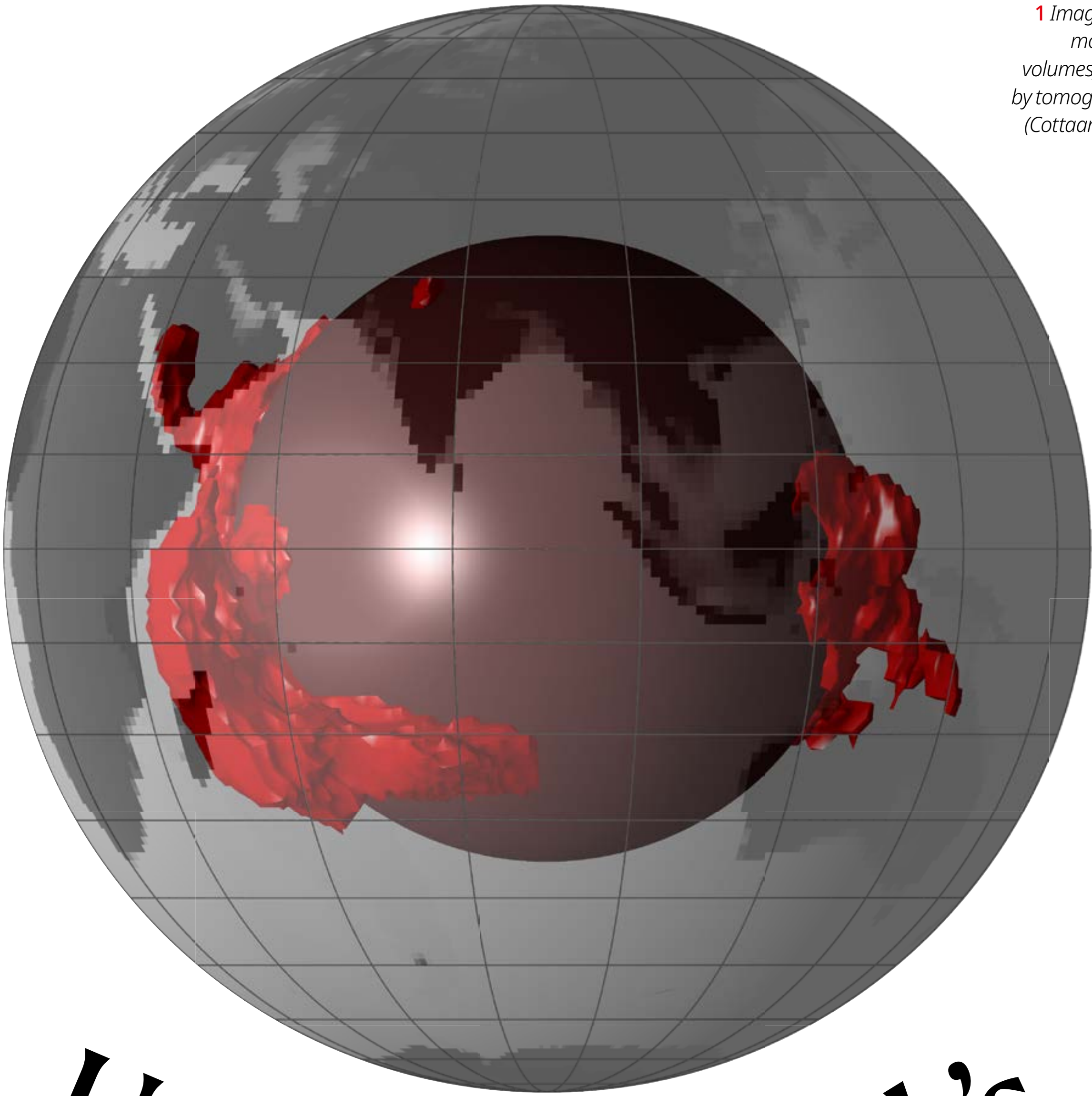


1 *Image of the LLSVP morphology (red volumes) as suggested by tomographic models (Cottaar & Lekić, 2016)*

Unlocking Earth's deep secrets

Sanne Cottaar, Carl Martin, Stuart Russell, and Lisanne Jagt explore the surprisingly variable nature – and unsatisfactory terminology – of Earth's core-mantle boundary

The most extreme boundary on Earth lies not at its surface, but nearly halfway to the centre of the planet at a depth of around 2900km. This is the boundary between Earth's mantle and core; it divides the solid, sluggish mantle from the dense, liquid, turbulently convecting outer core. The outer core consists of an iron alloy, while the mantle is dominantly rocky silicates.

The core-mantle boundary formed early in Earth's history as dense iron sank to the centre forming the core. Since then, the boundary has played an important role in the evolution and dynamics of our planet. The heat flux across it cools the outer core, causing convection and driving the geodynamo. Lateral and temporal variations in the heat flux can affect the stability of the geodynamo, resulting in a time-varying magnetic field. The flux across the core-mantle boundary also heats the base of the mantle, where upwelling mantle plumes form, which cause intraplate hotspot volcanism at the surface. This mechanism explains, for example, Hawaiian volcanism. Chemical exchange may also occur, although the direction and nature of material flux are debated.

The heat and chemical fluxes across the boundary are influenced by the heterogeneity surrounding it. To investigate this heterogeneity, we study seismic waves that interact with the core-mantle boundary. The travel times, amplitudes, frequency content, and complexities of these waves all provide different observations of the shapes and properties of the heterogeneity.

On the core side, the debate is open on the presence or visibility of variable stably stratified layer (see the *A&G* article by Hardy and Wong, 2019). On the mantle side, the heterogeneity is much stronger and more varied. On the large scale it is dominated by two continent-sized, antipodal, ~1000km-high regions of seismically slow velocities (down to ~7.1kms^{-1}), surrounded by a region of seismically fast velocities (up to ~7.7kms^{-1}). The slow velocities are interpreted as hotter regions, either clustered upwelling mantle plumes, or a base layer with a dense composition and upwelling plumes above. These regions are generally referred to as Large Low Shear Velocity Provinces (LLSVPs, see figure 1 and box-out 'Can you pick your own nickname?'). The surrounding fast regions are interpreted as cold downwelling regions or 'slab graveyards'. The ongoing mantle dynamics related to these upwellings and downwellings should cause a degree of dynamic topography on the core-mantle boundary, but both models and observations of this vary widely (reviewed by Koelemeijer 2021).

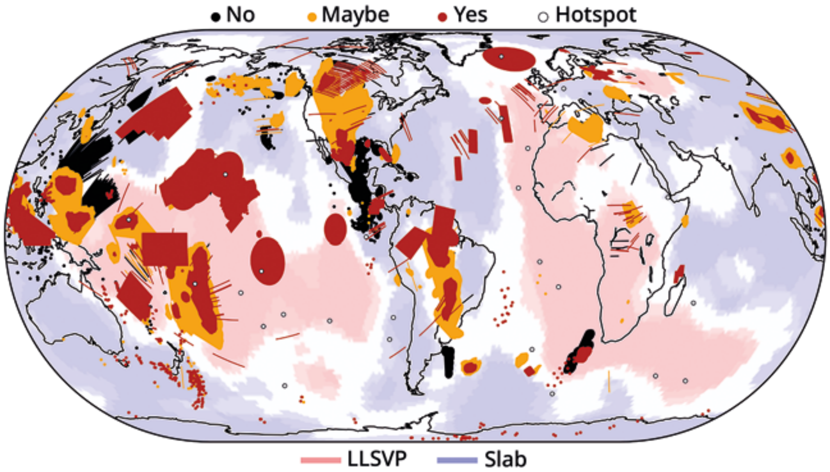
On a smaller scale, right on the core-mantle boundary, we find more extreme anomalies. These are referred to as Ultra-Low Velocity Zones (ULVZs). The zones are on the order of tens of kilometres thick and hundreds of kilometres wide. Shear waves propagate through with a velocity that is 20–30% lower than in the surrounding areas, with velocities of about 5.2–5.9kms^{-1}. The map of where ULVZs have been detected is patchy (see figure 2, also Yu and Garnero 2018). This patchiness arises largely from the limitations of finding suitable earthquake-seismometer geometries to sample the core-mantle boundary. Earthquakes occur predominantly at plate boundaries, and seismometers are mainly on land and concentrated in the northern hemisphere.

The seismic image of the morphology of ULVZs also remains fuzzy, and different seismologists would probably sketch them very differently when asked to provide a cartoon. This might partly be due to actual natural variability in the ULVZs we observe, but there is also the challenge that various seismic waves probe the ULVZs differently. Each seismic study makes simplifications in the modelling set-up and has trade-offs between model parameters. Most are limited to interpreting 1D (radial) or 2D (within the plane of the ray path) structure. Most of the early studies used waves that reflected off the core-mantle boundary or interacted with the boundary while entering or exiting the core. Here, we will discuss our recent use of shear (transverse) diffracted waves, which propagate along the core-mantle boundary as an interface wave (figure 3). We also present our steps towards constraining the 3D shape of ULVZs.

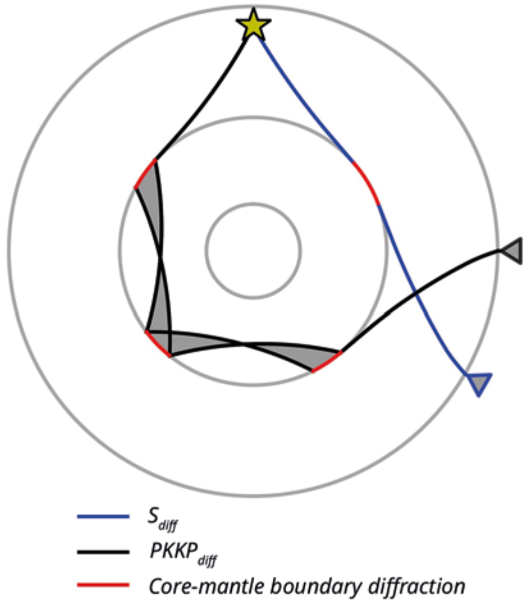
Sdiff postcursors

Shear (transverse) core-diffracted waves, called Sdiff waves (figure 3), provide us with their own unique constraints on ULVZs. Energy of the diffracted wave propagating along the core-mantle boundary gets trapped and resonates within a ULVZ at certain frequencies. Because velocities in the ULVZ are slow, this energy is delayed and refracted out of path (figure 4a). At the seismometer, this wave energy arrives 20–80 seconds after the main Sdiff wave, and we refer to these arrivals as postcursors. These postcursors are easiest to identify when there is a dense array of seismic stations, to allow us to observe the hyperbolic shift of the delay times with respect to the main Sdiff arrival (see figure 4(b–d)).

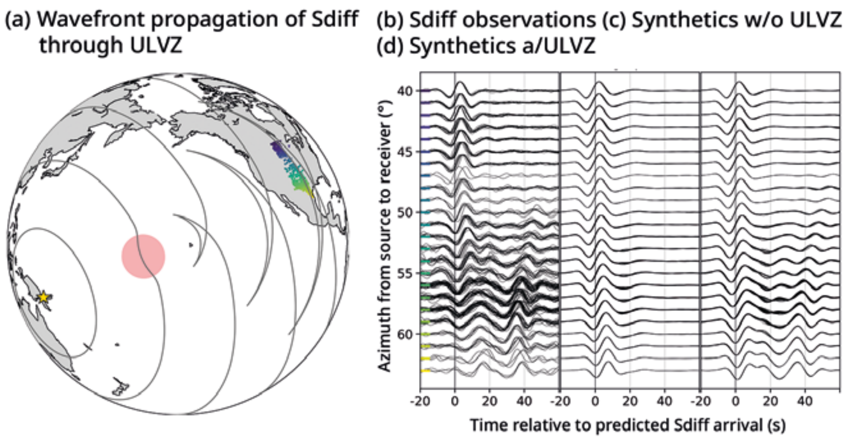
The timing and directionality of observed postcursors provide estimates of the size and velocity reduction of the ULVZ. The frequency content and amplitudes provide estimates of the height of the ULVZs. To model the ULVZ, we calculate the full seismic wavefield response to different ULVZ models. We assume a simplified ULVZ shape of a wide and thin cylinder,



2 *Compilation of ULVZ studies showing presence (red), potential presence (yellow) and absence (black) (from Yu & Garnero, 2018 and more recent studies). Background shows LLSVP (pink) and slab (light blue) regions (Cottaar & Lekić, 2016)*



3 *Ray paths of the seismic waves, shear core diffracted (Sdiff) and multiple P core diffractions (PKKPdiff), mentioned in the article. Red highlights where the waves are sensitive to the core-mantle boundary.*



4(a) *Geometry of example earthquake (yellow star) for which Sdiff samples the ULVZ near Hawaii (red circle) and is observed at stations across the US. Colour of stations indicates azimuth as plotted in (b). Wavefront are shown with predicted distortion due to ULVZ, showing the creation of a postcursor.* (b) *Observed waveforms shifted to expected Sdiff arrival time (at zero time) and organised by azimuth (colours relate to stations in (a)).* (c) *Synthetic waveforms without a ULVZ and thus without a postcursor.* (d) *Synthetic waveforms with a ULVZ showing a postcursor comparable to that in the observations.*

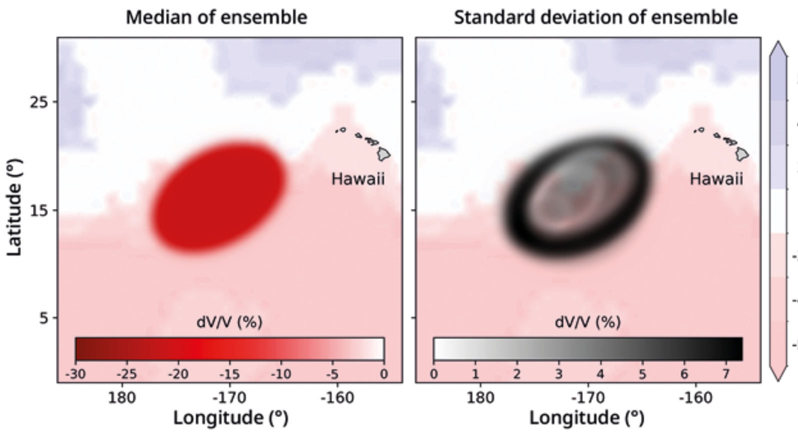
as it quickly becomes computationally infeasible to even explore this limited parameter space.

We detected the first Sdiff postcursors for a ULVZ which lies approximately beneath the Hawaiian hotspot (Cottaar & Romanowicz, 2012). The observed postcursors appear strong in seismic data filtered between 0.05 and 0.1Hz (10–20s), which we related to a ULVZ height of roughly 15–25km. We estimated the size at a rough diameter of 900km and a shear wave velocity reduction of 20%. Trade-offs between these parameters do remain, and differing data sets and approaches have since led to varied models of the Hawaiian ULVZ (e.g. Jenkins *et al.* 2021, Lai *et al.* 2022, Li, J *et al.* 2022). Comparable ULVZs have also been found using Sdiff in the vicinity of Iceland and the Galapagos archipelago (Yuan & Romanowicz, 2017, Cottaar *et al.* 2022). To understand if there is significance to these ULVZs underlying major volcanic hotspots, we need to uncover more of the global distribution of ULVZs.

Towards a global map

Currently, we are pushing towards a global analysis of all Sdiff waves including 7.5 million wave samples. Due to the geometries of suitable earthquakes and dense station arrays, the waves cover about 50% of the core-mantle boundary. Our current estimate is that our data set contains ~10 ULVZs that cause Sdiff postcursors (Martin *et al.* in prep.). All of these are situated at the boundary or just within the broad-scale LLSVPs. Our findings do not entirely align with the patchy compilation map of previous studies shown in figure 2. We need to consider that observable Sdiff postcursors might only occur for the largest dome-like features, while many other studies using different seismic waves suggest seeing ridges. Due to the typically large sizes, this type of ULVZ is sometimes referred to as a 'mega-ULVZ' (Thorne *et al.* 2013).

To deal with imaging the ULVZs with a large number of events, we have to move away from the computationally intensive method of forward modelling full wavefield simulations. We have developed a Bayesian inversion setup to estimate an elliptical shape for the ULVZs, which relies on the simple forward approximation of a wavefront (see figure 4(a) and Martin *et al.* 2023a). This allows us to estimate the location, shape and velocity reduction,



5 *Bayesian inversion results mapping the Hawaiian ULVZ on the core-mantle boundary. Left shows median velocity in the ensemble of models, and the right shows the standard deviation. The standard deviation shows a ring of large uncertainties, which illustrates the trade-off between a smaller and stronger anomaly and a larger and weaker anomaly. The background shows the likely LLSVP location (pink colours). The elliptical ULVZ model aligns along the boundary of the LLSVP.*

plus any trade-offs that remain, but not the frequency content of the postcursor, and thus not the height of the ULVZ. We can, however, include many more travel times for the postcursors from multiple events, which would otherwise require extensive forward modelling. The method works best when we have crossing ray paths sampling the ULVZ to determine the location and thus reduce the trade-offs overall. An example of the application is shown for the Hawaiian ULVZ in figure 5 (Martin *et al.* 2023*b*). The results suggest that the Hawaiian ULVZ is elongated and aligned with the edge of the LLSVP, which raises questions about the dynamical relationship between the two. Potentially, the ULVZ material is piled up along the edge of the LLSVP, as has been seen in geodynamical models (Li *et al.* 2017).

We have been pushing the resolution of our observations by looking at the data at higher frequencies. Higher frequency waves have sensitivity concentrated closer to the core-mantle boundary and thus can detect thinner structures. However, the signal-to-noise ratio deteriorates towards higher frequencies as the signals become more attenuated and seismic noise levels increase, for example due to deep ocean waves. We therefore make fewer quality observations. Additionally, the computational expense of sythentic seismograms increases drastically with frequency.

Within these higher frequencies, we found evidence of a thinner ULVZ that is ~5–10km thick beneath the central Pacific (Martin *et al.* in prep b). Furthermore, within the data sampling the Hawaiian ULVZ, we found a secondary high-frequency postcursor with very long delay times. This suggests an even thinner basal layer

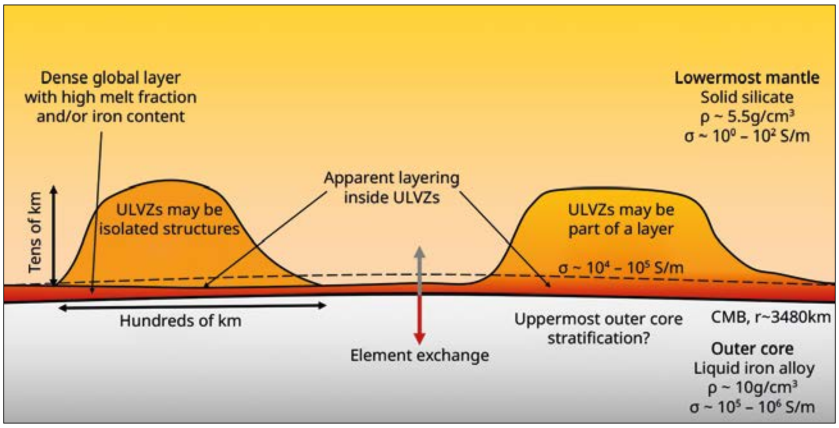
Can you pick your own nickname?

Seismologists have known for decades that lower mantle is dominated by two continent-sized zones where seismic velocities travel slowly, surrounded by patches of fast seismic velocities. The fast patches are thought to be regions where cold slabs subduct, while the slow zones remain more mysterious. Early on the slow zones were generally referred to as 'superplumes' or 'domes'. Some have nicknamed the one beneath the Pacific 'Jason', and the one beneath Africa and Atlantic as 'Tuzo', after Jason Morgan and John Tuzo Wilson, respectively, who pioneered the concept of mantle plumes in the 1960s and 70s.

Over the past two decades, the acronym LLSVP – Large Low Shear Velocity Provinces – has dominated in the scientific community, because it is more agnostic about the interpretation. But many people also find it unwieldy and it does little to spark the public imagination. We like to compare it to the term 'black holes', which is widely used, even with little knowledge of the nature and physics of black holes. The origin of that term appears debated, but one narrative (Horgan 2008) suggests that the astrophysicist John Wheeler was describing 'completely collapsed gravitational objects' during a 1967 conference when an audience member called out 'black holes'. Wheeler immediately adopted the term for its 'brevity and advertising value'. It is not surprising this term caught on quickly, and speaks to the imagination of many, including children.

Over the past several years, many popular science articles and YouTube videos are referring to LLSVPs as 'Earth blobs' or 'mantle blobs'. Time will tell if these terms become more common and widely known. For the moment, Google searches for these terms show ~1–2000 hits, compared to ~65000 for 'LLSVP' and a whopping ~92million for 'black hole'.

This article largely focuses on smaller and thinner patches at the core-mantle boundary which are a lot more anomalous than the LLSVPs as observed by their extremely reduced velocities. These are referred to as ULVZs – Ultra-Low Velocity zones, which is again a very descriptive but unimaginative acronym. In some media they have been referred to as mountains on the core-mantle boundary, but we do not think their morphology really resembles mountains. Suggestions for names of these anomalies are welcome!



6 *Cartoon of ULVZs and potential thin layer at the core-mantle boundary*

on the order of 2km thick that is roughly ~40% reduced in shear wave velocity, within the ULVZ (Li, Z *et al.* 2022).

Besides detecting new ULVZs, we also hope to use our global data set to provide a null map. Our null map will only be able to confirm absence of ULVZs of certain thickness, which will depend on the frequency to which we can push the observations, and of certain size, due to the nature of Sdiff postcursors. Other seismic data types might observe ULVZ-like structures that are not detectable by Sdiff postcursors. Making confident and high-quality null observations is a tricky new venture.

Global layering at the core-mantle boundary

We also posed the question of whether there is a thin and global layer of dense material at the core-mantle boundary, which would be difficult to observe. Observed ULVZs could represent local thickening of this layer (figure 6). As the density jump at the boundary is 4500kg/m^3 – greater than that at Earth's surface – it is plausible that a wide range of material could become trapped at the interface and create layering. The presence of a thin conductive global layer at the core-mantle boundary is further supported by geodetic observations of Earth's rotation and nutations, which suggest there must be significant electromagnetic coupling between the mantle and core (Buffett *et al.* 2002; Holme & de Viron 2013).

A different way to pose this question is in terms of resolution – how thin can a global layer be before it is invisible to seismologists? Computational advances mean that we can now compute the global seismic wavefield up to sufficiently high frequencies to test this. We initially tested the visibility of a molten silicate layer, which would only be observable in compressional waves (shear waves don't propagate in fluids). We produced numerous wavefields with and without a global melt layer of varying thickness, to find the seismic wave most sensitive to such a layer. We settled on the exotic PKKPdiff wave, which has three diffracted paths on the core-mantle boundary (figure 3). A global dataset of travel times of this wave (>12 500 samples) shows such a strong degree of scatter that we could neither confirm nor deny the existence of a layer. However, it is plausible that a layer of several kilometre thickness could be 'hidden' within this scatter and invisible even to this quite sensitive wave (Russell *et al.* 2022).

Following body wave exploration, we went on to test the presence of a layer using the centre frequencies (eigenfrequencies) of normal modes – the very-long period whole-Earth oscillations that are excited by large earthquakes. We combined several published datasets of these frequencies and forward modelled the effect of layering. While these are very long-wavelength observations, the modelling reveals that they have surprising sensitivity to extremely thin and highly anomalous layers at the boundary. The forward modelling of such long period waves is computationally efficient, allowing the exploration of a broader set of potential properties than is possible with body waves. For some Earth models that already fit normal mode centre frequencies well, the fit is further improved by the presence of a layer of nearly 2km thickness, with well-fitting properties similar to the basal layer detected within the Hawaiian ULVZ (Russell *et al.*). This result is not unique, and the well-fitting parameter space is broad, requiring further testing. Until then the presence of a global layer remains elusive to seismology but is a realistic possibility that may better fit seismic observations.

"We can now say with some confidence that not every surface hotspot has a mega-ULVZ at its base, at least not one that is observable by Sdiff"

The thicker ULVZs are clearly better observed, and our seismological constraints help our quest to understand what the ULVZs are and what their role is in global dynamics. Their aspect ratios of 30:1 to 40:1 in width:height suggest they are very dense and thus pond widely. The most likely candidate for increased density is enrichment in iron. The iron could come from early differentiation of the planet, i.e. remnants of a basal magma ocean (Labrosse *et al.* 2007), from the outer core (although suggested mechanisms for transfer from the core vary, e.g. Lesher *et al.* 2020) or brought down by subducted slabs which might partially melt (e.g. Andrault *et al.* 2014). Iron-enriched material could also present a remnant from a Moon-forming impactor (Yuan *et al.* 2023). Potentially multiple sources are at play. The strong shear velocity reduction could also be explained by partial melt. However, it is unlikely to be an explanation by itself, as mantle material might have to be enriched in iron in the first place to cause melting (e.g. Boukaré *et al.* 2015).

Geodynamical models with partial melt have also shown that this does not easily explain the observed morphologies (Dannberg *et al.* 2021). This is largely because any iron in the mantle material fractionates into the melt, causing the melt to be so dense that it sinks to the bottom and forms an extensive layer. A hybrid model is possible, where the ULVZ is generally enriched in iron and contains a basal layer of (partial) melt, potentially representing the global layer. Better constraints on P wave velocity as well as shear wave velocity could further our understanding (see box 'Constraints from compressional waves'). Global maps of ULVZ presence and potential causes could be tested on how they might affect variability in the geodynamo and magnetic field.

It is also worth exploring whether the ULVZs represent the base of mantle plumes causing hotspots at the surface. A number of mega-ULVZs were found near the major hotspots of Hawaii, Samoa, Iceland and Galapagos, suggesting a connection, and we are working on observations near Macdonald and Saint Helena. However, we also have evidence of postcursors for ULVZs not near a hotspot. And we can now say with some confidence that not every surface hotspot has a mega-ULVZ at its base, at least not one that is observable by Sdiff. All the ULVZs we have found are within the LLSVPs, and most hotspots fed by mantle plumes lie above the LLSVPs. Some dynamical connections between mantle plumes, LLSVPs and ULVZs are likely.

Geochemical observations from ocean island basalts, generated by mantle plumes originating from the core-mantle boundary, provide insights into the connection between surface volcanism and deep reservoirs of anomalous materials. These data reveal anomalies such as high helium isotope ratios, solar-like neon isotopes, and negative deviations in tungsten

Constraints from compressional waves

In this article, we mainly focus on imaging ULVZs with shear diffracted waves which constrain the shear wave velocity or Vs within the ULVZ. We could gain new clues to their nature by constraining the compressional wave velocities (Vp) within the ULVZs. Different scenarios predict different dVs:dVp ratios. We have hunted for evidence of postcursors arriving after diffracted compressional waves, or Pdiff waves, for which we have pushed data to frequencies around 1Hz (figure 7). Here we show the first evidence of scattered energy after the main Pdiff arrival with a hyperbolic time shift as a function of source-receiver azimuth like that seen for the Sdiff postcursors (figure 4). We are still working on the question of what these observations tell us about the Hawaiian ULVZ.

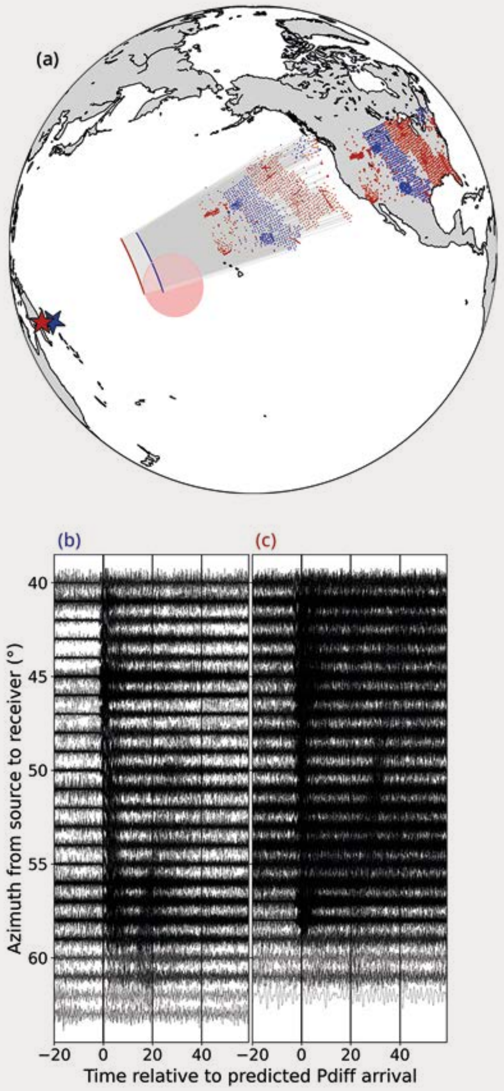


Figure 7 (a) *Map showing geometry of two example earthquakes (stars) recorded at stations across the US. Grey shaded regions show the area where Pdiff is sensitive to the core-mantle boundary. Pink circle shows the estimated Hawaiian ULVZ (from Li et al. 2022).* **(b)** *and* **(c)** *Pdiff waveforms for the two example earthquakes aligned by expected Pdiff arrival (zero time) and organised by azimuth (angle between North and the direction between the earthquake and station). Scattered postcursor energy arrives later at smaller azimuths.*

isotope ratios. The helium and neon indicate sampling of mantle material that has not been extensively degassed by recycling across the surface. This suggests that it originates from a dense and relatively stable reservoir at the base of the mantle. However, there must be some entrainment to bring it to the surface and observe it. The anomalous tungsten signature (deviations in $^{182}W/^{184}W$) is an indication of a reservoir that segregated early (<60Myr from formation) in Earth's history. ^{182}W is the product of the relatively short-lived and now extinct hafnium-182 isotope. ^{182}Hf is lithophile (silicate-loving) and ^{184}W is siderophile (iron-loving), so variations observed now must have been set early in Earth's history before hafnium depleted. The most obvious process is the 'quick' segregation between the rocky mantle and metal core which caused a very negative deviation in the tungsten ratio within the core. Present-day deviating tungsten ratios sample reservoirs from the core or from iron-rich remnants of an early-segregated basal magma ocean (Deng & Stixrude 2021).

However, it remains uncertain if all chemical anomalies can be solely explained by sampling material from the LLSVPs, without requiring entrainment from ULVZs. The LLSVPs themselves could be complex structures and may contain a mixture of different materials. Additionally, it is unclear how material from the ULVZs at the potential base of a mantle plume or within the LLSVPs would be entrained and contribute to the observed anomalies. Further interdisciplinary research is needed to understand all the clues given to us to reveal Earth's secrets. ●

ACKNOWLEDGEMENTS
Sanne Cottaar (centre left) is professor of Global Seismology and thanks the Royal Astronomical Society for the award of the Harold Jeffreys Lectureship. The lecture can be found on the RAS YouTube channel as part of the Ordinary Meeting 22 April 2022. **Carl Martin** (left) and **Stuart Russell** (centre right) are research students and **Lisanne Jagt** (right) a post-doctoral researcher; we are all at the Department of Earth Sciences, University of Cambridge, although Carl is now at Utrecht University and Stuart at the University of Münster.

'We' in the article has a fluid meaning. The early work of Sdiff postcursor by main author Sanne Cottaar was done as a PhD student working with Barbara Romanowicz. Zhi Li discovered and modelled the high frequency postcursor for the Hawaiian ULVZ. Thomas Bodin was involved in setting up the Bayesian mapping method. Jessica Irving collaborated with us on uncovering thin global layers at the core-mantle boundary using body waves and normal modes. We collaborate and discuss across disciplines with Juliane Dannberg, Bob Myhill, Rita Parai, and many others.

For our seismic data we are immensely thankful for the many seismic array deployments available. Our work has particularly relied heavily on the US Transportable Array (usarray.org/researchers/obs/transportable). The seismology community is very good about sharing data, and most are made available through IRIS (www.iris.edu). Additionally, we have made use of many previously published centre frequencies for normal modes.

Besides data, we have also used open-source software. For our processing we use a lot of ObsPy (www.obspy.org). For full waveform synthetics we make use of CSEM (Capdeville *et al.* 2002) , Instaseis (van Driel *et al.* 2015), AxiSEM, (Nissen-Meyer *et al.* 2014) and AxiSEM3D (Leng *et al.* 2019).

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