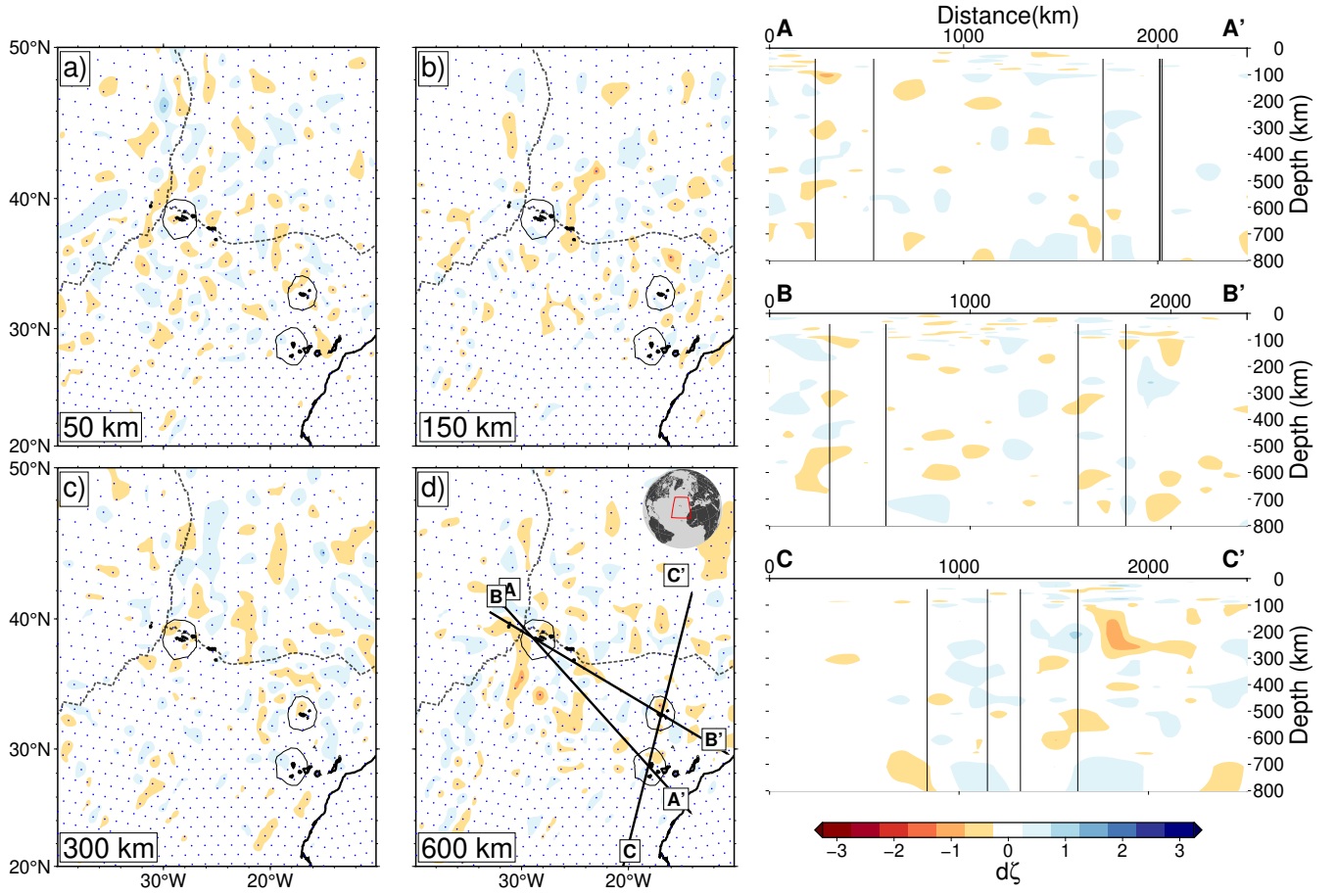


Figure S10: **Simple plume structure resolution test checking leakage of isotropic to anisotropic structure.** ζ_S output of synthetic inversion resolution test with the same setup as in Fig. S9, with no variations in ζ in the input model. The retrieved anisotropic structure shown is due to leakage from the input isotropic structure. The random and weak nature of the retrieved anomalies indicate negligible leakage. $\zeta_S = \frac{V_{SH}^2 - V_{SV}^2}{2V_S^2}$, and $d\zeta$ is plotted with respect to SGLOBE-rani. Blue dots correspond to the surface locations of the inversion grid nodes.

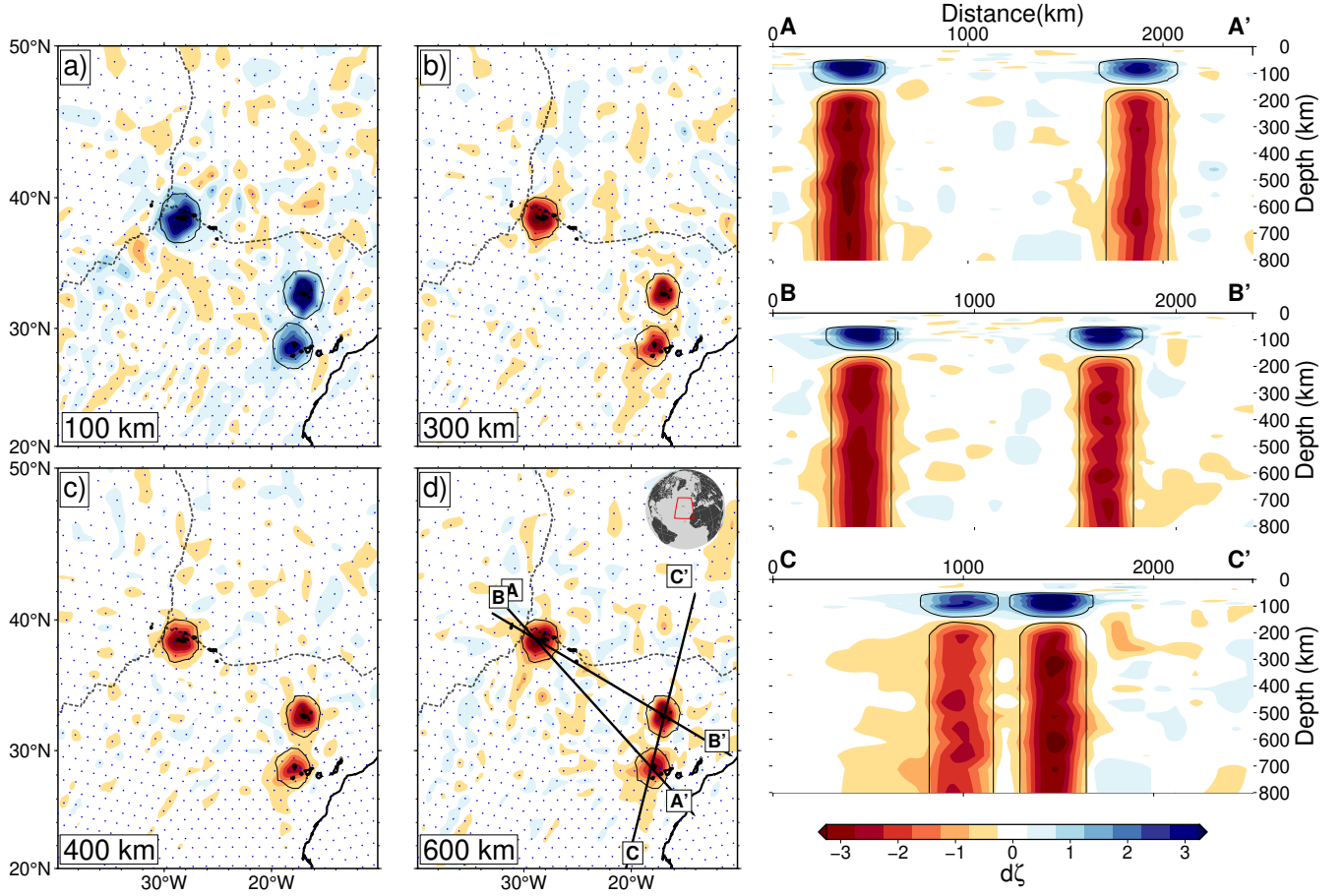


Figure S11: **Simple plume structure resolution test (Anisotropy)**. Similar test as in Fig. S9, but with input of anisotropic structure of $\pm 5\%$ stacked Gaussian column ζ_S anomalies underneath Azores, Canaries and Madeira. Black contour is of input $\pm 1\%$ ζ_S . $\zeta_S = \frac{V_{SH}^2 - V_{SV}^2}{2V_S^2}$.

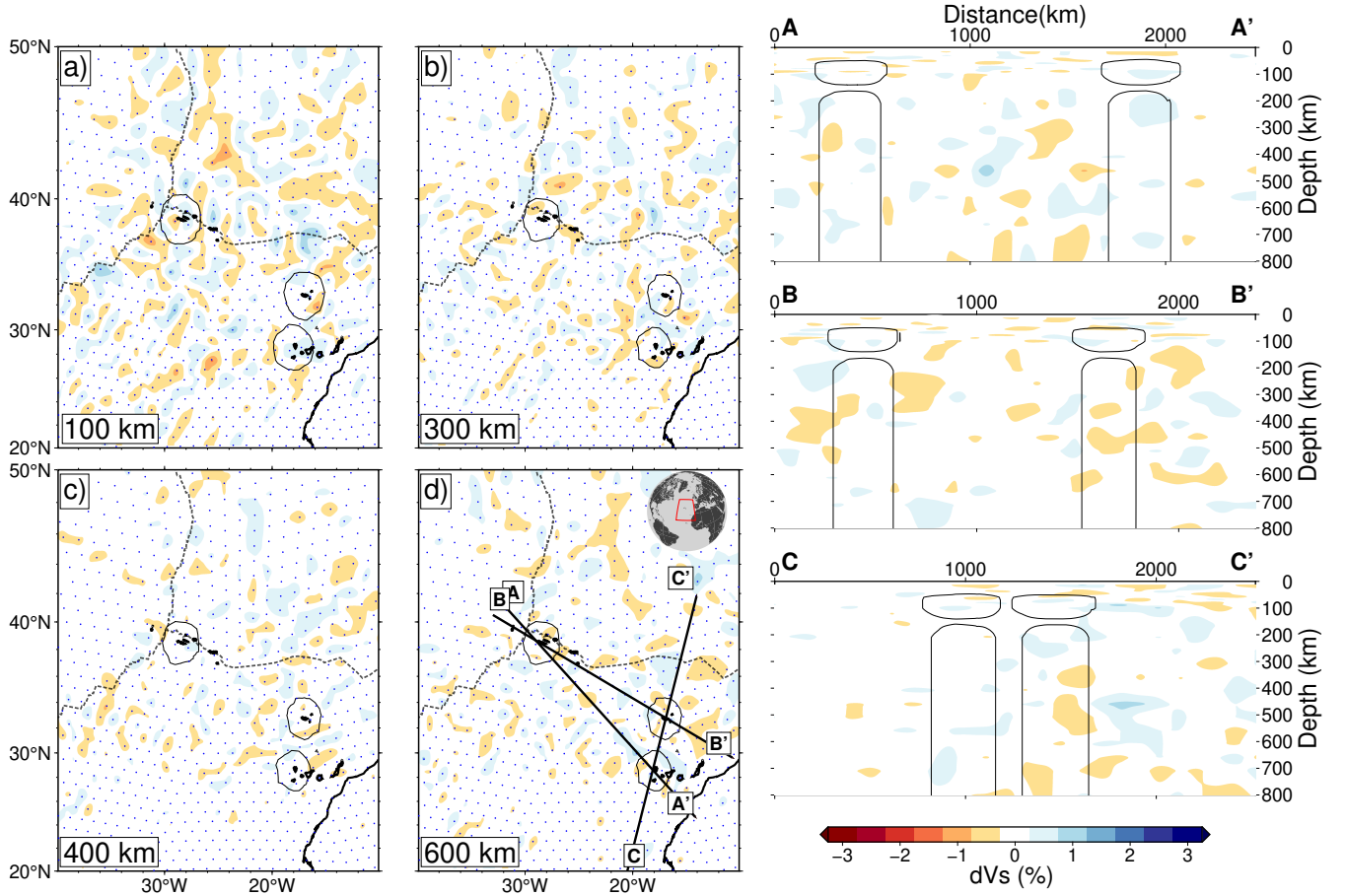


Figure S12: **Simple plume structure resolution test checking leakage of anisotropic to isotropic structure.** Same input as in Fig. S11, but a synthetic inversion showing isotropic V_S structure. The random and weak nature of the retrieved V_S anomalies indicate negligible leakage from anisotropy into isotropic structure.

2.4 Resolution test with realistic input structure: using output model from real data inversion as input model

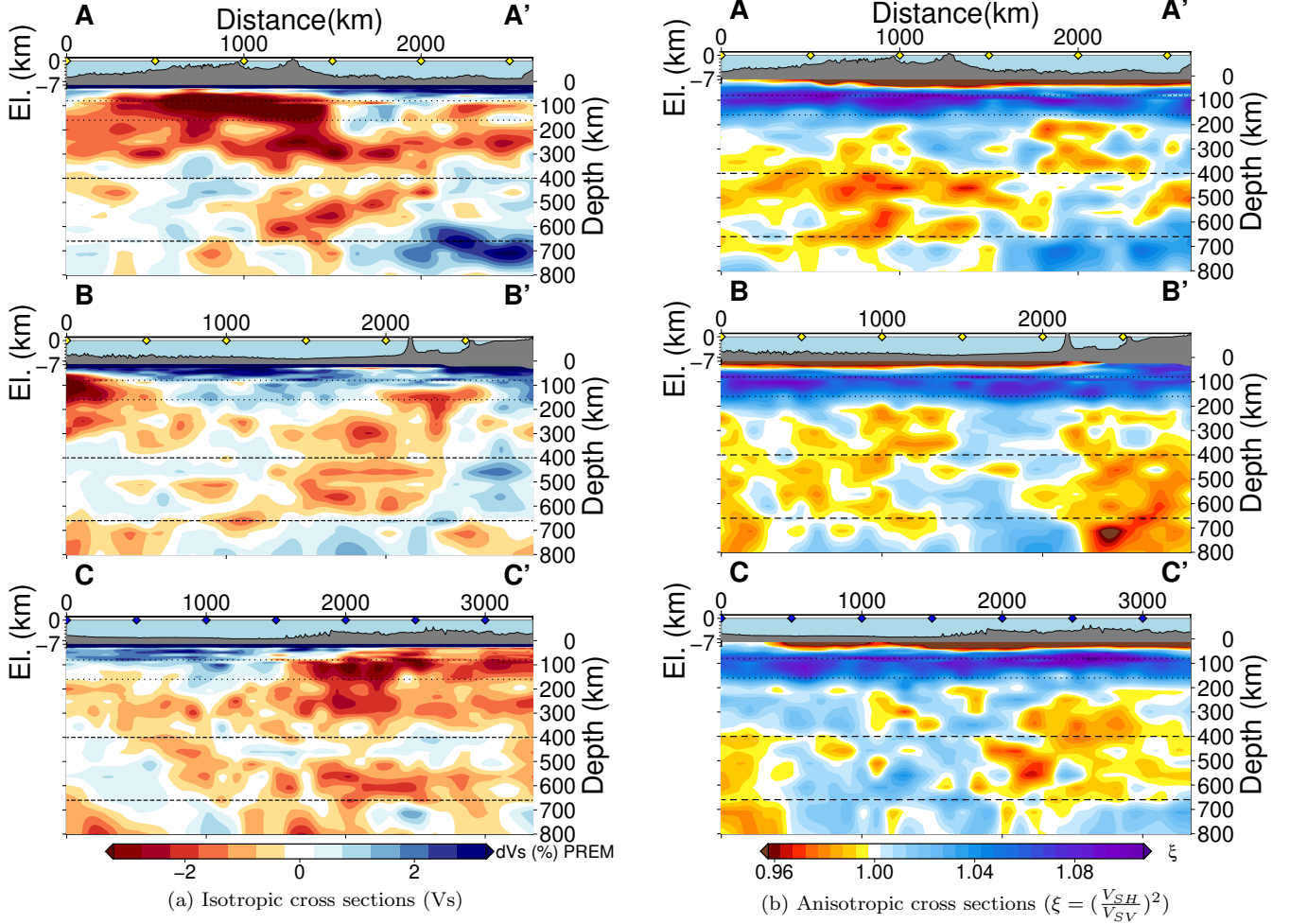


Figure S13: Vertical cross sections of isotropic and anisotropic structure obtained from synthetic inversions using as input model our images obtained from real data 3-D inversions presented (Fig. 3a). Gaussian noise was added to the synthetic data to hinder an entirely circular inversion test. We use a noise level determined by the ratio of the observed-data norm to the uncorrelated-uncertainties norm. Isotropic V_S is plotted in perturbations from PREM. Anisotropy is plotted in $\xi = (\frac{V_{SH}}{V_{SV}})^2$. The retrieved structures agree well with the input model (Fig. 3a), albeit with some additional small-scale structures due to the noise added to the synthetic data.

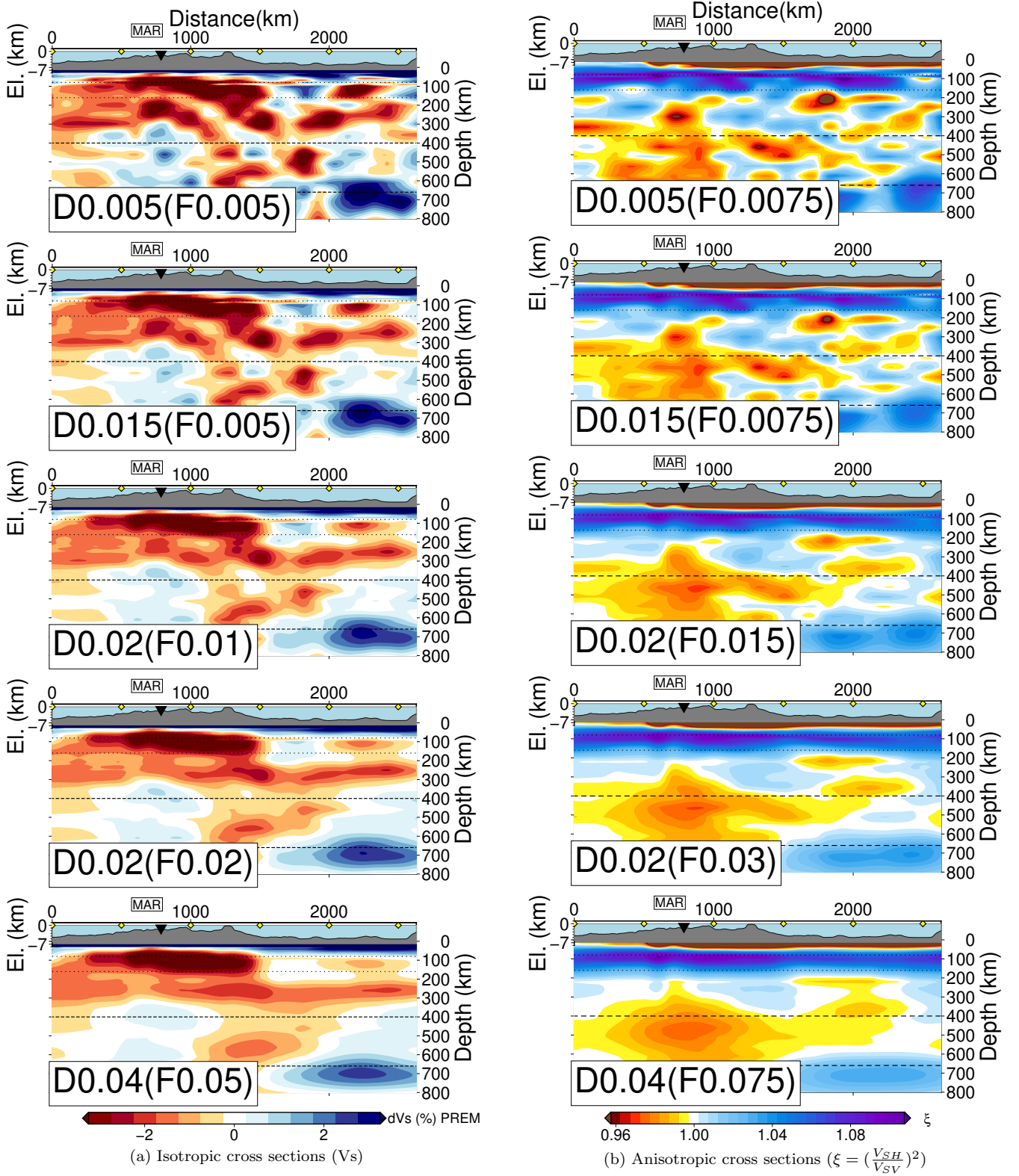


Figure S14: **Effect of regularisation (Azores region).** Vertical cross sections of isotropic and anisotropic structure from real data inversions with increasing regularisation towards the bottom of the figure. Isotropic V_S is plotted in perturbations from PREM. Anisotropy is plotted in $\xi = (\frac{V_{SH}}{V_{SV}})^2$. D= Damping value used to scale term penalising 3D model norm, F= Flattening value used to scale term penalising 3D model gradient, see the Methods section in the main text for more details. Structure is along transect A-A' in Fig S18 f).

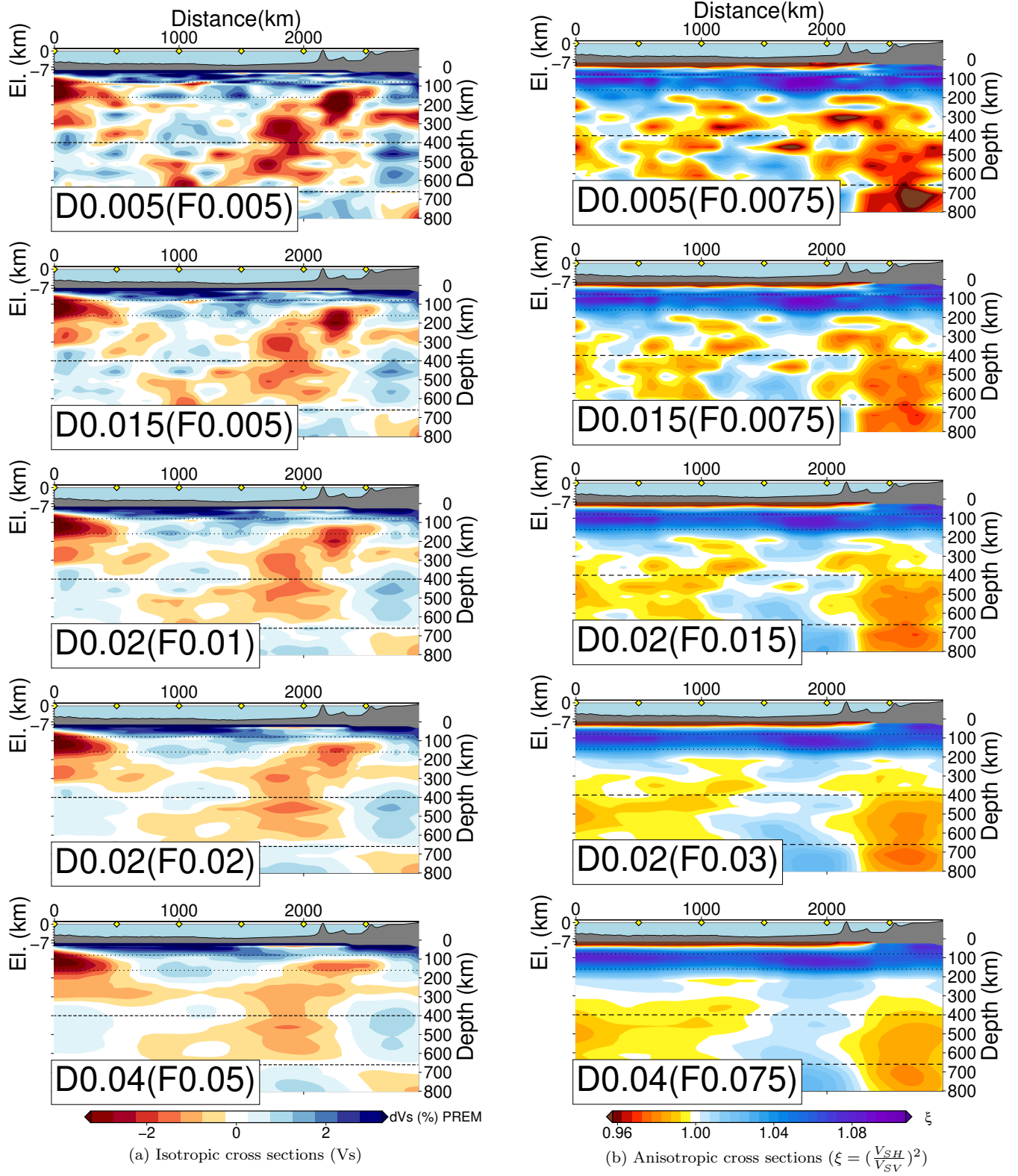


Figure S15: **Effect of regularisation (Canaries region).** Same as in Fig. S14, but for cross sections in the Canary Islands region. Structure is along transects B-B' in Fig S18 f).

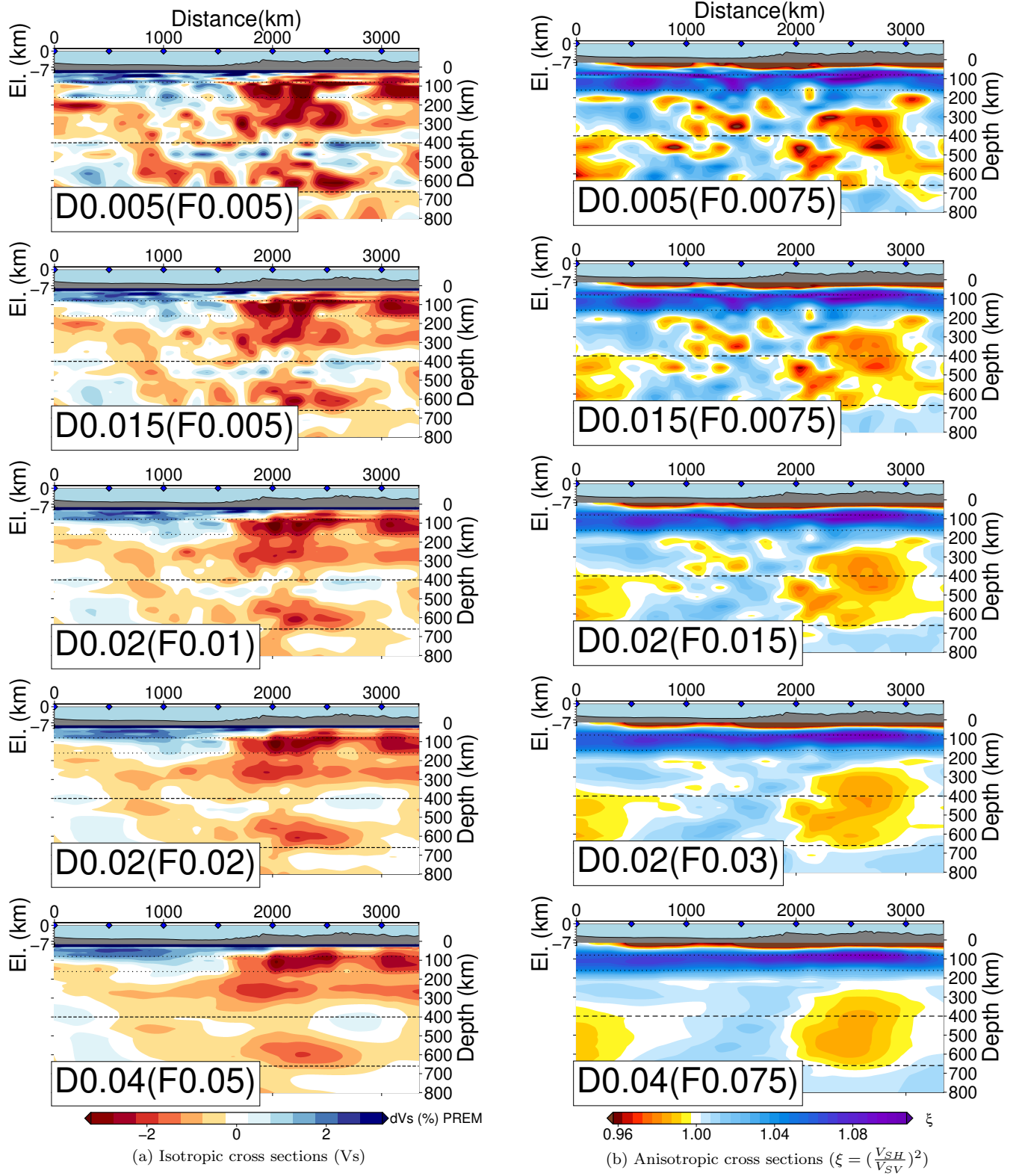


Figure S16: **Effect of regularisation (N-S structure)**. Same as in Fig. S14, but for N-S cross sections in the UPFLOW region region. Structure is along transects C- C' in Fig S18 f).

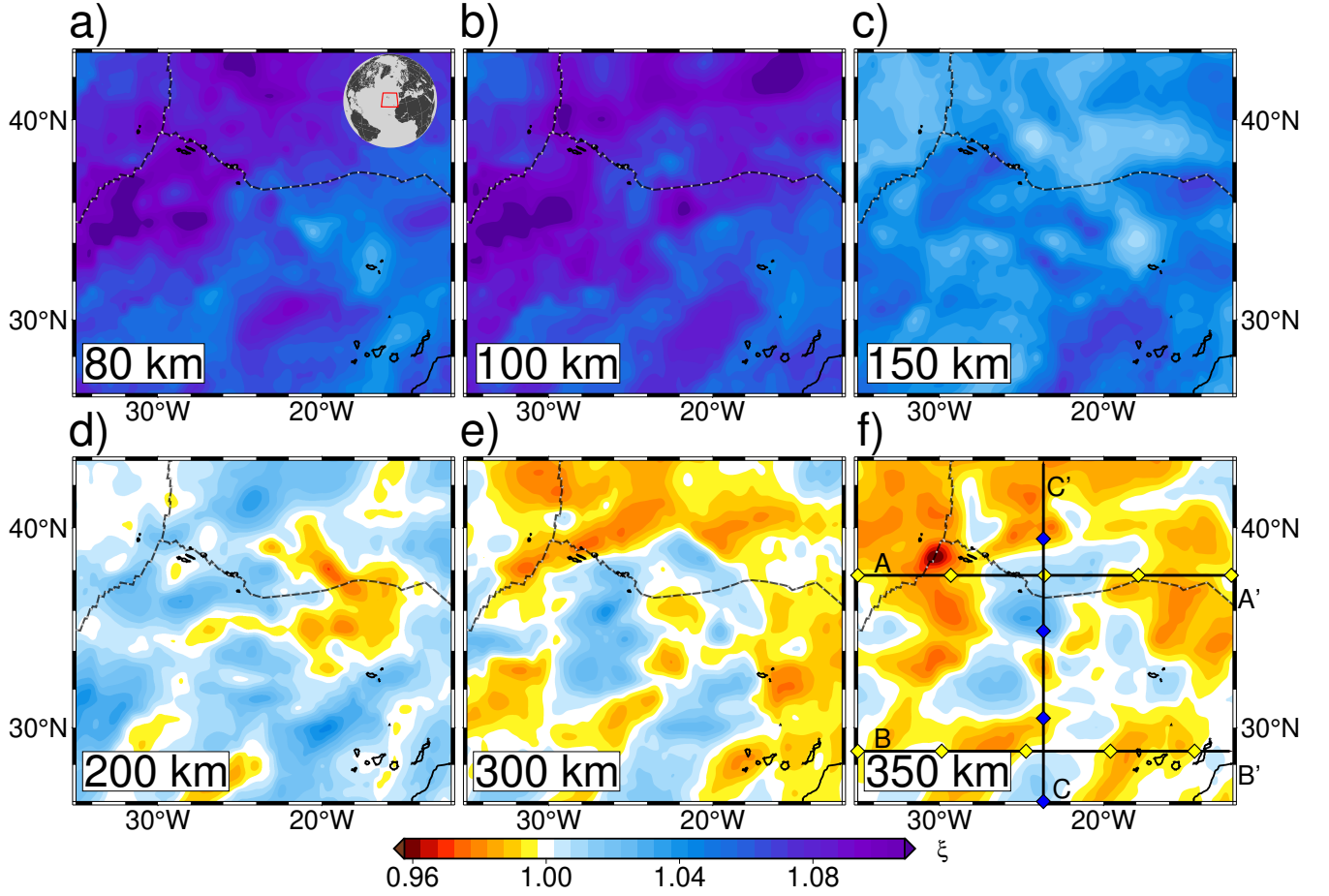


Figure S17: **Anisotropic depth slices.** Additional anisotropic constant depth slices of the final tomographic model, plotted in $\xi = (V_{SH}/V_{SV})^2$. Cross-section lines in panel (f) correspond to the cross sections shown in Fig. 3b) of the main paper.

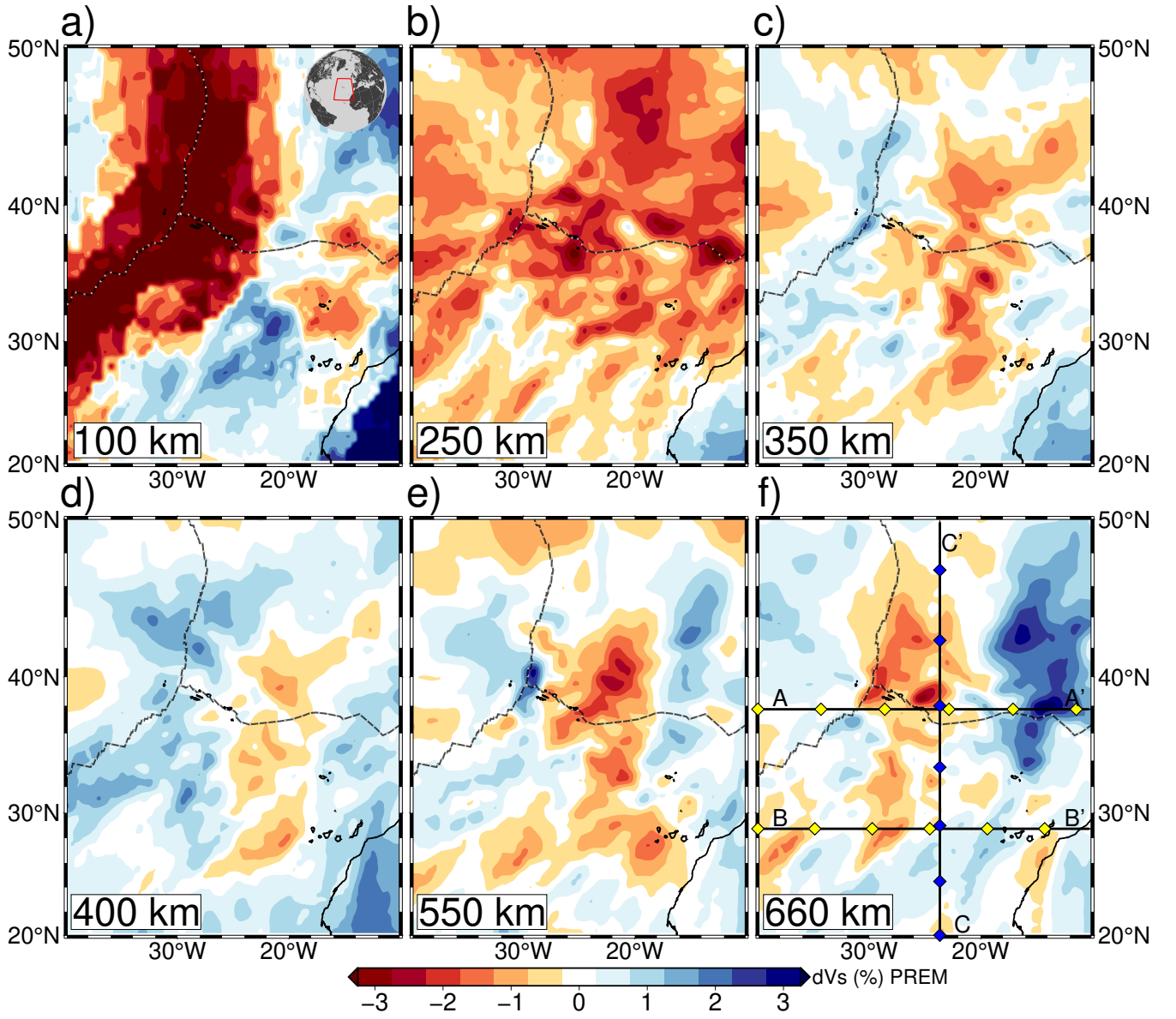


Figure S18: **Isotropic depth slices.** Additional isotropic depth slices through the final tomographic model, covering an extended area relative to those shown in the main text to facilitate comparison with other large-scale tomography models. V_S is plotted as a perturbation with respect to PREM. Cross section lines in panel f) show the locations of cross sections of previously published V_S model in Figs. S22 -S26.

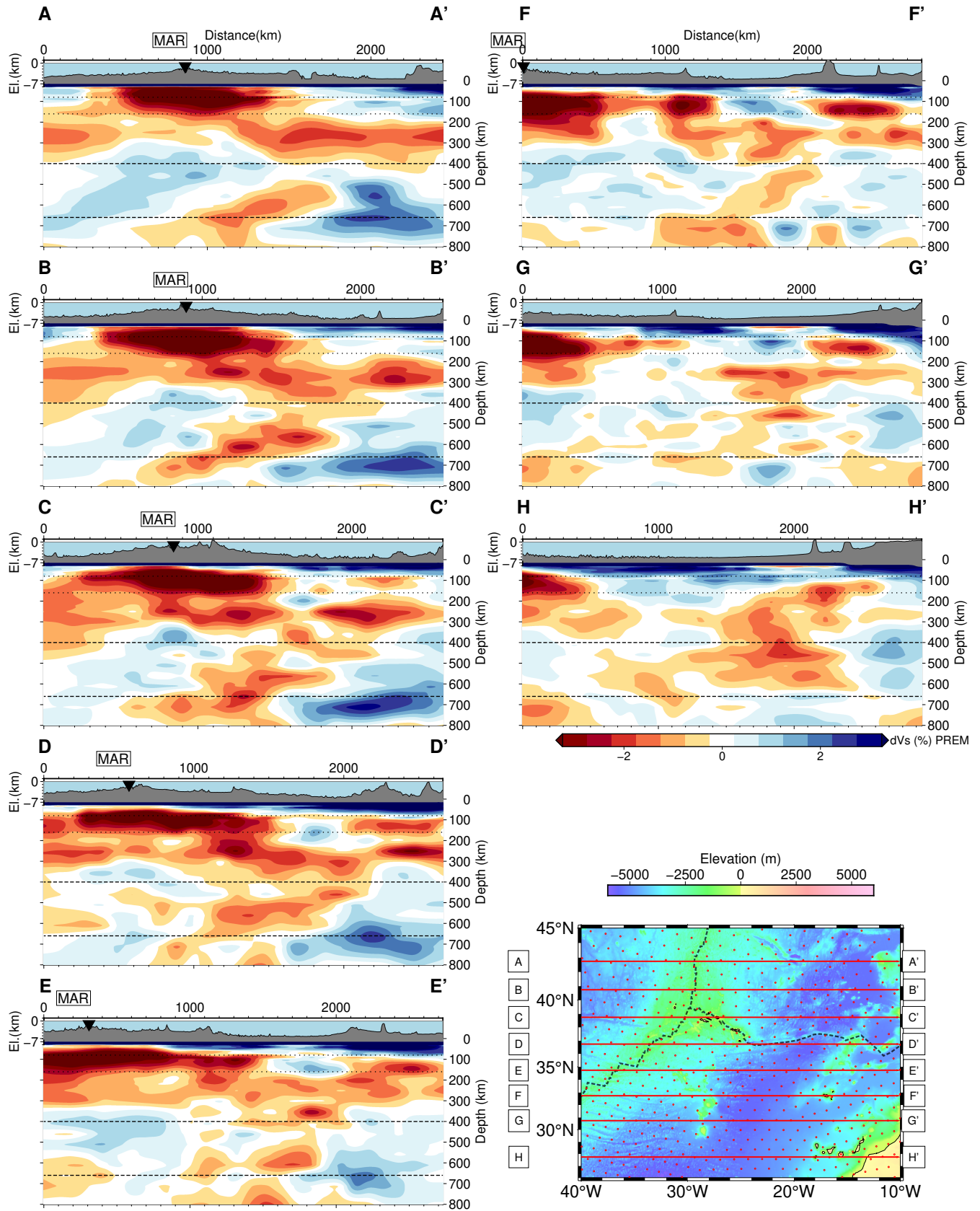


Figure S19: **Isotropic cross sections.** Additional isotropic cross sections through our final tomography model. Isotropic V_S is plotted as a perturbation from PREM. The Mid-Atlantic Ridge (MAR) is indicated by a black triangle and label. Grey topography is plotted above each tomography cross section, shown at an exaggerated vertical scale.

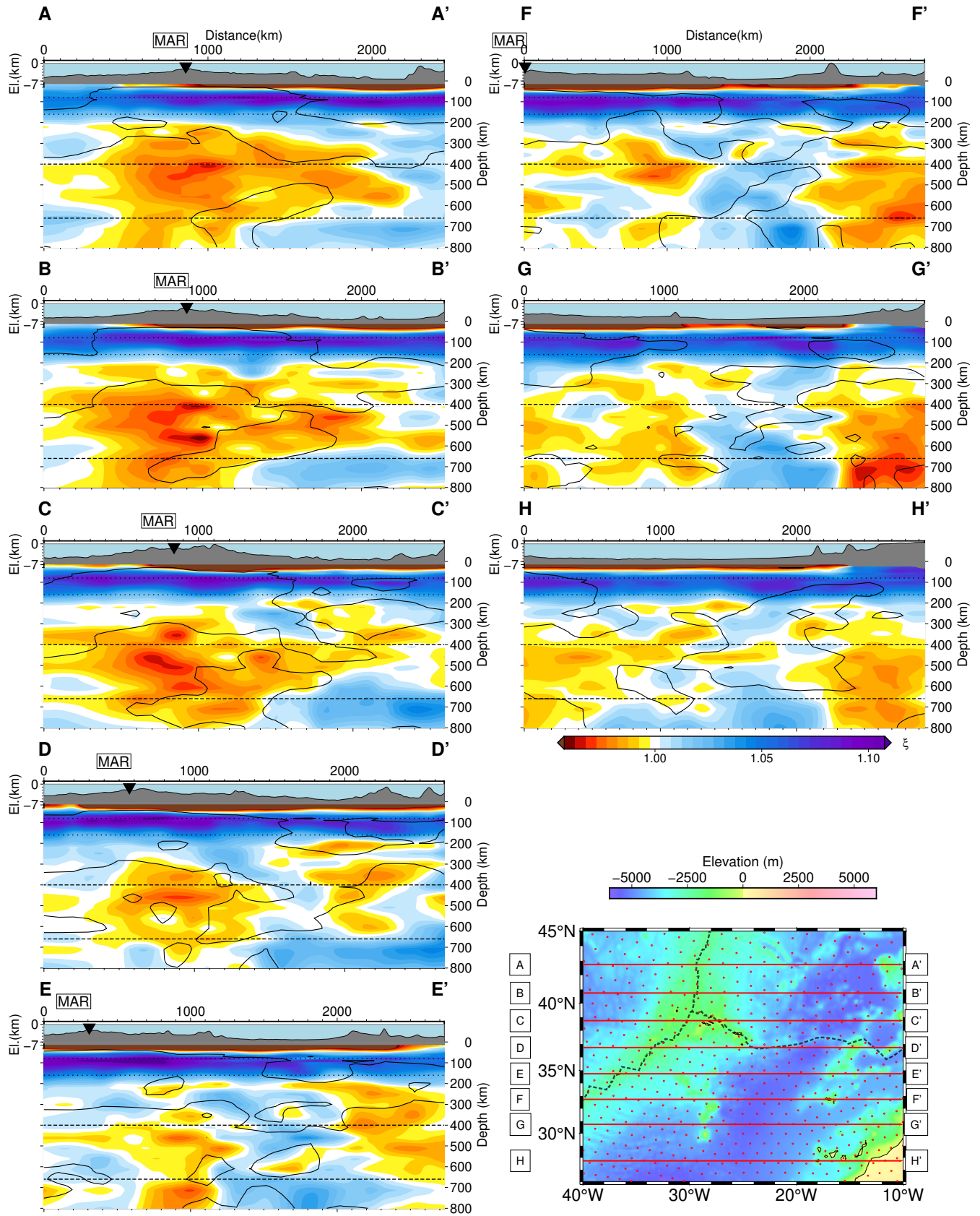


Figure S20: **Anisotropic cross sections.** Additional anisotropic cross sections through our final model, shown in terms of $\xi = (V_{SH}/V_{SV})^2$. Black contours show the -0.5% V_S perturbation along the same transects. The Mid-Atlantic Ridge (MAR) is indicated by a black triangle and label. Grey topography is plotted above each tomography cross section, shown at an exaggerated vertical scale.

5 Waveform fitting process

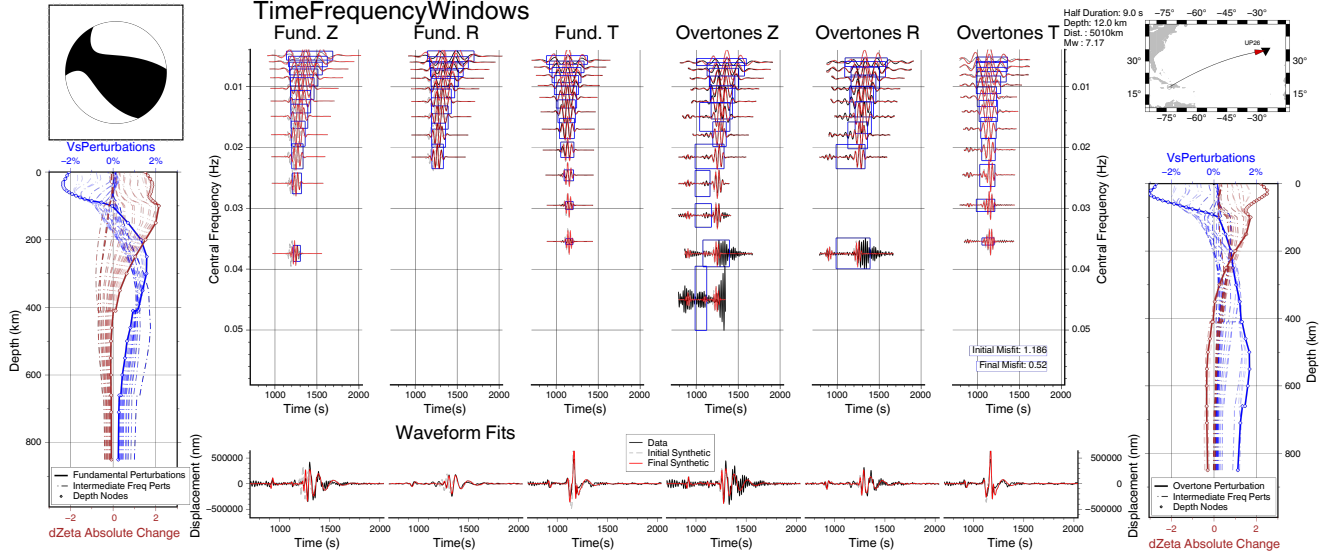


Figure S21: **Example of waveform fitting process.** Waveform fitting results for a M_w 7.17 earthquake in Haiti on 2021-08-14, 12:29:08 (UTC) recorded by UPFLOW station UP26. The top left panel shows the focal mechanism (Ekström et al., 2012; Dziewoński et al., 1981). The bottom left panel displays perturbations in V_s (blue) and ζ_s (red-brown) with depth, retrieved from fitting the fundamental mode. Solid lines represent depth perturbations that minimize misfit once all windows are included in the misfit equation, while dashed lines indicate perturbations from intermediate algorithm steps with only certain frequency windows considered. The six top middle panels show the time-frequency windows selected and the fit achieved for all components for the fundamental mode (left three panels) and the full mode sum (right three panels). The six bottom middle panels depict the waveform fit achieved, filtered between the maximum and minimum frequencies of the component windows. The top right panel maps the event location, minor arc, and UPFLOW ocean bottom seismometer station, along with additional event information. The bottom right panel shows model perturbations similar to those in the bottom left panel but for the full mode sum windows. Solid lines in this bottom right panel represent the final path-averaged model perturbations determined for this ray path.

6 Previous Tomographic Models

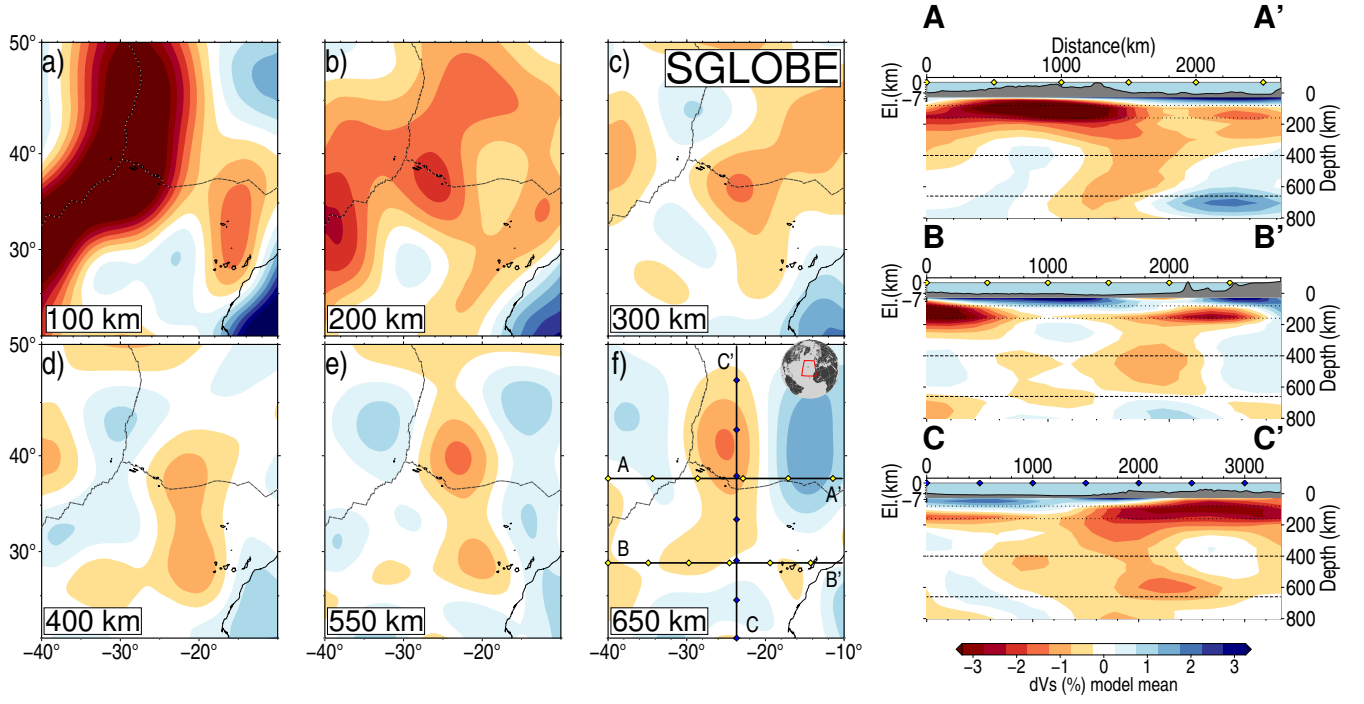


Figure S22: **SGLOBE-rani** V_S . Isotropic S-wave velocity (V_S) perturbations for seismic model SGLOBE-rani, shown relative to the depth-averaged reference V_S value at each depth Chang et al. (2015). Panels (a–f) show constant depth slices of V_S perturbation; (A–C) are cross-section profiles of V_S shown on panel (f).

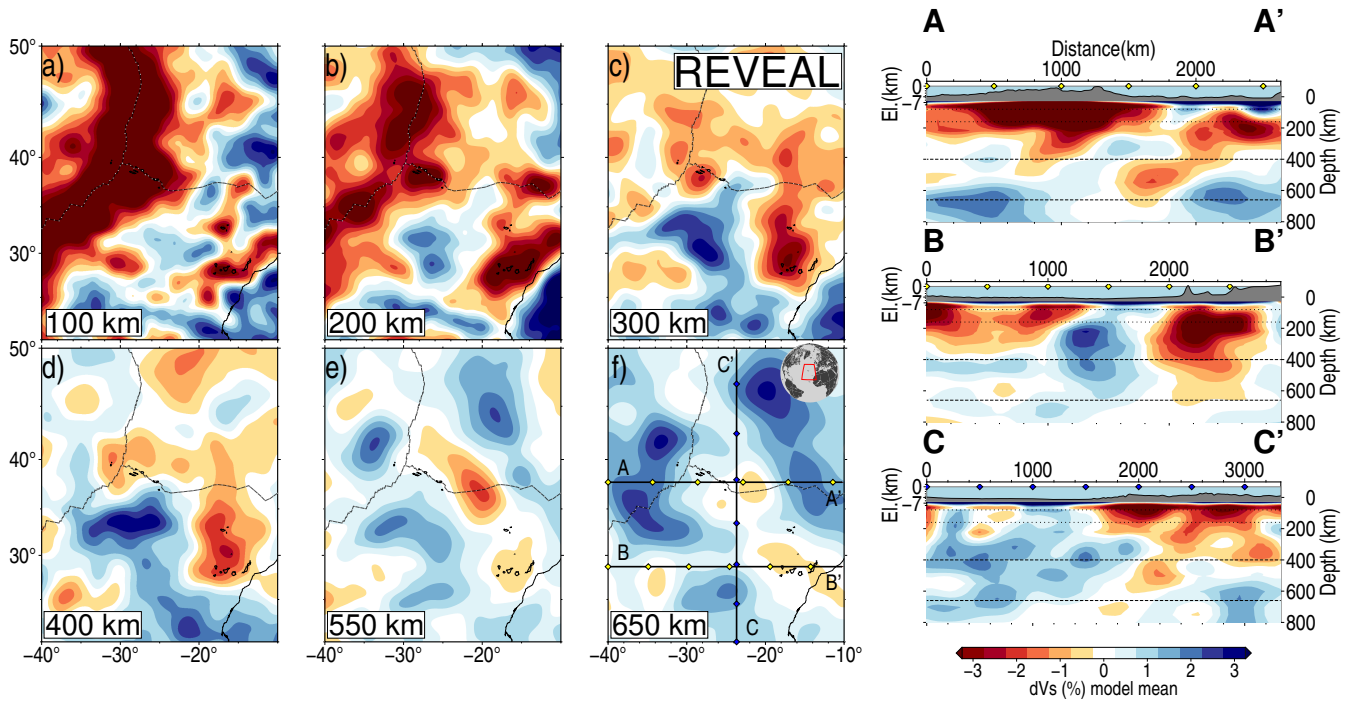


Figure S23: **REVEAL** V_S . Same as in Fig. S22, but for the global model REVEAL (Thrustarson et al., 2024).

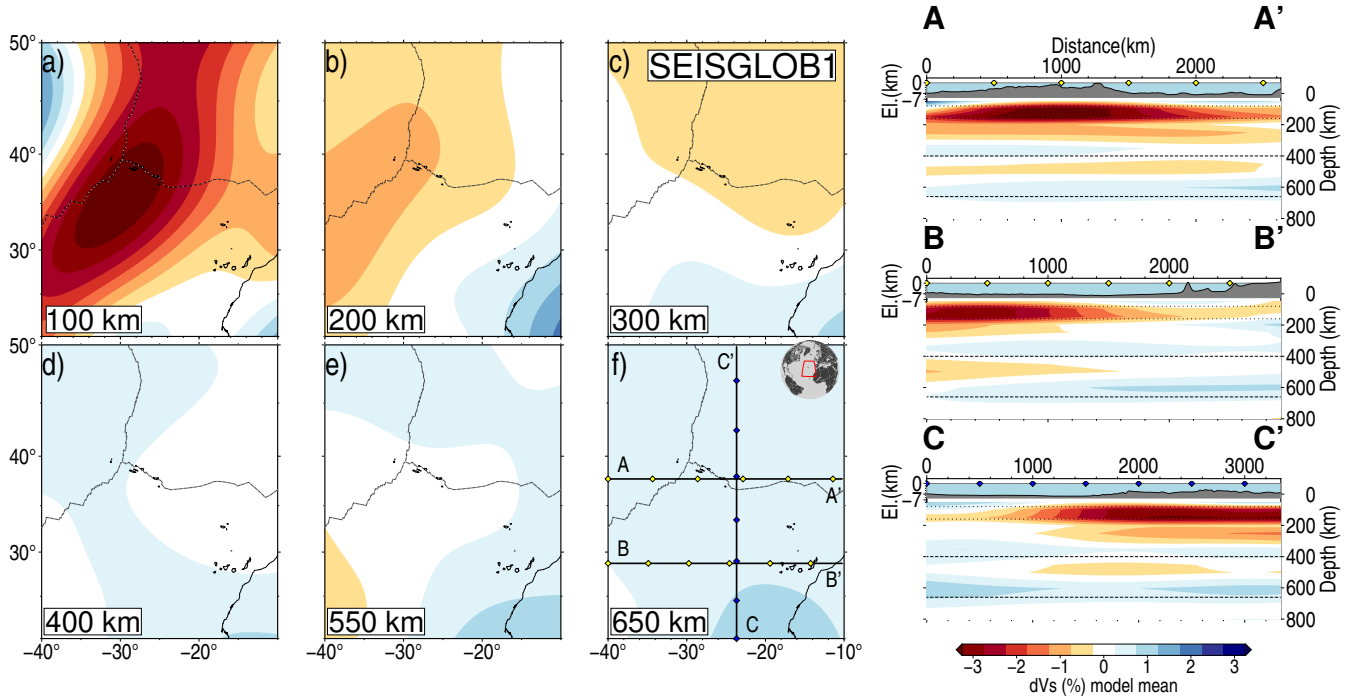


Figure S24: **SEISGLOB1** V_{SV} . Same as in Fig. S22, but for the global model SEISGLOB1 (Durand et al., 2016).

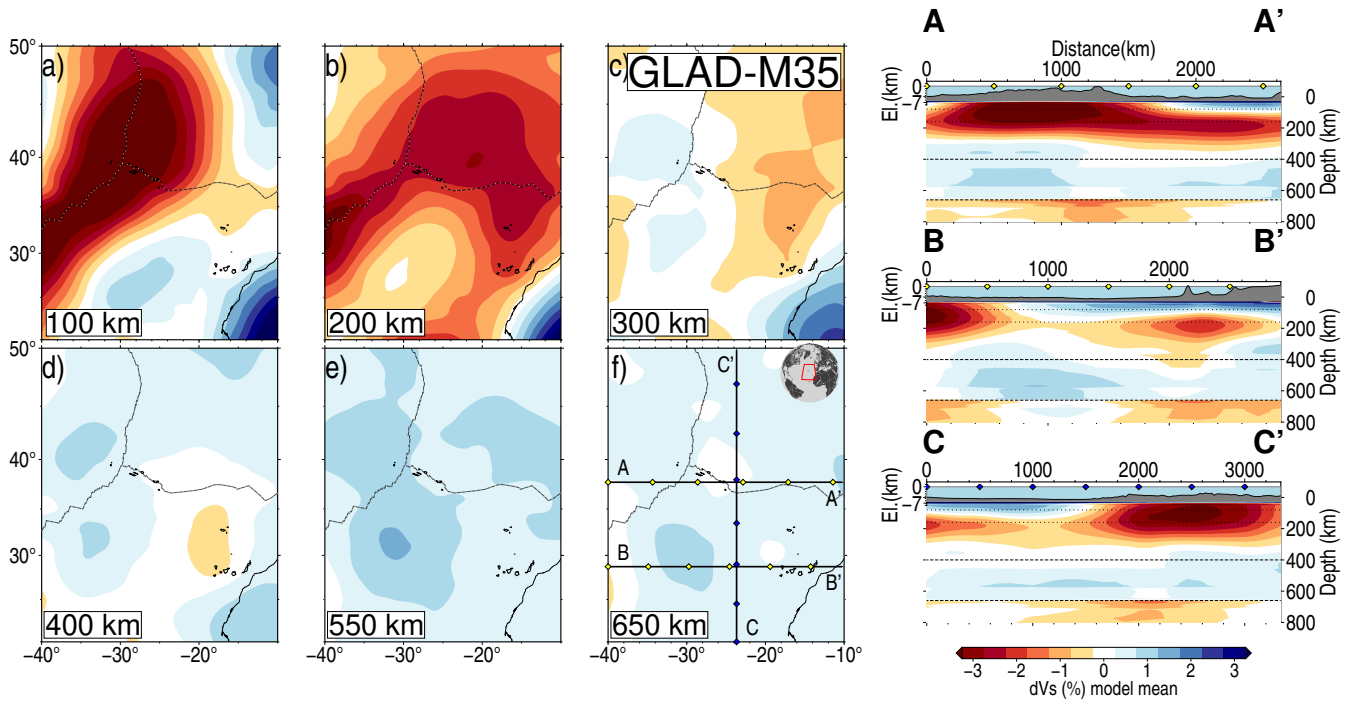


Figure S25: **GLAD-M35** V_S . Same as in Fig. S22, but for the global model GLAD-M35 (French and Romanowicz, 2014).

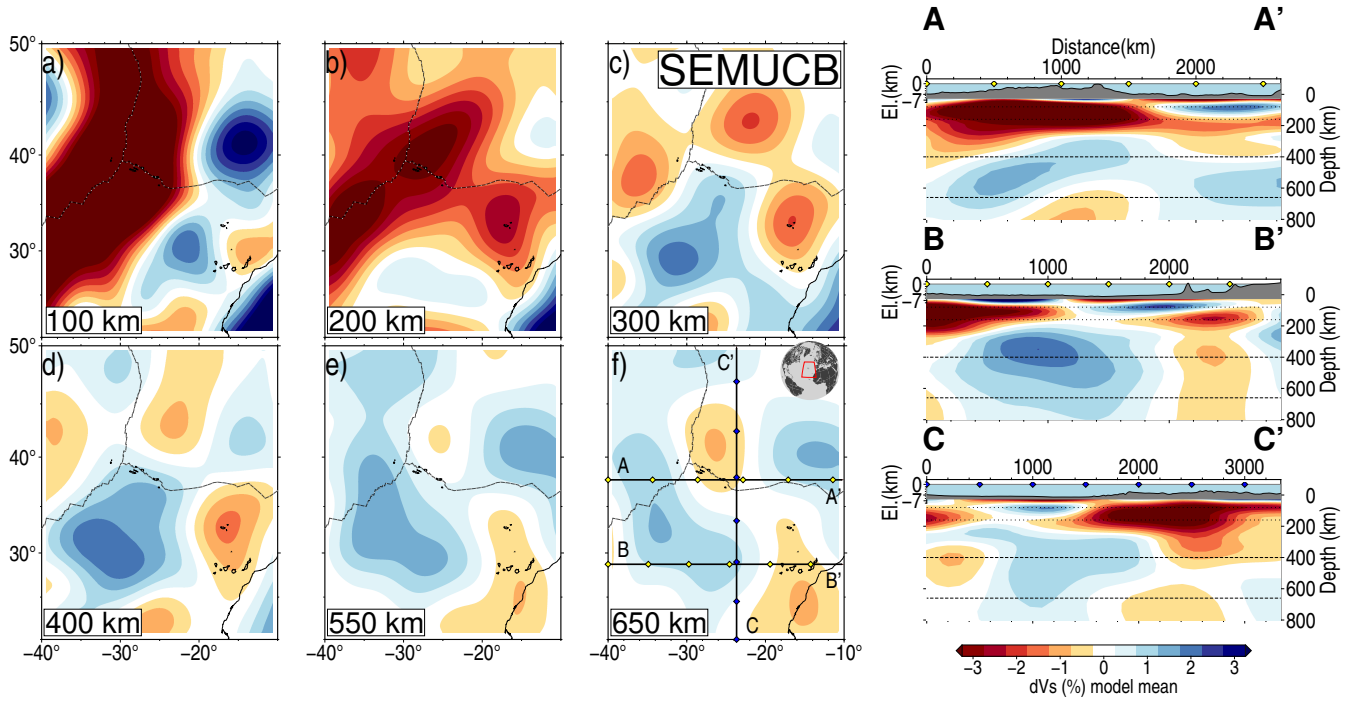


Figure S26: **SEMUCB-WM1** V_S . Same as in Fig. S22, but for the global model SEMUCB-WM1 (Cui et al., 2024).

7 List of Earthquakes used in this study

Nr.	Latitude (°)	Longitude (°)	Depth (km)	Datetime [UTC]	Magnitude
1	0.88	-26.75	15	2000-08-31 20:30:09	5.38
2	-1.72	-13.11	15	2000-09-10 21:37:48	5.45
3	4.15	-32.58	15	2000-09-23 02:13:38	5.44
4	4.23	-32.56	15	2000-09-23 02:17:49	5.68
5	-1.27	-23.77	15	2000-10-27 09:10:10	5.8
6	0.83	-28.10	15	2000-10-29 06:05:32	5.28
7	0.81	-25.67	15	2000-10-30 01:03:31	5.61
8	-5.72	-11.39	15	2000-12-15 14:08:22	5.27
9	1.08	-27.83	15	2001-01-02 19:37:39	5.48
10	-0.76	-22.21	15	2001-01-05 11:54:18	5.47
11	-7.52	-13.76	15	2001-07-12 06:12:24	5.63
12	-2.89	-12.47	15	2001-07-30 19:50:15	5.15
13	5.56	-32.66	15	2001-10-10 10:02:04	5.22
14	3.54	-31.20	15	2002-03-14 21:03:24	5.4
15	-0.86	-14.39	15	2002-08-03 14:18:19	5.71
16	-0.62	-13.39	15	2002-10-02 15:57:08	5.27
17	-8.30	-71.66	539	2002-10-12 20:09:18	6.85
18	28.72	-43.21	15	2002-11-18 00:31:35	5.14
19	23.34	-44.81	15	2002-11-29 11:49:33	5.32
20	10.83	-43.30	15	2002-12-15 05:56:28	5.29
21	-10.84	-13.18	15	2002-12-21 14:12:42	5.13
22	-4.97	-11.37	15	2003-01-11 07:30:13	5.07
23	35.81	-35.00	15	2003-01-18 20:37:53	5.16
24	2.82	-31.47	15	2003-02-13 04:45:29	5.3
25	-6.66	-11.80	15	2003-02-13 05:59:16	5.35
26	0.89	-26.98	15	2003-03-07 12:23:16	5.49
27	35.17	-35.65	15	2003-04-02 03:43:20	6.24
28	25.50	-45.26	15	2003-04-02 08:04:08	5.04
29	18.29	-58.72	40	2003-05-14 06:03:39	6.6
30	36.93	3.58	15	2003-05-21 18:44:30	6.8
31	-7.37	-71.89	556	2003-06-20 06:19:47	7.03
32	3.85	-30.91	15	2003-07-15 17:50:06	5.07
33	35.13	-35.75	15	2003-08-02 17:30:38	5.74
34	35.48	-35.99	15	2003-08-02 17:53:44	5.33
35	35.32	-35.79	15	2003-08-06 17:18:03	5.36
36	7.65	-36.43	15	2003-08-06 19:55:39	5.01
37	7.01	-34.23	15	2003-08-27 12:39:06	5.12
38	-0.80	-13.77	15	2003-09-21 23:15:21	5.99
39	35.34	-35.98	15	2003-09-25 18:43:13	5.65
40	-1.28	-15.43	15	2003-10-11 23:08:48	5.38
41	-0.27	-19.26	15	2003-11-09 19:52:52	6.58

42	-0.10	-19.64	15	2003-11-09 22:56:33	5.36
43	-0.39	-20.13	15	2003-12-21 07:41:06	6.53
44	-0.52	-20.38	16	2003-12-23 05:58:44	5.75
45	7.79	-37.73	15	2004-01-16 18:07:58	6.15
46	13.54	-44.87	12	2004-02-07 23:41:02	5.19
47	-0.48	-16.13	12	2004-03-03 20:24:49	5.33
48	10.94	-43.28	12	2004-03-08 23:39:17	6.01
49	5.64	-32.85	12	2004-03-12 20:30:49	5.18
50	-7.12	-13.05	12	2004-03-17 06:41:00	5.23
51	32.48	-40.18	12	2004-03-18 23:09:46	5.38
52	-3.23	-12.18	12	2004-04-04 18:04:38	5.31
53	3.82	-32.21	12	2004-04-19 08:14:16	5.58
54	33.06	-39.34	12	2004-04-20 21:41:36	5.31
55	32.97	-39.41	12	2004-04-21 01:20:46	5.07
56	0.99	-27.05	12	2004-04-24 08:03:11	5.37
57	-7.32	-13.66	12	2004-05-05 05:24:22	5.16
58	12.76	-44.48	12	2004-05-11 23:58:58	5.46
59	-1.20	-15.22	12	2004-05-12 23:23:57	5.33
60	0.87	-25.66	12	2004-09-24 10:35:01	5.82
61	0.94	-28.83	12	2004-10-25 20:59:58	5.57
62	0.76	-25.29	12	2004-12-20 09:52:47	5.04
63	-0.47	-20.53	12	2005-01-12 08:40:22	6.78
64	-1.20	-15.56	12	2005-01-29 21:01:13	5.45
65	-0.90	-24.50	16	2005-03-21 16:14:40	5.41
66	7.28	-34.02	12	2005-03-24 07:33:55	5.35
67	-0.09	-20.67	12	2005-03-28 00:01:34	5.2
68	8.19	-39.17	12	2007-08-20 22:42:35	6.54
69	27.78	-44.10	12	2007-09-01 01:28:07	5.17
70	35.24	26.92	18	2007-09-23 00:54:33	5.34
71	54.18	-161.46	40	2007-10-02 18:00:10	6.33
72	-22.64	-70.62	38	2007-11-14 15:41:11	7.72
73	-22.67	-66.48	262	2007-11-18 05:40:17	6.02
74	15.06	-61.41	148	2007-11-29 19:00:32	7.4
75	-7.44	37.49	12	2007-12-08 19:55:23	5.62
76	-23.02	-70.41	31	2007-12-16 08:09:21	6.71
77	39.43	33.10	12	2007-12-20 09:48:32	5.66
78	-19.64	-69.42	120	2007-12-25 16:20:55	5.82
79	52.21	-168.10	14	2007-12-26 22:05:00	6.36
80	39.55	33.05	15	2007-12-26 23:47:15	5.58
81	51.11	-131.24	12	2008-01-05 11:01:11	6.59
82	36.98	22.87	92	2008-01-06 05:14:23	6.17
83	32.30	85.32	13	2008-01-09 08:26:52	6.4
84	43.51	-128.27	17	2008-01-10 01:37:23	6.32
85	3.95	-31.97	15	2008-01-22 03:30:55	4.82
86	-2.38	28.82	12	2008-02-03 07:34:15	5.93

87	-20.27	-70.76	46	2008-02-04 17:01:36	6.33
88	10.85	-41.71	17	2008-02-08 09:38:22	6.94
89	16.35	-94.51	87	2008-02-12 12:50:20	6.46
90	36.24	21.79	20	2008-02-14 10:09:29	6.85
91	36.29	21.67	15	2008-02-14 12:09:02	6.54
92	36.24	21.73	18	2008-02-20 18:27:12	6.16
93	77.02	19.28	13	2008-02-21 02:46:21	6.07
94	40.73	-29.26	12	2008-02-23 11:03:55	5.33
95	40.90	-29.15	12	2008-02-23 11:56:09	4.9
96	36.39	-33.77	12	2008-03-02 01:34:21	5.11
97	0.82	-29.86	21	2008-03-09 17:17:29	5.1
98	35.43	81.37	12	2008-03-20 22:33:12	7.09
99	43.23	-29.02	12	2008-03-23 13:07:25	4.83
100	34.38	25.32	59	2008-03-28 00:16:24	5.54
101	-1.14	-23.87	15	2008-04-24 12:15:05	6.47
102	37.84	28.94	12	2008-04-25 04:48:57	4.96
103	36.26	22.05	20	2008-05-10 20:53:07	5.43
104	7.51	-35.01	13	2008-05-23 19:35:40	6.47
105	4.32	-73.79	15	2008-05-24 19:20:48	5.87
106	63.92	-21.17	12	2008-05-29 15:46:06	6.29
107	35.93	-0.48	12	2008-06-06 20:03:01	5.49
108	37.93	21.63	25	2008-06-08 12:25:36	6.37
109	35.67	27.69	42	2008-07-15 03:26:39	6.39
110	8.18	-38.54	15	2008-09-10 13:08:21	6.61
111	39.50	73.64	12	2008-10-05 15:53:01	6.7
112	16.50	-87.17	12	2009-05-28 08:25:04	7.34
113	18.61	-72.62	12	2010-01-12 21:53:17	7.03
114	-38.09	-75.41	20	2010-02-27 08:01:29	7.36
115	32.31	-115.39	13	2010-04-04 22:41:09	7.19
116	-1.51	-77.51	198	2010-08-12 11:54:20	7.07
117	28.10	59.11	15	2010-12-20 18:42:06	6.54
118	-27.02	-63.21	586	2011-01-01 09:57:03	7.03
119	-38.71	-73.84	19	2011-01-02 20:20:26	7.13
120	28.61	63.90	52	2011-01-18 20:23:31	7.23
121	52.09	-171.77	74	2011-06-24 03:09:51	7.25
122	-7.68	-74.66	144	2011-08-24 17:46:15	7.02
123	38.64	43.40	12	2011-10-23 10:41:28	7.13
124	16.60	-98.39	15	2012-03-20 18:02:54	7.46
125	-35.31	-72.41	34	2012-03-25 22:37:20	7.12
126	28.57	-112.76	16	2012-04-12 07:16:04	7.04
127	12.02	-89.17	12	2012-08-27 04:37:39	7.34
128	71.44	-9.84	24	2012-08-30 13:43:35	6.74
129	10.00	-85.64	30	2012-09-05 14:42:23	7.62
130	1.89	-76.22	159	2012-09-30 16:31:44	7.24
131	52.61	-132.06	12	2012-10-28 03:04:37	7.77

132	14.11	-92.43	21	2012-11-07 16:35:56	7.37
133	55.69	-134.97	14	2013-01-05 08:58:31	7.53
134	1.16	-77.40	152	2013-02-09 14:16:14	6.97
135	27.89	62.21	51	2013-04-16 10:44:32	7.74
136	5.77	-78.19	21	2013-08-13 15:43:21	6.63
137	26.70	65.04	12	2013-09-24 11:30:08	7.76
138	-16.03	-74.81	46	2013-09-25 16:42:52	7.04
139	35.37	23.37	15	2013-10-12 13:11:56	6.76
140	-19.85	-71.39	21	2014-04-01 23:58:11	7.0
141	-20.43	-70.60	29	2014-04-03 02:43:35	7.73
142	11.70	-86.22	142	2014-04-11 20:29:19	6.61
143	17.55	-101.25	19	2014-04-18 14:27:36	7.27
144	49.65	-127.59	17	2014-04-24 03:10:18	6.58
145	40.30	25.67	12	2014-05-24 09:25:18	6.86
146	12.33	-88.45	41	2014-10-14 03:51:43	7.28
147	7.98	-82.63	20	2014-12-08 08:55:00	6.56
148	52.70	-32.74	25	2015-02-13 18:59:28	7.07
149	27.91	85.33	12	2015-04-25 06:11:58	7.88
150	27.67	86.08	12	2015-05-12 07:05:27	7.23
151	36.55	70.42	209	2015-10-26 09:09:46	7.5
152	38.47	20.53	15	2015-11-17 07:10:12	6.5
153	-10.73	-71.12	611	2015-11-24 22:45:46	7.55
154	-10.11	-71.28	627	2015-11-24 22:51:00	7.65
155	38.39	72.91	12	2015-12-07 07:50:13	7.19
156	59.75	-153.27	111	2016-01-24 10:30:37	7.12
157	36.44	71.04	211	2016-04-10 10:28:59	6.64
158	-0.12	-80.25	22	2016-04-16 23:58:57	7.78
159	0.13	-17.72	27	2016-08-29 04:30:18	7.1
160	42.75	13.16	12	2016-10-30 06:40:24	6.59
161	11.83	-89.20	12	2016-11-24 18:43:53	6.93
162	39.27	74.14	19	2016-11-25 14:24:37	6.64
163	-19.27	-63.79	606	2017-02-21 14:09:09	6.5
164	-33.13	-72.07	26	2017-04-24 21:38:37	6.86
165	36.79	27.56	12	2017-07-20 22:31:16	6.64
166	-0.87	-14.15	22	2017-08-18 02:59:39	6.63
167	18.59	-98.63	51	2017-09-19 18:14:47	7.14
168	34.83	45.84	18	2017-11-12 18:18:25	7.4
169	9.45	-84.58	30	2017-11-13 02:28:29	6.6
170	17.56	-83.86	16	2018-01-10 02:51:44	7.52
171	-15.95	-74.78	41	2018-01-14 09:18:52	7.12
172	56.22	-149.12	34	2018-01-23 09:32:04	7.92
173	16.53	-97.88	20	2018-02-16 23:39:46	7.16
174	-20.63	-62.81	569	2018-04-02 13:40:41	6.83
175	10.76	-63.05	160	2018-08-21 21:32:03	7.27
176	-11.18	-70.82	628	2018-08-24 09:04:10	7.09

177	49.14	-129.89	16	2018-10-22 06:16:36	6.75
178	37.27	20.60	16	2018-10-25 22:54:58	6.84
179	71.51	-10.81	15	2018-11-09 01:49:47	6.81
180	61.49	-150.02	48	2018-11-30 17:29:34	7.05
181	-8.10	-71.68	588	2019-01-05 19:25:41	6.77
182	-30.18	-71.39	61	2019-01-20 01:32:58	6.64
183	-2.26	-77.09	121	2019-02-22 10:17:28	7.48
184	-14.78	-70.14	274	2019-03-01 08:50:49	7.02
185	-5.25	-75.36	127	2019-05-26 07:41:52	7.99
186	13.07	-89.55	46	2019-05-30 09:03:33	6.59
187	35.78	-117.58	12	2019-07-06 03:20:05	7.03
188	-34.32	-72.24	25	2019-08-01 18:28:16	6.78
189	38.29	39.02	12	2020-01-24 17:55:24	6.76
190	19.33	-79.55	24	2020-01-28 19:10:52	7.69
191	34.05	25.64	12	2020-05-02 12:51:09	6.6
192	-23.22	-68.44	109	2020-06-03 07:35:40	6.79
193	16.02	-96.07	22	2020-06-23 15:29:12	7.38
194	54.83	-159.28	36	2020-07-22 06:13:16	7.85
195	0.84	-29.99	17	2020-08-30 21:20:37	6.52
196	-28.01	-71.41	34	2020-09-01 04:09:39	6.86
197	7.79	-37.18	12	2020-09-06 06:51:23	6.61
198	0.94	-26.91	14	2020-09-18 21:44:07	6.86
199	54.48	-159.70	37	2020-10-19 20:55:00	7.58
200	37.78	26.63	12	2020-10-30 11:51:34	6.99
201	51.32	100.39	14	2021-01-11 21:33:07	6.79
202	6.72	-82.70	17	2021-07-17 20:56:15	6.15
203	28.49	-43.67	12	2021-07-17 21:31:21	5.38
204	7.39	-82.83	18	2021-07-21 21:15:25	6.71
205	56.79	-34.43	22	2021-07-27 16:18:52	4.77
206	64.56	-17.15	12	2021-07-27 22:12:16	5.09
207	-8.30	-80.14	28	2021-07-29 00:32:16	5.88
208	-5.03	-80.73	44	2021-07-30 17:10:21	6.17
209	27.71	-111.51	15	2021-07-31 15:39:24	5.54
210	62.59	-25.34	18	2021-08-01 00:33:44	4.81
211	36.24	27.00	12	2021-08-01 04:31:28	5.58
212	28.44	-43.75	12	2021-08-10 18:58:24	4.88
213	53.97	-35.18	12	2021-08-12 10:59:19	4.91
214	53.98	-35.24	12	2021-08-13 07:38:23	5.0
215	55.17	-157.45	25	2021-08-14 11:57:50	7.0
216	18.50	-73.64	12	2021-08-14 12:29:20	7.13
217	18.45	-74.06	12	2021-08-15 03:20:48	5.73
218	29.67	-42.79	12	2021-08-29 16:55:30	4.83
219	29.89	-42.74	12	2021-08-31 22:02:54	4.92
220	29.89	-42.73	12	2021-08-31 22:24:26	4.87
221	29.86	-42.76	13	2021-08-31 22:54:52	4.93

222	-27.80	-71.35	42	2021-09-01 18:35:50	5.69
223	42.16	-29.34	12	2021-09-02 14:17:58	4.82
224	17.03	-99.76	22	2021-09-08 01:47:53	6.96
225	11.92	-87.99	28	2021-09-22 09:57:13	6.54
226	11.90	-87.86	34	2021-09-22 12:57:04	5.69
227	22.94	-108.14	12	2021-09-23 16:47:56	5.7
228	35.10	25.16	12	2021-09-27 06:17:23	5.94
229	32.80	-39.93	12	2021-09-28 10:45:54	4.74
230	32.61	-40.00	12	2021-09-28 10:57:01	4.83
231	32.61	-40.00	12	2021-09-28 17:38:25	4.9
232	-9.51	-71.24	609	2021-10-02 12:52:37	5.94
233	29.94	67.98	13	2021-10-06 22:01:11	5.96
234	-11.73	-71.73	14	2021-10-10 00:20:44	5.6
235	58.05	-32.44	12	2021-10-10 16:09:35	4.87
236	56.45	-156.63	67	2021-10-11 09:10:30	6.9
237	34.98	26.44	24	2021-10-12 09:24:08	6.36
238	34.40	28.38	26	2021-10-19 05:32:32	5.89
239	38.59	-30.39	12	2021-10-31 19:36:16	4.7
240	10.98	-86.89	28	2021-11-09 02:53:54	5.95
241	10.98	-86.75	33	2021-11-09 06:25:20	6.37
242	36.78	-33.37	12	2021-11-10 11:02:12	4.84
243	32.53	-40.14	12	2021-11-10 13:19:52	4.68
244	32.43	-40.10	14	2021-11-10 14:57:02	4.66
245	27.57	55.98	17	2021-11-14 12:07:04	6.06
246	27.54	56.03	14	2021-11-14 12:08:39	6.13
247	-26.30	-63.12	577	2021-11-17 21:38:55	5.57
248	13.42	-91.23	32	2021-11-18 16:57:01	5.87
249	12.91	-90.59	16	2021-11-23 05:56:35	5.54
250	-4.73	-76.73	110	2021-11-28 10:52:25	7.47
251	-18.67	-71.35	36	2021-12-07 09:39:42	5.58
252	44.28	-129.82	12	2021-12-07 21:30:19	5.52
253	44.22	-129.69	14	2021-12-08 00:36:41	5.84
254	44.18	-129.63	15	2021-12-08 01:21:09	5.8
255	44.16	-129.54	12	2021-12-08 07:18:31	5.53
256	-29.55	-71.43	49	2021-12-11 14:54:23	5.67
257	15.54	-92.17	173	2021-12-13 07:03:09	5.7
258	40.36	-124.41	29	2021-12-20 20:10:30	6.21
259	60.16	-153.41	154	2021-12-21 22:42:16	5.97
260	18.81	-107.08	25	2021-12-22 23:23:04	6.08
261	35.06	26.87	18	2021-12-26 18:59:04	5.6
262	34.65	25.23	54	2021-12-29 05:08:09	5.71
263	37.57	-31.75	12	2021-12-31 00:58:33	4.91
264	35.19	-35.44	20	2022-01-04 03:18:41	5.98
265	11.65	-87.41	31	2022-01-06 16:25:10	6.21
266	-11.83	-76.75	117	2022-01-07 10:27:10	5.66

267	-26.73	-71.28	15	2022-01-08 03:24:14	5.88
268	40.72	21.36	19	2022-01-09 21:43:50	5.54
269	28.37	-43.71	13	2022-01-10 22:29:28	4.93
270	28.49	-43.64	12	2022-01-10 23:26:47	5.8
271	34.86	31.79	26	2022-01-11 01:07:56	6.59
272	40.17	-29.70	21	2022-01-13 06:46:15	4.84
273	30.10	-42.17	17	2022-01-27 11:03:39	4.87
274	-19.13	-69.48	114	2022-01-28 00:31:27	5.53
275	5.27	-82.62	19	2022-01-28 11:14:14	6.06
276	46.99	-27.14	12	2022-02-03 04:05:58	4.82
277	-4.50	-76.95	120	2022-02-03 15:58:59	6.44
278	29.68	-42.77	12	2022-02-05 01:18:06	5.04
279	36.39	71.00	221	2022-02-05 04:16:02	5.82
280	-0.42	-19.81	17	2022-02-08 11:59:32	6.18
281	57.59	-32.94	12	2022-02-13 10:02:26	4.99
282	14.03	-91.57	64	2022-02-16 07:12:25	6.19
283	-22.57	-66.19	260	2022-02-22 06:12:56	6.0
284	64.57	-17.18	12	2022-02-22 10:11:26	5.12
285	30.15	-42.50	16	2022-02-26 01:23:55	5.17
286	18.15	-95.50	125	2022-03-03 14:40:34	5.72
287	56.61	-34.29	18	2022-03-04 15:53:29	4.72
288	40.79	-29.19	12	2022-03-06 02:26:13	4.72
289	16.90	-95.09	105	2022-03-06 03:29:22	5.59
290	-28.59	-68.77	116	2022-03-06 09:35:11	5.54
291	26.84	54.49	19	2022-03-16 23:15:48	5.85
292	25.11	-45.38	18	2022-03-17 04:58:24	4.96
293	61.67	2.21	22	2022-03-21 05:32:58	5.32
294	10.89	-43.06	16	2022-03-22 16:35:15	6.61
295	0.83	-79.83	24	2022-03-27 04:28:14	5.83
296	31.66	-40.80	15	2022-04-09 22:33:18	5.42
297	52.55	-32.16	18	2022-04-11 22:13:03	4.73
298	-22.84	-68.38	126	2022-04-20 11:19:10	5.72
299	11.43	-87.11	36	2022-04-21 07:42:53	6.62
300	11.11	-87.32	20	2022-04-23 22:05:50	5.5
301	11.12	-87.35	17	2022-04-23 22:10:12	5.6
302	23.46	-44.88	12	2022-05-07 18:55:27	4.76
303	-23.48	-66.76	218	2022-05-10 23:06:36	6.73
304	-29.56	-71.99	36	2022-05-20 09:07:53	5.76
305	35.50	-3.49	12	2022-05-20 12:35:54	5.45
306	84.32	1.26	12	2022-05-21 07:01:28	5.86
307	-17.63	-69.46	162	2022-05-24 12:58:02	5.54
308	-14.79	-70.26	234	2022-05-26 12:02:30	7.17
309	-14.30	-75.94	54	2022-05-27 01:07:36	5.55
310	64.58	-17.74	12	2022-05-28 08:06:20	4.75
311	23.36	-44.86	12	2022-05-28 13:46:15	4.93

312	23.39	-44.88	12	2022-05-28 14:19:06	5.57
313	34.67	-36.97	12	2022-05-30 01:44:08	4.67
314	35.50	-3.43	22	2022-06-02 12:55:16	4.9
315	21.42	-45.65	12	2022-06-02 21:25:15	4.92
316	43.70	-28.87	13	2022-06-06 01:28:29	4.71
317	43.72	-28.85	12	2022-06-06 20:59:58	5.35
318	43.72	-28.87	12	2022-06-06 21:23:52	5.19
319	43.69	-28.85	12	2022-06-07 03:55:20	5.03
320	-8.98	-71.25	621	2022-06-08 00:55:48	6.48
321	-18.96	-12.47	12	2022-06-11 17:55:05	5.54
322	44.42	-130.33	13	2022-06-15 11:56:35	5.59
323	32.94	69.56	16	2022-06-21 20:54:38	6.15
324	26.49	54.14	12	2022-06-25 03:37:15	5.55
325	-17.24	-73.94	12	2022-06-26 02:02:38	5.64
326	35.88	-0.38	12	2022-06-26 19:17:54	4.65
327	44.48	-28.17	12	2022-06-29 06:05:53	4.92
328	44.57	-28.13	12	2022-06-29 08:15:44	4.81
329	26.68	55.18	12	2022-07-01 21:32:08	6.04
330	26.69	55.13	12	2022-07-01 23:25:14	6.08
331	-2.02	-79.80	91	2022-07-14 22:30:14	5.72
332	78.69	5.62	20	2022-07-18 18:40:38	6.01
333	44.26	-28.31	14	2022-07-22 03:15:49	4.93
334	26.73	55.22	12	2022-07-23 16:09:07	5.55
335	64.55	-17.24	12	2022-07-24 13:45:47	5.04
336	0.76	-77.82	12	2022-07-25 13:33:33	5.65
337	-22.23	-68.61	120	2022-07-27 18:59:03	6.2
338	-21.89	-70.25	67	2022-07-28 04:15:06	6.13
339	50.40	90.70	13	2022-07-29 13:01:14	5.52
340	25.05	63.55	26	2022-07-31 13:42:14	5.6
341	63.80	-22.46	12	2022-07-31 17:48:02	5.38
342	-0.23	-80.93	12	2022-08-21 10:28:04	5.54
343	29.71	-42.79	12	2022-08-26 05:38:16	4.93
344	-0.64	-21.23	27	2022-09-04 09:42:37	6.88
345	52.17	-30.13	12	2022-09-05 13:49:29	5.06
346	18.57	-103.44	19	2022-09-19 18:05:26	7.66
347	18.44	-103.63	19	2022-09-20 08:17:14	5.86
348	18.28	-103.07	24	2022-09-22 06:16:16	6.71
349	54.14	-35.17	12	2022-09-26 09:59:58	5.7
350	54.18	-35.23	15	2022-09-26 15:18:47	4.85
351	54.27	-35.32	13	2022-09-27 12:46:08	4.77
352	53.98	-35.25	12	2022-09-27 13:07:37	5.05
353	54.11	-35.21	12	2022-09-27 13:46:53	5.03
354	54.04	-35.30	13	2022-09-27 21:18:21	4.98
355	54.01	-35.24	12	2022-09-27 22:28:52	4.82
356	54.02	-35.21	12	2022-09-28 10:03:07	5.09

357	53.70	-35.23	12	2022-09-28 14:13:47	5.13
358	17.86	-61.52	31	2022-09-28 19:48:44	5.28
359	53.95	-35.33	12	2022-09-28 23:06:44	4.95
360	53.87	-35.27	12	2022-09-29 02:06:47	4.85
361	53.71	-35.21	12	2022-09-29 02:24:02	5.18
362	54.03	-35.20	12	2022-09-29 06:36:04	5.18
363	53.86	-35.22	12	2022-09-29 08:14:53	4.8
364	54.02	-35.19	12	2022-09-29 09:32:29	4.93
365	54.27	-35.22	12	2022-10-02 16:09:26	4.72
366	23.73	-108.53	16	2022-10-02 19:00:26	5.55
367	54.19	-35.23	12	2022-10-03 10:19:22	4.82
368	-5.01	-80.71	41	2022-10-05 08:26:21	5.89
369	-1.05	-23.52	14	2022-10-09 16:38:14	6.19
370	53.99	-35.32	12	2022-10-10 13:23:51	4.77
371	4.32	-87.64	12	2022-10-16 12:48:25	6.39
372	7.53	-82.30	13	2022-10-20 11:57:21	6.72
373	-14.57	-76.38	13	2022-10-28 20:22:12	5.96
374	-14.49	-76.39	16	2022-10-29 00:09:52	5.85
375	-2.48	-76.29	148	2022-10-31 13:22:46	5.63
376	39.83	15.63	281	2022-10-31 21:42:51	5.48
377	13.01	-89.69	50	2022-11-04 04:26:13	5.7
378	28.29	-112.34	14	2022-11-04 10:02:53	6.1
379	43.88	13.39	12	2022-11-09 06:07:30	5.72
380	14.13	-91.08	79	2022-11-12 04:39:47	5.81
381	-37.59	-73.68	21	2022-11-13 02:25:02	6.31
382	35.80	26.40	89	2022-11-20 23:25:02	5.46
383	35.14	-35.06	13	2022-11-22 02:09:02	5.59
384	30.74	-116.42	12	2022-11-22 16:39:10	6.15
385	40.86	31.04	12	2022-11-23 01:08:18	6.1
386	54.10	-34.99	12	2022-11-29 23:50:39	5.54
387	-0.96	10.38	12	2022-12-04 09:53:15	5.58
388	54.09	-35.44	12	2022-12-04 11:14:01	5.38
389	17.20	-100.60	20	2022-12-11 14:31:36	5.98
390	12.65	-88.86	57	2022-12-15 14:32:24	5.68
391	40.62	-124.25	17	2022-12-20 10:34:32	6.36
392	16.32	-62.06	163	2023-01-20 11:23:43	6.2
393	-26.64	-63.13	588	2023-01-20 22:09:42	6.73
394	-26.65	-63.01	596	2023-01-24 18:37:02	6.33
395	37.55	37.45	15	2023-02-06 01:18:10	7.78
396	37.21	36.84	26	2023-02-06 01:28:22	6.78
397	38.08	37.22	12	2023-02-06 10:24:58	7.7
398	36.06	36.03	12	2023-02-20 17:04:31	6.34
399	-2.84	-79.87	65	2023-03-18 17:12:57	6.72
400	36.44	70.78	192	2023-03-21 16:47:25	6.56
401	-23.42	-66.58	228	2023-03-22 16:00:37	6.45

402	7.59	-82.39	21	2023-04-04 22:18:18	6.36
403	49.11	-129.77	22	2023-04-13 15:54:58	6.08
404	15.17	-90.99	253	2023-05-17 23:02:03	6.4
405	8.90	-77.11	12	2023-05-25 03:05:39	6.49
406	23.20	-108.42	12	2023-06-18 20:30:30	6.39
407	20.24	-61.14	25	2023-07-10 20:28:33	6.57
408	15.01	-94.07	37	2023-07-14 09:29:03	6.32
409	54.44	-160.90	32	2023-07-16 06:48:30	7.17
410	-38.18	-70.44	193	2023-07-17 03:05:17	6.67
411	12.62	-88.39	53	2023-07-19 00:22:09	6.5
412	-0.44	-19.80	30	2023-08-17 16:41:09	6.07
413	4.34	-73.57	20	2023-08-17 17:04:58	6.19
414	30.94	-8.31	24	2023-09-08 22:11:06	6.86
415	34.59	61.96	12	2023-10-07 06:41:06	6.16
416	34.60	61.87	12	2023-10-07 07:12:51	6.26
417	34.59	62.03	12	2023-10-11 00:41:57	6.24
418	34.62	62.09	12	2023-10-15 03:36:03	6.3
419	-28.83	-71.58	50	2023-10-31 12:33:51	6.64
420	-16.06	-72.77	118	2023-12-20 12:11:26	6.26
421	-7.26	-71.49	618	2024-01-20 21:31:09	6.71
422	41.19	78.56	16	2024-01-22 18:09:14	7.05
423	14.08	-90.82	84	2024-01-27 05:52:50	6.07
424	-8.32	-71.44	634	2024-01-28 09:39:02	6.55
425	29.82	-42.69	12	2024-03-14 21:10:29	6.06
426	14.39	-92.66	48	2024-05-12 11:39:13	6.34
427	-16.01	-74.64	34	2024-06-16 14:47:38	6.03
428	-15.89	-74.75	26	2024-06-28 05:36:45	7.14
429	-16.08	-74.68	22	2024-06-29 07:05:38	6.06
430	-23.14	-67.72	136	2024-07-19 01:50:59	7.33
431	14.61	-90.00	268	2024-07-21 02:53:51	6.22
432	12.84	-89.89	31	2024-08-28 21:57:59	6.1
433	51.46	-130.75	12	2024-09-15 22:22:56	6.52
434	0.85	-29.69	19	2025-03-28 17:17:40	6.57
435	52.67	-33.47	19	2025-04-03 14:09:59	6.87

Table 1: **Table of earthquakes used in final tomographic model.** Events are plotted in map in Figure S1. Events are from the GCMT catalogue (Dziewoński et al., 1981; Ekström et al., 2012). The use of obspyDMT (Hosseini and Sigloch, 2017) was invaluable for catalogue creation.

References

- Chang, S. J., Ferreira, A. M. G., Ritsema, J., Heijst, H. J. V., and Woodhouse, J. H. (2015). Joint inversion for global isotropic and radially anisotropic mantle structure including crustal thickness perturbations. *Journal of Geophysical Research: Solid Earth*, 120(6):4278–4300.
- Cui, C., Lei, W., Liu, Q., Peter, D., Bozdağ, E., Tromp, J., Hill, J., Podhorszki, N., and Pugmire, D. (2024). GLAD-M35: a joint P and S global tomographic model with uncertainty quantification. *Geophysical Journal International*, 239:478–502.
- Durand, S., Debayle, E., Ricard, Y., and Lambotte, S. (2016). Seismic evidence for a change in the large-scale tomographic pattern across the D'' layer. *Geophysical Research Letters*, 43(15):7928–7936.
- Dziewoński, A. M., Chou, T. A., and Woodhouse, J. H. (1981). Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. *Journal of Geophysical Research*, 86:2825–2852.
- Ekström, G., Nettles, M., and Dziewoński, A. M. (2012). The global CMT project 2004-2010: Centroid-moment tensors for 13,017 earthquakes. *Physics of the Earth and Planetary Interiors*, 200-201:1–9.
- French, S. W. and Romanowicz, B. A. (2014). Whole-mantle radially anisotropic shear velocity structure from spectral-element waveform tomography. *Geophysical Journal International*, 199:1303–1327.
- Hosseini, K. and Sigloch, K. (2017). Obspydmt: A python toolbox for retrieving and processing large seismological data sets. *Solid Earth*, 8:1047–1070.
- Thrustarson, S., van Herwaarden, D. P., Noe, S., Schiller, C. J., and Fichtner, A. (2024). REVEAL: A global full-waveform inversion model. *Bulletin of the Seismological Society of America*, 114:1392–1406.