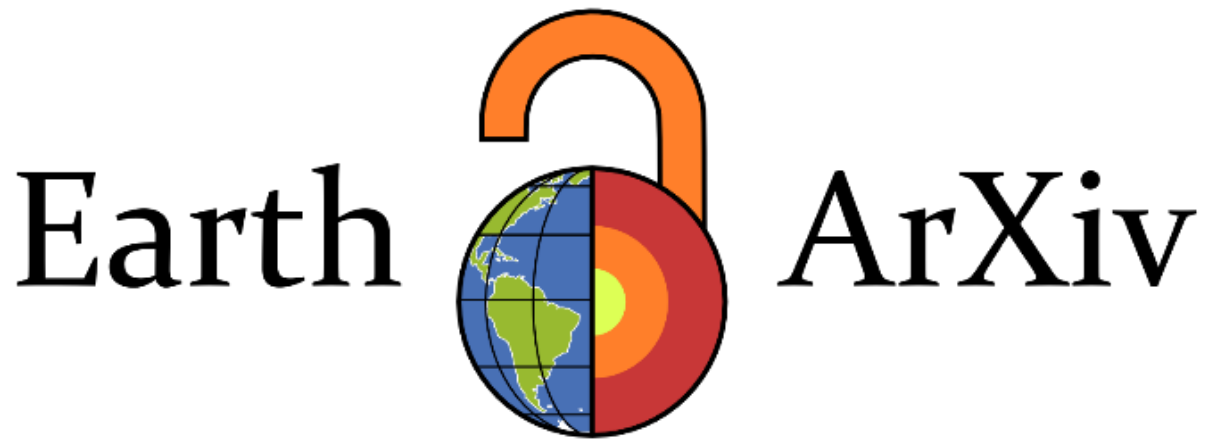




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Seismic Evidence for an Ultralow Velocity Zone Beneath the Cape Verde Hotspot

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Key Points:

- Ultralow velocity zone beneath the Cape Verde hotspot found through seismic wave-form modeling.
- The Cape Verde ULVZ spans roughly 800 km laterally and 40 km in height with a 20% shear velocity drop.
- Results support an emerging global association between mantle plumes and mega-ultralow velocity zones.

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Abstract

Mega ultralow velocity zones (mega-ULVZs), thin patches of strongly reduced seismic velocity with large horizontal extent just above the core-mantle boundary (CMB), are increasingly found beneath deep mantle plumes, suggesting a link to hotspot volcanism. The Cape Verde hotspot is thought to overlie a deep plume, but whether a ULVZ exists at its base has remained unknown. We present core-diffracted shear-wave (Sdiff) waveforms whose postcursor arrivals are not present in synthetics computed from 3D tomographic mantle models. Instead, the data are best explained, to first order, by a quasi-cylindrical ULVZ near (9°N, 20°W) with ~ 800 km lateral extent, ~ 40 km height, and a $\sim 20\%$ shear-velocity reduction. These results suggest the presence of a mega-ULVZ at the root of the Cape Verde plume and strengthen evidence that such structures are common features of deep mantle upwellings.

Plain Language Summary

Deep inside the Earth, just above the core, some regions contain structures with extremely low seismic velocities, known as ultralow velocity zones (ULVZs). These structures are often found beneath volcanic hotspots and might be linked to the rising plumes of hot mantle materials. The Cape Verde hotspot in the Atlantic ocean is one such hotspot which is linked to a deep mantle plume, but no ULVZ has been found at its base. Analyzing seismic waves that travel along the core mantle boundary, we detect secondary arrivals that show the presence of a ULVZ below the Cape Verde hotspot with lateral dimensions of ~ 800 km and a height of ~ 40 km. Shear-wave velocity reduction for this structure is roughly 20%. Our results provide further evidence for the hypothesis that large ULVZs are closely linked to the deep mantle plumes beneath surface hotspots.

1 Introduction

Plumes of hot upwelling material rooted in the deep mantle have been proposed as a possible origin of hotspot volcanism (Morgan, 1971). Global full waveform seismic tomography (French & Romanowicz, 2015) has confirmed this hypothesis by providing evidence for the presence of broad low shear-velocity conduits extending quasi-vertically from the Core Mantle Boundary (CMB) through the lower mantle in the vicinity of all major hotspots located above the large low velocity provinces (LLVPs). On the other hand, thin patches of small lateral extent (order of 10^2 km), 10-40 km in height, and extreme low shear ($\sim 30\%$) and compressional ($\sim 10\%$) velocity, ultralow velocity zones (ULVZs), were discovered at the CMB (Garnero & Helmberger, 1996, 1998) and later shown to be present in many locations around the globe (e.g. Yu and Garnero (2018)). Cottaar and Romanowicz (2012) and Thorne et al. (2013) found exceptionally large (~ 800 - 1000 km in lateral extent) ULVZs, dubbed mega-ULVZs, at the roots of the Hawaiian and Samoa plumes, respectively. Many studies have subsequently confirmed the presence of mega-ULVZs in these locations (e.g. Krier et al. (2021); Li et al. (2022)) as well as under other prominent hotspots such as Iceland (Yuan & Romanowicz, 2017), Marquesas (Kim et al., 2020), Galapagos (Cottaar et al., 2022), and Pitcairn (Li et al., 2024). These observations point to a possible physical relationship between mega-ULVZs and broad deep mantle plumes, and to the possibility that mega-ULVZs might systematically be present at the root of such plumes. Understanding the distribution and properties of mega-ULVZs may shed light on the nature and role of ULVZs in mantle dynamics and evolution (Dannberg et al., 2021; Cottaar et al., 2022). A recent study searching for large ULVZs at the global scale using Sdiff waves (Atkins et al., 2026) confirmed a strong spatial correlation between the detection of mega-ULVZs and the location of major hotspots.

The Cape Verde hotspot is a long-lived hotspot currently active in the Atlantic Ocean. The Cape Verde archipelago currently consists of nine main islands in the southwestern part of the Cape Verde Rise. The underwater swell is ~ 1800 km in diameter and the swell

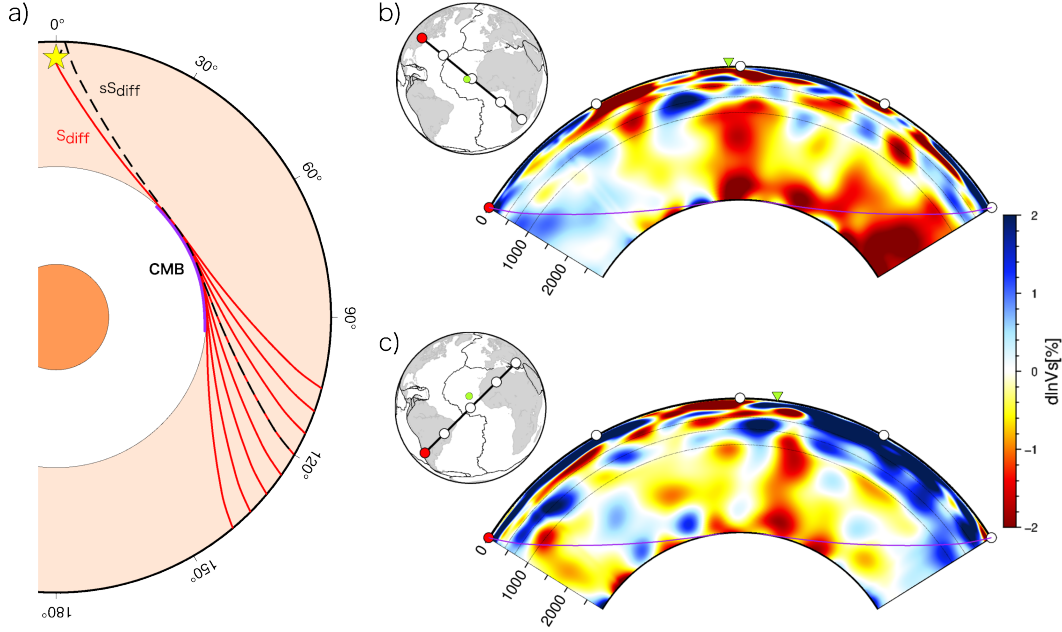


Figure 1. (a) Raypaths of Sdiff phase (red) with epicentral distances between 105° to 140° from the source (yellow star) together with the sSdiff raypath (black dashed line) for an epicentral distance of 120° are computed for a 1D model, (PREM, Dziewonski and Anderson (1981)). The segment of the core-mantle boundary (CMB) sampled by Sdiff and sSdiff raypaths is highlighted in purple. (b) and (c) Whole-mantle depth cross-sections of relative shear-velocity variations (dlnVs) in model SEMATL23 (Munch et al., 2024) along typical Sdiff raypaths (purple) going through the Cape Verde plume. The Cape Verde hotspot is plotted as a green triangle and as a green circle in the inset plots.

is ~2 km high over the surrounding ocean floor (Wilson et al., 2013). It is associated with elevated surface heat flow (Courtney & White, 1986) and a geoid anomaly of +8 m (Monnereau & Cazenave, 1990). Geochemical and isotope studies of the Cape Verde hotspot show a contribution from deep mantle sources. Basalts from the different islands display heterogeneity, but the overall signatures are consistent with the presence of lower-mantle material in the source (Doucelance et al., 2003; Millet et al., 2008). A broad low-velocity conduit extending vertically from the CMB to the top of the lower mantle has been imaged consistently by global full waveform tomography (French & Romanowicz, 2015; Lei et al., 2020). At shallower depths, the plume becomes more difficult to trace (Fig. 1b & c), as it likely branches into narrower conduits that deflect and meander across the upper mantle, as confirmed recently by higher resolution modeling (Munch et al., 2024). However, no evidence for the presence of an ULVZ beneath Cape Verde (e.g. Atkins et al. (2026)) has yet been found.

While most studies, including the pioneering ones, detected and characterized ULVZs using a variety of core reflected or transmitted seismic phases, diffracted waves (e.g., Sdiff, Fig. 1a) are more sensitive to the full lateral extent of mega-ULVZs. The Sdiff phase propagates along the CMB for a significant portion of its path and is therefore highly sensitive to velocity perturbations in the lowermost mantle. Distortions in the Sdiff waveform as a function of azimuth and the presence of additional, delayed phases, or “post-cursors”, can be used to constrain the lateral and height variations of ULVZ structures (Cottaar & Romanowicz, 2012; Yuan & Romanowicz, 2017; Cottaar et al., 2022; Wolf

& Long, 2023; Wolf et al., 2024). Here we use Sdiff to detect and characterize a potential ULVZ beneath the Cape Verde hotspot.

2 Data and Methods

2.1 Data Catalogue

We use Sdiff transverse component records at epicentral distances between 100° and 130° . When Sdiff traverses an ULVZ, it undergoes pronounced multipathing, generating postcursors that arrive tens of seconds after the main phase, which itself can be slightly delayed. The characteristic hyperbolic moveout of these postcursors serves as a diagnostic signature of ULVZ structure (Cottaar & Romanowicz, 2012).

We visually inspected all events since January 1995, with magnitudes above Mw 6 between latitudes 20°S to 40°S and longitude 66°W to 72°W , where Sdiff paths to existing broadband stations from different datacenters (Earthscope, ORFEUS, GFZ, BGR, ETH, INGV, IGP, RESIF, KNMI, KOERI, LMU, NIEP, NOA, UIB-NORSAR, IGN, ICGC) sampled the lowermost mantle beneath Cape Verde along a northeast-southwest direction. We also examined earthquakes in southern Africa (south of 15°S latitude), for which Sdiff raypaths traversed the same lowermost-mantle region along a northwest-southeast direction and were recorded by the USArray. For each event, the transverse-component (SH) waveforms were bandpass filtered between 7 and 18 s, and only traces with signal-to-noise ratio (SNR) greater than 3 were retained. The selected waveforms were then organized by azimuth from the source, windowed around the Sdiff arrival predicted by the Preliminary Reference Earth Model (PREM; Dziewonski and Anderson (1981)), and stacked in 1° azimuthal bins.

We identified two events that provide clear evidence for the presence of a large ULVZ beneath Cape Verde. The primary event (Event 1: April 3, 2017) is a Mw 6.5 (depth = 30 km) rare intraplate earthquake in Botswana, for which Sdiff phases were recorded by the dense USArray at distances $>100^\circ$ (Fig. 2a), and sampled the lowermost mantle beneath Cape Verde. These data show a pronounced, quasi-hyperbolically shaped, Sdiff postcursor consistent with an ULVZ at this location (Fig. 2b) (Su, 2022). The second event (Event 2: February 2, 2015), a Mw 6.3 (depth = 172 km) earthquake in Argentina also shows a clear, though faint postcursor, that may originate from the same ULVZ (Fig. 3a). Together, these events provide two independent source–receiver geometries and complementary raypath coverage of the same region at the CMB. Most other western South American earthquakes recorded in eastern Europe are too noisy to reliably characterize Sdiff postcursors on their own (Fig. S1).

2.2 Forward Modeling

To compute synthetic seismograms and obtain forward-modeling constraints on the ULVZ properties, we use the “sandwiched” Coupled Spectral Element Method (Capdeville et al., 2003), in which the Spectral Element Method (SEM) is used in the depth-range where 3D wave propagation must be resolved at high accuracy, while outside of this shell, wave propagation is computed using efficient Normal Mode Summation (NMS) in a radially symmetric “1D” Earth model. The two computations are coupled along the boundaries of the annulus using a Dirichlet-to-Neumann transformation. By restricting SEM to the volume of interest, the overall computational cost is substantially reduced relative to a fully global SEM 3D simulation. Here, the annulus where 3D structure is considered extends from the CMB up to 370 km above it. This setup has been used in previous ULVZ modeling projects (e.g. Cottaar and Romanowicz (2012); Yuan and Romanowicz (2017); Cottaar et al. (2022)) and allows us to compute synthetics efficiently and accurately down to 10 s period with a finely meshed lowermost mantle suitable for resolving ULVZ-scale structure. For each event, neglecting the 3D structure outside of the shell

amounts essentially to a constant shift in the arrival times of the Sdiff across the array of stations considered. Source parameters and moment tensor solutions used in the waveform simulations are taken from the Global Centroid Moment Tensor Project (Ekström et al., 2012).

We use PREM (Dziewonski & Anderson, 1981) as the background 1D model for the normal-mode solution and SEMUCB-WM1 (French & Romanowicz, 2014) as the 3D mantle model in the deep mantle, onto which we superimpose a cylindrical low-velocity anomaly at the CMB to represent the ULVZ. The ULVZ is parameterized by its location, radius, height, and shear-velocity reduction. This simplified cylindrical geometry has been shown to successfully reproduce observed Sdiff postcursors to first-order in previous studies (Cottaar & Romanowicz, 2012; Yuan & Romanowicz, 2017; Cottaar et al., 2022; Wolf & Long, 2023; Li et al., 2024).

Our initial trial location is guided by the shear velocity minima of SEMUCB-WM1 beneath Cape Verde. We then identify the azimuth at which the Event 1 postcursors exhibit the smallest time delays and back-project along this direction to estimate candidate ULVZ locations. The same procedure is applied to Event 2 to refine the preferred location. We also vary the height, radius, and velocity reduction of the cylinder, although strong trade-offs among these parameters make them difficult to constrain independently (e.g. Li et al. (2024)).

3 Results

Waveforms from Event 1 (Fig. 2b) exhibit exceptionally clear main Sdiff arrivals, with $\text{SNR} > 3$ at most stations, and prominent postcursors. Given their clarity, we first focus our ULVZ analysis on this event. As a reference, we first compute synthetic waveforms using SEMUCB-WM1 without any imposed ULVZ structure (Fig. 2c). Although these synthetics account for the source radiation pattern and the long-wavelength 3D structure of the lowermost mantle, they contain no postcursor energy. Reproducing the observed postcursors therefore requires an additional, localized, strong shear velocity anomaly near the CMB.

We identify the azimuth range over which the postcursors are most prominent (290° – 310°). Within this range, a quasi-hyperbolic postcursor arrives 30–40 s after the main Sdiff phase, with the smallest delay near an azimuth of 298° . Guided by these constraints, we run a series of trial simulations exploring different ULVZ locations and, after visual evaluation of the waveform fits, identify a preferred model: a cylinder of 800 km diameter, 40 km height, and 20% shear-velocity reduction, centered at (8.65°N , 19.64°W). Synthetics for this model are shown in Fig. 2d. A comparison with alternative ULVZ models is presented in Fig. S2; owing to the strong trade-off between ULVZ height and velocity reduction in the limited frequency range considered (e.g., Wolf et al. (2024); Martin et al. (2024)), we restrict this comparison to variations in velocity reduction at a fixed height of 40 km.

Although the waveforms for Event 2 are noisier and the postcursors are less distinct than those observed for Event 1, the observed Sdiff (Fig. S3) and sSdiff (Fig. 3b) arrivals can also be explained by a cylindrical ULVZ at the same location and with dimensions consistent with those inferred from Event 1. Because the postcursors are more clearly visible for the depth phase, sSdiff, we primarily use the sSdiff observations for the modeling (Fig. 3d).

4 Discussion and Conclusions

Our observations and modeling show that the Sdiff postcursors recorded for two independent events sampling the lowermost mantle beneath Cape Verde from different

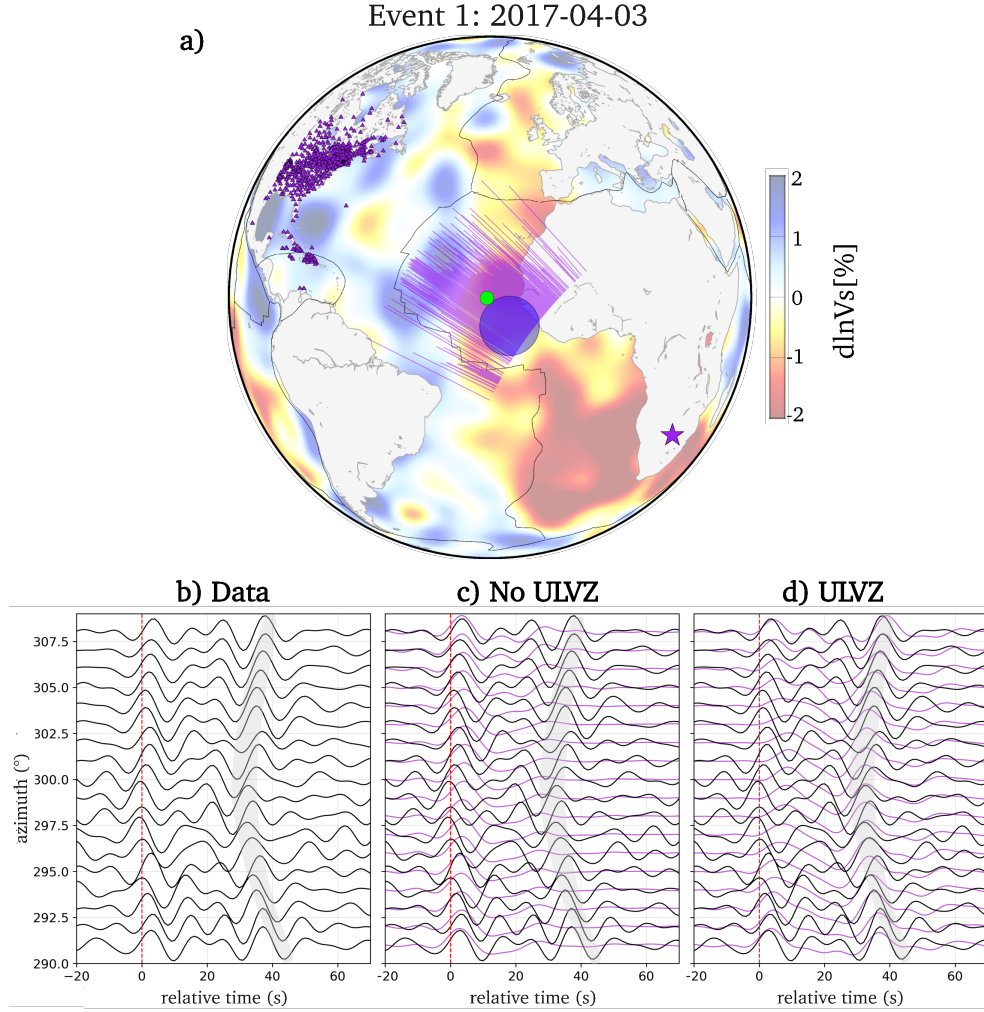


Figure 2. Sdiff raypaths and SH waveforms for 2017-04-03 Mw 6.5 earthquake in Botswana (Event 1). (a) The star shows the epicenter of Event 1. All the Sdiff raypaths where it grazes the CMB are drawn as violet colored lines. The corresponding stations where Sdiff phases are recorded are shown as violet triangles. The background model is SEMUCB-WM1 (French & Romanowicz, 2014) presented in terms of relative shear wave velocity deviations (in percent) from the global 1D average at 2800 km. The green circle shows the location of the Cape Verde hotspot. The blue circle shows the projection at 2800 km depth of the proposed model for the Cape Verde ULVZ at (8.65°N, 19.64°W) (b) Tangential component Sdiff data for event 1. The interpreted postcursors are highlighted in grey; (c) Waveform comparisons between data (black) and synthetic waveforms (purple) for tomography model SEMUCB-WM1 ; (d) Waveform comparisons between data (black) and synthetic waveforms (purple) for our proposed ULVZ model superimposed on SEMUCB-WM1. All the waveforms are filtered between 7s - 18s period and stacked in 1° azimuth bins.

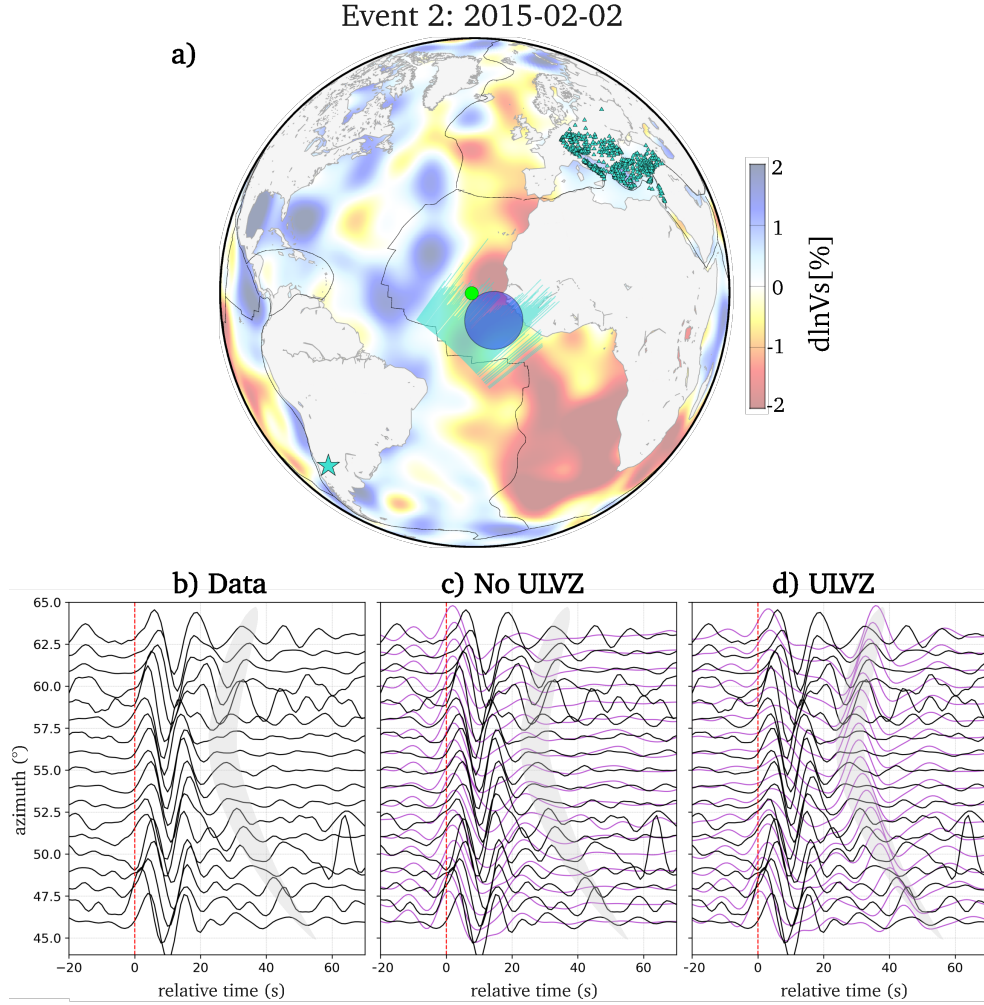


Figure 3. sSdiff raypaths and SH waveforms for 2015-02-02 Mw 6.3 earthquake in Argentina (Event 2). (a) The star shows the epicenter of Event 2. The portion of sSdiff raypaths grazing the CMB are drawn as turquoise lines. The corresponding stations where sSdiff phases are recorded are depicted as turquoise triangles. The background model is SEMUCB-WM1 (French & Romanowicz, 2014) presented in terms of relative shear wave velocity deviations (in percent) from the global 1D average at 2800 km. The green circle shows the location of the Cape Verde hotspot. The blue circle shows the projection at 2800 km depth of the proposed model for the Cape Verde ULVZ at (8.65°N, 19.64°W) (b) Tangential component sSdiff data for event 2. The interpreted postcursors are highlighted in grey; (c) Waveform comparisons between data (black) and synthetic waveforms for tomography model SEMUCB-WM1 (violet); (d) Waveform comparisons between data (black) and synthetic waveforms for our proposed ULVZ model superimposed on SEMUCB-WM1 (violet). All the waveforms are filtered between 7s - 18s period and stacked in 1° azimuth bins.

directions can be explained by the presence of an ULVZ at the base of the mantle in the central Atlantic, in the vicinity of the Cape Verde hotspot. The preferred model, a cylindrical body of ~ 800 km lateral extent, ~ 40 km height, and 20% shear-velocity reduction, makes the Cape Verde ULVZ comparable in scale to the mega-ULVZs documented beneath Hawai'i (Cottaar & Romanowicz, 2012; Jenkins et al., 2021; Kim et al., 2026), Iceland (Yuan & Romanowicz, 2017), Samoa (Thorne et al., 2013), Galapagos (Cottaar et al., 2022), Pitcairn (Li et al., 2024), St. Helena (Davison et al., 2024), and Marquesas (Kim et al., 2020).

As in many ULVZ studies, strong trade-offs between ULVZ height, diameter and velocity reduction exist (Li et al., 2024). Our ULVZ model is thus not unique. To first order, a cylindrical anomaly explains the post-cursor arrival times quite well, qualitatively. In fact, we have found *a posteriori* that Sdiff record sections for several other events in South America exhibit post-cursors that are compatible with the proposed model (Fig. S4). Constraining the detailed geometry of the ULVZ would require further modeling, and in particular broadening the frequency range to higher frequencies, which is computationally challenging for the Coupled-CSEM code at present. Also, joint Pdiff-Sdiff waveform modeling (e.g., Kim et al. (2026)) could better constrain both the geometry of the structure and its possible physical interpretation. We leave this for further studies.

The Cape Verde hotspot is one of the major hotspots imaged tomographically as a broad low-velocity conduit extending from the CMB to the upper mantle to the CMB (French & Romanowicz, 2015; Munch et al., 2024), and ocean island basalts from the archipelago carry isotopic signatures consistent with a deep, primitive mantle source (Doucance et al., 2003; Millet et al., 2008). The location of the mega-ULVZ inferred from our waveform modeling coincides with a pronounced low-velocity anomaly in several recent global tomographic models (Fig. S5), including REVEAL (Thrustarson et al., 2024), SPiRaL (Simmons et al., 2021) and GLAD-M35 (Cui et al., 2024), further supporting a link between the ULVZ and the Cape Verde mantle plume. The detection of a mega-ULVZ at its base therefore reinforces an emerging pattern (Fig. 4): many broad plumes rooted in the lowermost mantle that have been examined with adequate seismic coverage are associated with a mega-ULVZ at its base (e.g. Cottaar and Romanowicz (2012); Thorne et al. (2013); Yuan and Romanowicz (2017); Atkins et al. (2026)). This recurring spatial correlation suggests that large ULVZs are present at the roots of many, and perhaps all broad mantle plumes. Their further identification remains a challenge because of the available distribution of earthquake sources and broadband arrays which limits the sampling of the D'' region by relevant seismic phases (e.g. Atkins et al. (2026)).

The composition and physical state of ULVZs remain debated. Partial melting of silicate material at the base of the mantle, possibly enriched in iron (Williams & Garnero, 1996; Yuan & Romanowicz, 2017), and solid-state assemblages enriched in iron-bearing (Mg,Fe)O (Wicks et al., 2010; Kim et al., 2026) have both been proposed, and recent joint analyses of P- and S-diffracted phases under Hawai'i seem to favor the latter (Jagt et al., 2024; Kim et al., 2026), although the quasi-circular base of this and other ULVZs and their location within the roots of major mantle plumes suggests that a model where ULVZs represent a thickening of a partially molten thin core-mantle interaction layer (Yuan & Romanowicz, 2017) cannot be ruled out. Our shear-wave-only dataset cannot constrain compressional velocity or density and therefore cannot discriminate between these scenarios beneath Cape Verde.

Taken together, our results add Cape Verde to the growing list of major hotspots associated with mantle plumes that house large ULVZs at their base, and reinforce the view that such structures are a common, perhaps systematic, feature at the roots of mantle plumes. Further characterization of the lowermost mantle beneath the remaining hotspots, particularly those poorly sampled by current networks, will be essential to determine whether

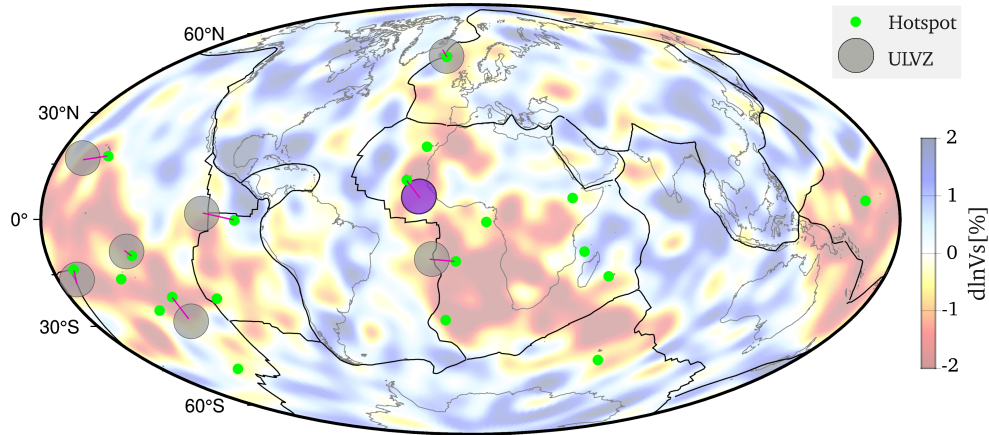


Figure 4. Global distribution of hotspots (green circles) where plumes were detected as conduits extending from the CMB through most of the lower mantle from SEMUCB-WM1 model (French and Romanowicz (2015), for the categories ‘Primary Plume’ and ‘Clearly resolved’). The detected ULVZs that are associated with these mantle plumes are shown as grey regions (Hawaii: Cottaar and Romanowicz (2012); Li et al. (2022); Samoa: Thorne et al. (2013); Iceland: Yuan and Romanowicz (2017); Marquesas: Kim et al. (2020); Galapagos: Cottaar et al. (2022); St Helena: Davison et al. (2024); Pitcairn: Li et al. (2024)). The ULVZ associated with the Cape Verde hotspot is shown as a purple circle. The ULVZs shown are not to scale.

this association is universal and to clarify what ULVZs reveal about the long-term thermochemical evolution of the deep mantle.

Data Availability Statement

Data were collected from the following on-line data centers: BGR (<https://eida.bgr.de/>), Earthscope (<http://service.iris.edu/>), ETH (<https://eida.ethz.ch/>), GEOFON (<https://geofon.gfz-potsdam.de/>) (GEOFON Data Centre, 1993), ICGC (<https://www.icgc.cat/en/Ciutada/Explora-Catalunya/Terratremols>), IGN (<http://www.ign.es/>), INGV (http://cnt.rm.ingv.it/en/webservices_and_software), IPGP (<http://ws.ipgp.fr/>) (Institut de Physique du Globe de Paris (IPGP) & École et Observatoire des Sciences de la Terre de Strasbourg (EOST), 1982), KNMI (<http://rdsa.knmi.nl/>), KOERI (<http://www.koeri.boun.edu.tr/new/en>), LMU (<http://erde.geophysik.uni-muenchen.de/>), NIEP (<https://www.infp.ro/>), NOA (<http://bbnet.gein.noa.gr/HL/>), ORFEUS (<http://www.orfeus-eu.org/>), RESIF (<https://seismology.resif.fr/>) (RESIF, 1995), and UIB-NORSAR (<https://eida.geo.uib.no/>).

Conflict of Interest declaration

The authors declare there are no conflicts of interest for this manuscript.

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Supplementary Information

For paper: *Seismic Evidence for an ultralow velocity zone beneath the Cape Verde Hotspot*

Ev: 2023-07-17; Mw 6.6; dp 186 km

Ev: 2024-12-13; Mw 6.4; dp 109 km

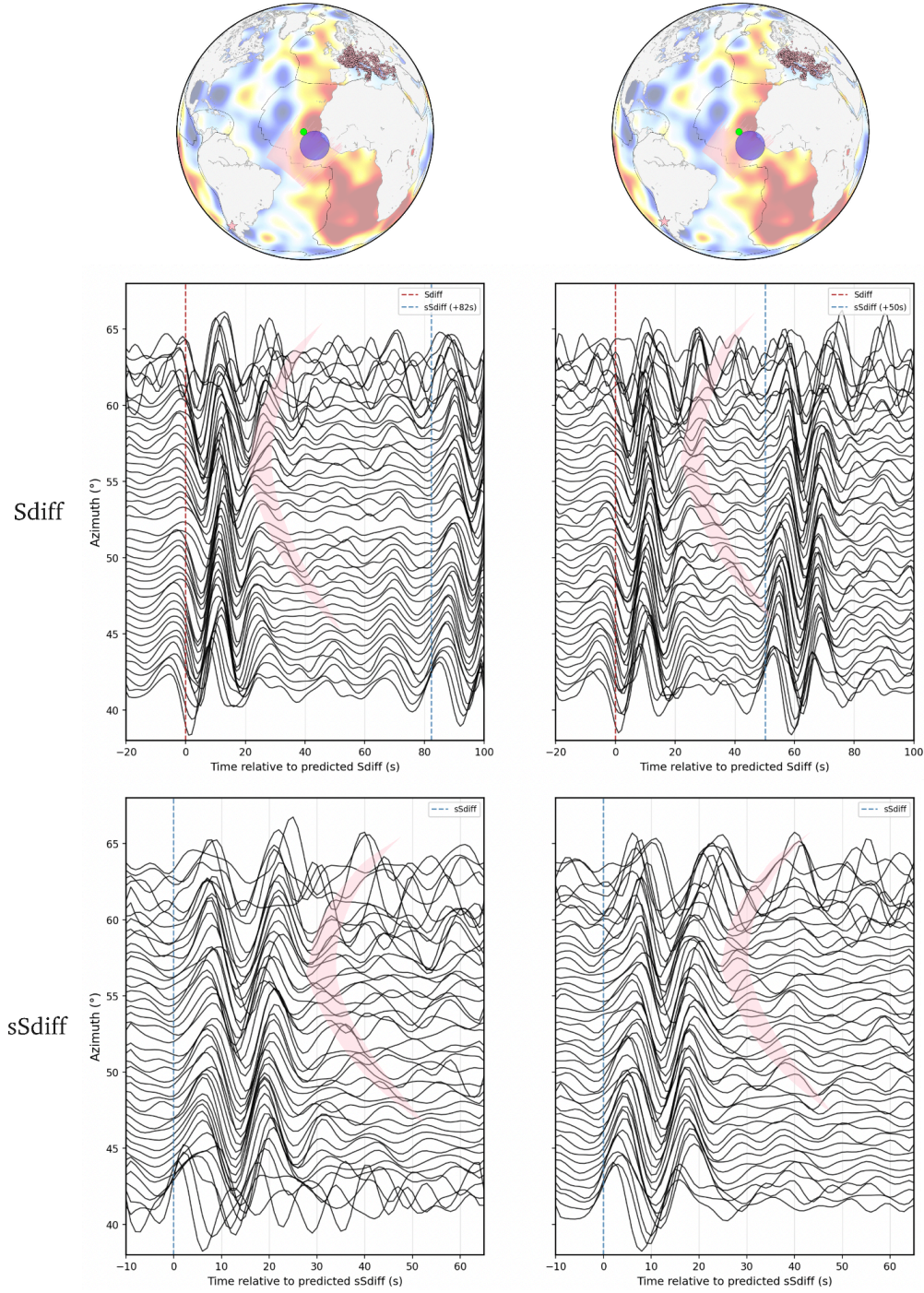


Fig S1: Raypaths and SH waveforms for two events in South America exhibiting Sdiff and sSdiff postcursors. All the waveforms are filtered between 7s - 18s period and stacked in 0.5° azimuth bins. The interpreted postcursors are highlighted in pink. Maps show the earthquake epicenter (star), seismic stations (triangles) and the Sdiff raypaths where it grazes the CMB (colored lines) respectively.

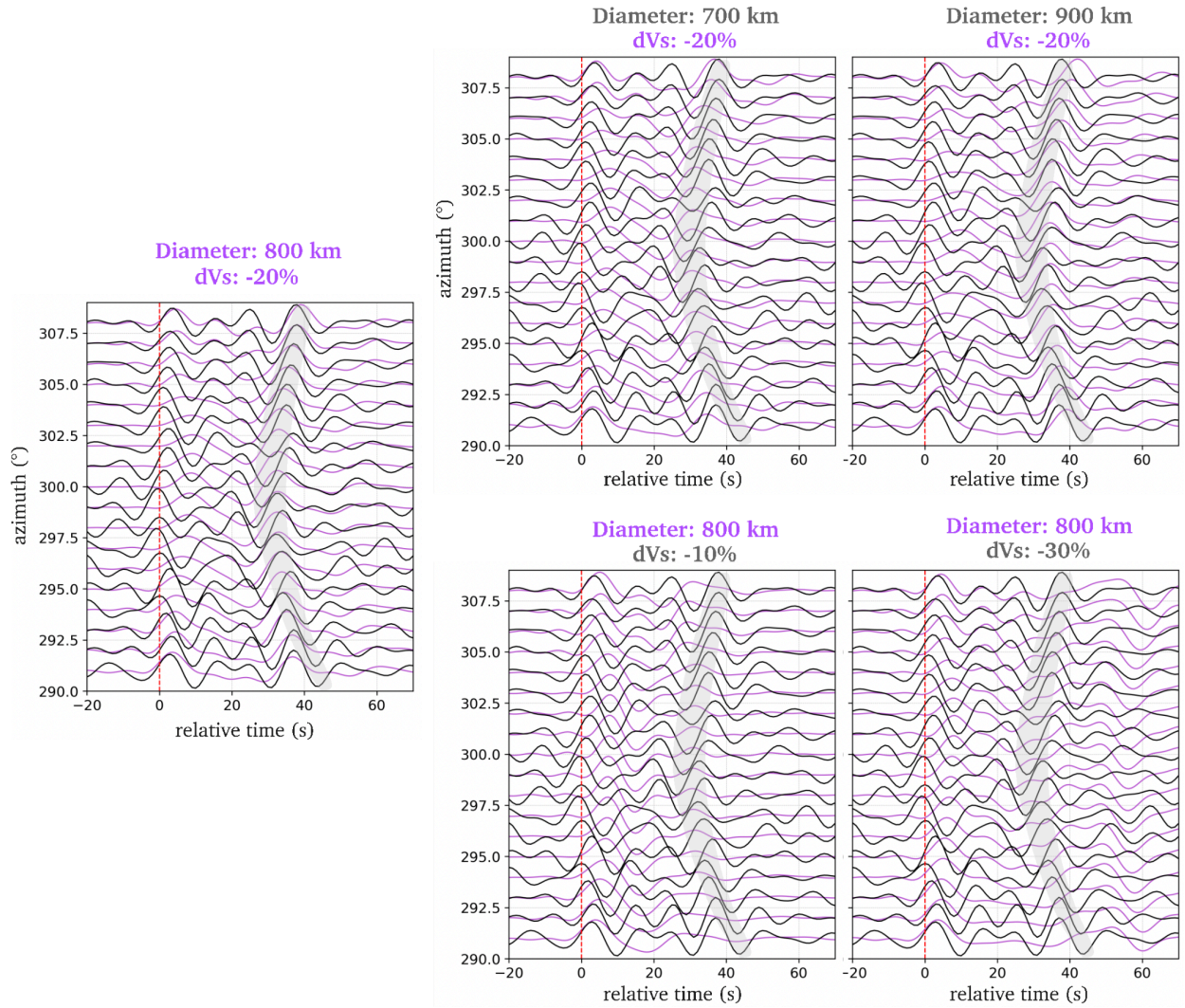


Fig S2: Synthetic waveform comparison between the best-fitting ULVZ model and alternative ULVZ models for Event 1. The ULVZ height is fixed at 40 km in all cases, while the ULVZ diameter and S-wave velocity reduction are varied. All the waveforms are filtered between 7s - 18s period and stacked in 1° azimuth bins.

Event 2: 2015-02-02

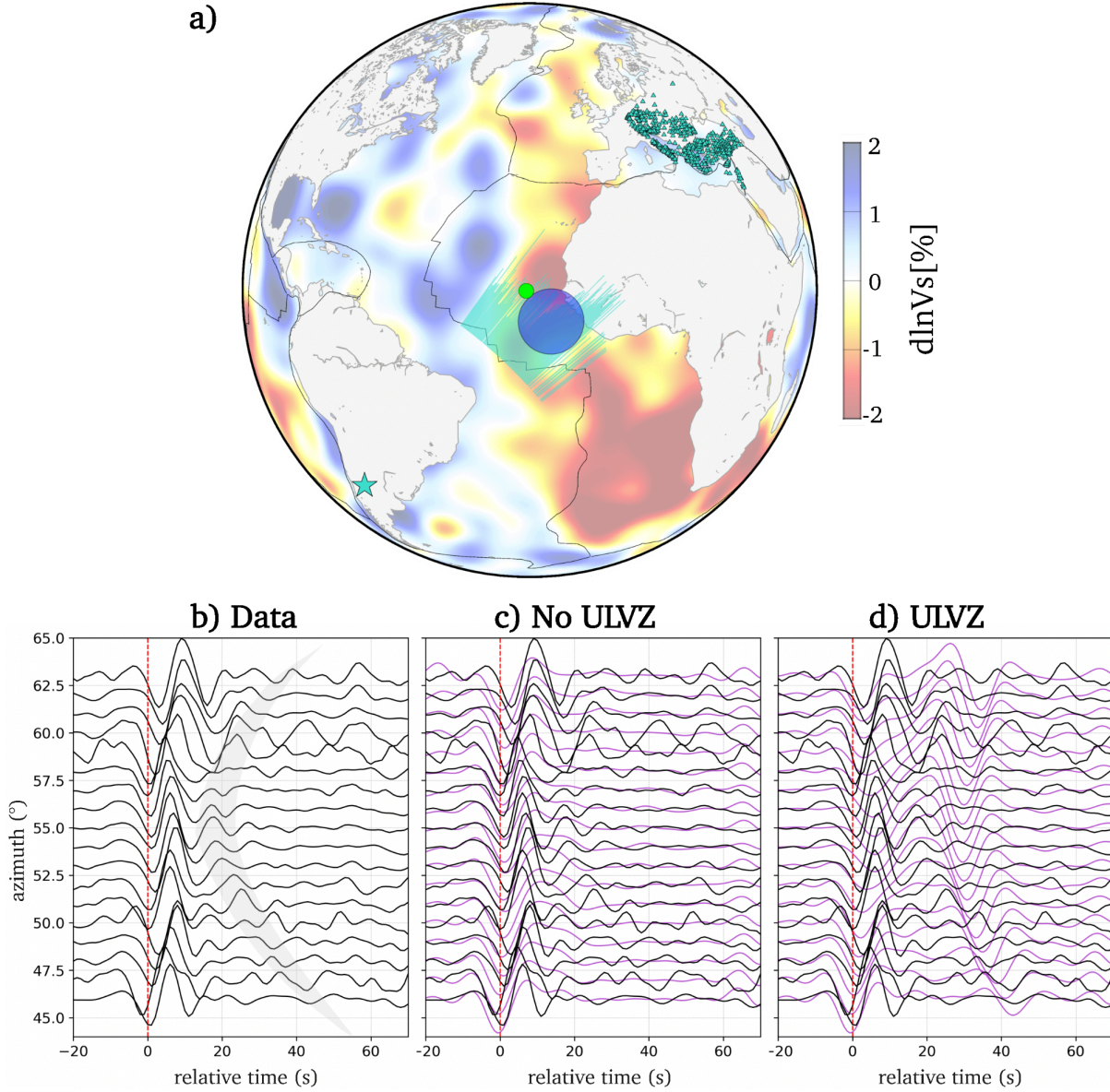


Fig S3: Raypaths and SH waveforms for 2015-02-02 Mw 6.3 earthquake in Argentina (Event 2). (a) The star shows the epicenter of Event 2. All the Sdiff raypaths where it grazes the CMB are drawn as turquoise lines. The corresponding stations where Sdiff phases are recorded are depicted as turquoise triangles. The background model is SEMUCB-WM1 (French and Romanowicz, 2014) presented in terms of shear wave velocity deviations from the global 1D average at 2800 km. The green circle shows the location of the Cape Verde hotspot. The blue circle shows the projection at 2800 km depth of the proposed model for the Cape Verde ULVZ at (8.65°N, 19.64°W) (b) Tangential component Sdiff data for event 2. The interpreted postcursors are highlighted in grey; (c) Waveform comparisons between data (black) and synthetic waveforms (purple) for tomography model SEMUCB-WM1 ; (d) Waveform comparisons between data (black) and synthetic waveforms for our proposed ULVZ model superimposed on SEMUCB-WM1 (violet). All the waveforms are filtered between 7s - 18s period and stacked in 1° azimuth bins.

Ev: 2023-07-17; Mw 6.6; dp 186 km

Ev: 2024-12-13; Mw 6.4; dp 109 km

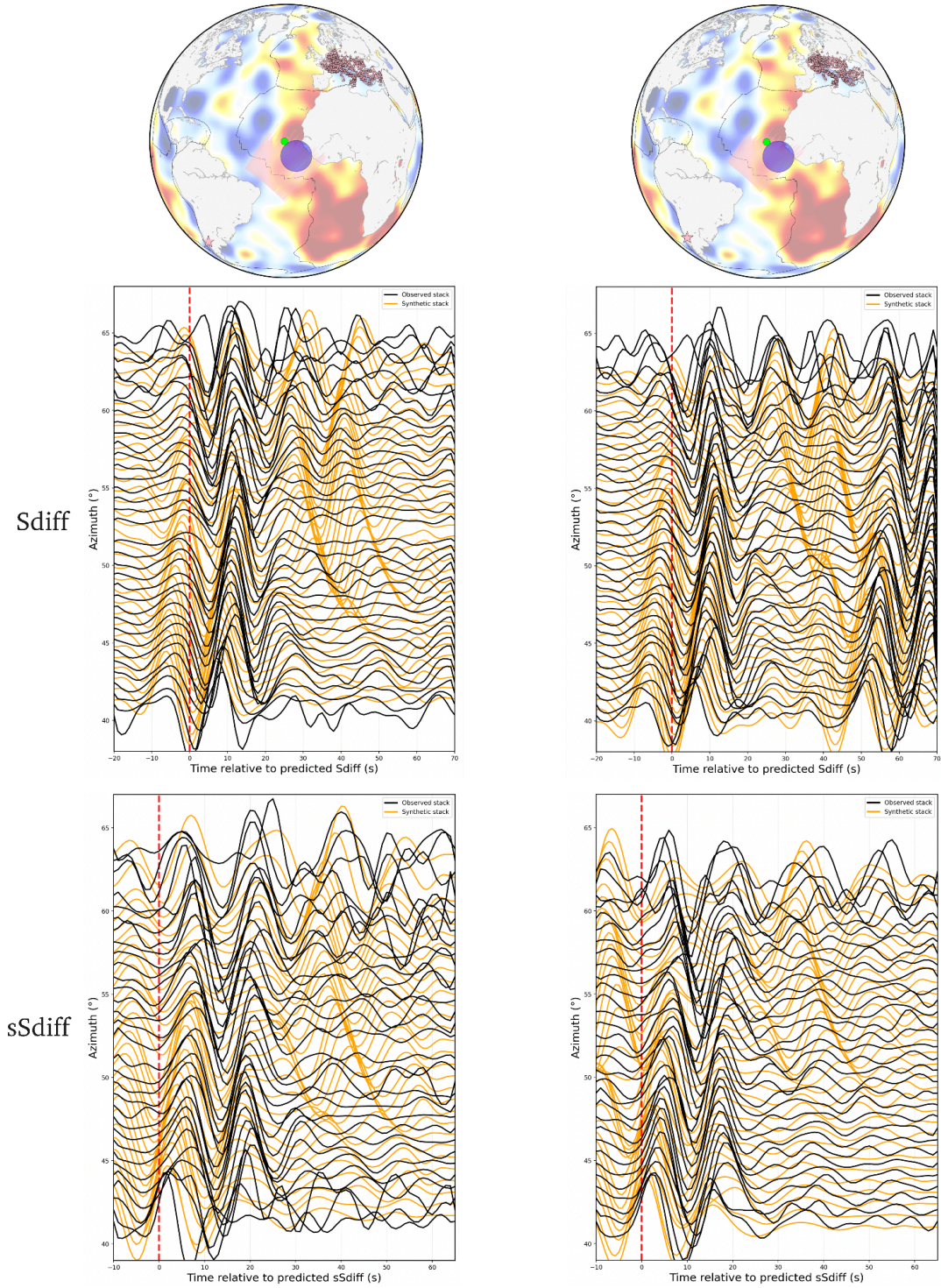


Fig S4: Raypaths and SH waveform comparison for two events in South America exhibiting Sdiff and sSdiff postcursors. Waveform comparisons are between the data (black) and synthetic waveforms (orange) for our proposed ULVZ model superimposed on SEMUCB-WM1. All the waveforms are filtered between 7s - 18s period and stacked in 0.5° azimuth bins. Maps show the earthquake epicenter (star), seismic stations (triangles) and the Sdiff raypaths where it grazes the CMB (colored lines) respectively.

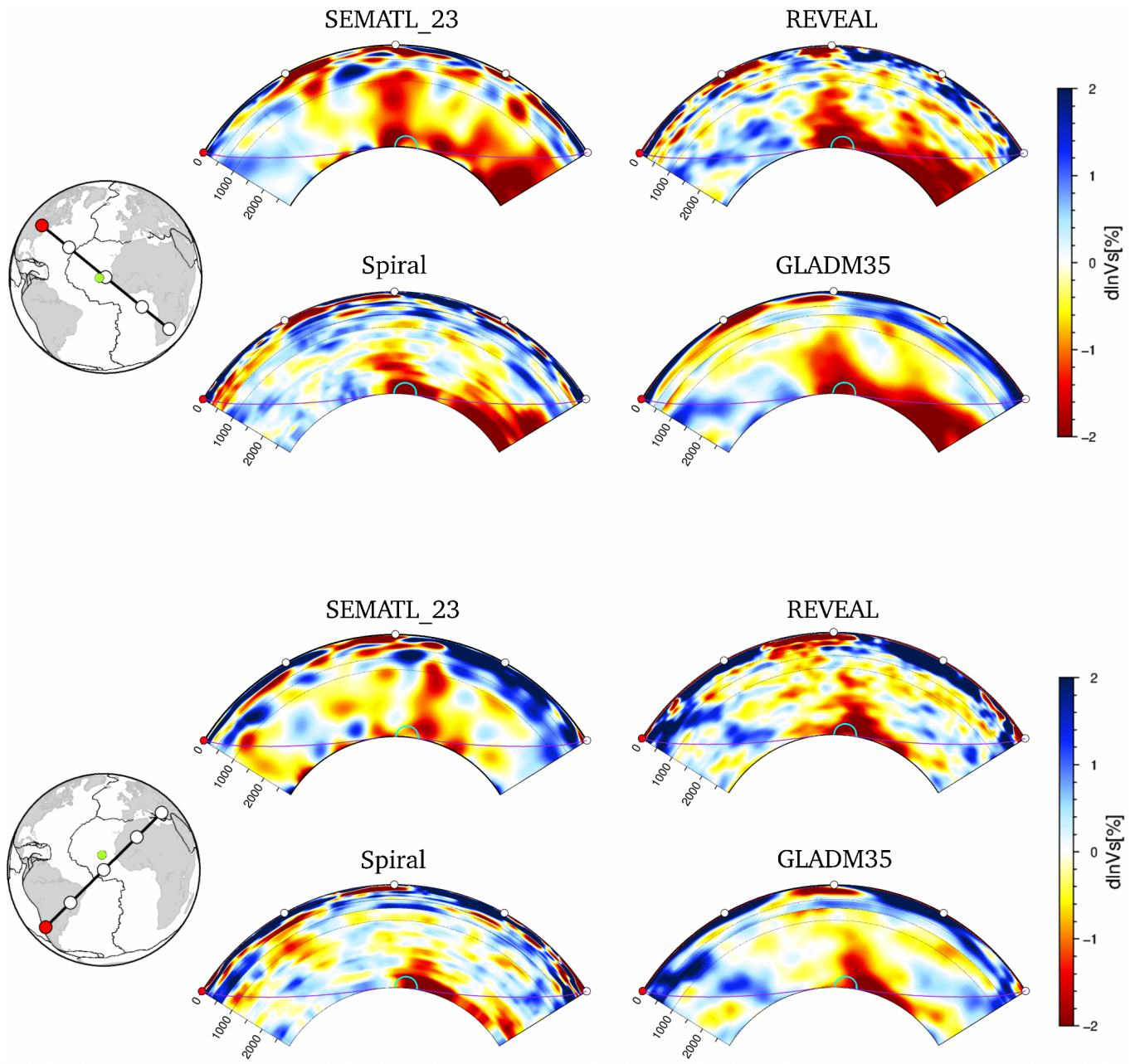


Fig S5: Whole-mantle depth cross-sections of relative shear-velocity variations ($d\ln V_s$) in different models along typical S_{diff} raypaths (purple) going through the Cape Verde plume along two azimuths (same as Fig. 1b & c). The best modeled ULVZ at (8.65°N , 19.64°W) is shown as a cyan dome on the core-mantle boundary (not to scale). The Cape Verde hotspot is plotted as a green circle in the inset plots.