Seismic evidence for partial melting at the root of major hot spot plumes

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Ultralow-velocity zones are localized regions of extreme material properties detected seismologically at the base of Earth’s mantle. Their nature and role in mantle dynamics are poorly understood. We used shear waves diffracted at the core-mantle boundary to illuminate the root of the Iceland plume from different directions. Through waveform modeling, we detected a large ultralow-velocity zone and constrained its shape to be axisymmetric to a very good first order. We thus attribute it to partial melting of a locally thickened, denser- and hotter-than-average layer, reflecting dynamics and elevated temperatures within the plume root. Such structures are few and far apart, and they may be characteristic of the roots of some of the broad mantle plumes tomographically imaged within the large low-shear-velocity provinces in the lower mantle.

Fig. 1. Geometry of the ULVZ study. (A) Map showing the illumination of the Iceland plume root region by seismic waves considered in this study. The numbers and “beach balls” correspond to earthquakes listed in table S1. Sdiff paths sampling the lowerrmost 300 km of the mantle are color-coded according to event. Brown triangles indicate locations of recording stations. The black circle indicates the preferred location and size of the proposed axisymmetric ULVZ, plotted at the core-mantle boundary. Iceland and continents are plotted at Earth’s surface. (B) Depth cross section through the Iceland plume in the model SEMUCB_WM1 (15), corresponding to the dashed line in (A), showing lateral variations in shear velocity (Vs) relative to the global mean (dlnVs = dVs/Vs). The thin black dashed lines mark depths of 1000 and 2600 km. The broken line segment on the core-mantle boundary shows the preferred location and lateral extension of the ULVZ. The location of the Iceland hot spot is indicated by a green triangle; the red star indicates the event epicenter. S, Sdiff (black), and SKS (brown) ray paths are indicated by solid and dashed lines, spanning the epicentral distance range available for event 1.
in amplitude of the main phase is observed where the postcursor is largest. (ii) There is also a move-out of the postcursor, with fading amplitudes, at azimuths −35° to −42°. We verified that these effects originate at the base of the mantle by inspecting the corresponding SKS waveforms, which have similar paths as Sdiff waves in the upper mantle (Fig. 1B) but do not exhibit the same waveform disturbances (fig. S1).

To constrain the causative structure, we used the same approach as developed earlier for the study of the Hawaiian ULVZ (18), applied to densely sampled broadband seismic waveform data (17). We forward-modeled synthetic waveforms in models that include three-dimensional (3D) structure in shear velocity in the bottom 400 km of the mantle (17). We used a coupled spectral-element/normal-mode code (18) previously applied to model structures in D∗ at the border of the African LLSVP (19) and under Hawaii (20). The approach that we used allowed a relatively fast calculation down to a cut-off period of 8 s.

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We compared the 3D synthetics generated by varying the position, radius, and height of the cylinder and the internal velocity reduction with the corresponding waveform data for event 1. Our best-fitting models are located close to the Iceland hot spot, with a diameter of ~800 ± 50 km, a height of ~15 ± 5 km, and a shear velocity reduction of ~23 ± 5% (e.g., Fig. 1B, figs. S3 and S4, and table S2). The corresponding 3D synthetics (Fig. 2C and fig. S5) reproduce the main characteristics of the observed waveforms well—in particular, the arrival time of the postcursor to within a few seconds.

We do not expect this model to provide a perfect fit to the observed waveforms, because mantle heterogeneities located higher than 400 km above the core-mantle boundary may introduce waveform distortions, and the radiation pattern of the earthquake may slightly differ from the centroid moment tensor (CMT) solution (17) at these short periods. The sides of the structure are unlikely to be perfectly vertical. Trade-offs also exist between cylinder radius, velocity reduction, and height. In addition, there are a few degrees of uncertainty in the ULVZ position.

The data from event 1 by itself span a limited range of azimuths. Importantly, the same cylindrical model predicts the main characteristics of Sdiff waveforms and their codas for seven other events that we did not use in its construction (Fig. 2, E to L, and figs. S6 to S12), for which the waveforms span a wide range of azimuths around the ULVZ (Fig. 1A) and a combined distance range of over 40° (table S1), thus illuminating the region from several different directions and angles. An axisymmetric ULVZ is expected to produce a postcursor with a hyperbolic shape move-out, symmetric with respect to the great circle linking the source to the center of the ULVZ (e.g., fig S13). We further demonstrated that the base of the ULVZ under Iceland is close to circular in shape by producing composite record sections, combining waveforms from events 1 and 3 (Fig. 3, A to C).

We did this by rotating the reference frame for one
event with respect to the other until the source locations illuminated the ULVZ from the same angle. This allowed us to reconstruct a more complete arc of the diffraction hyperbola, which is only possible if the ULVZ is close to axisymmetric. Such a rotation also works well for the pair of events 2 and 3, noting that event 2, in its original location, illuminates the ULVZ from a completely different side (Fig. 3, D to F).

In addition, the $S_{\text{diff}}$ waveforms are measurably affected only for paths that approach the modeled ULVZ to within a distance that is less than ~800 km—i.e., one diameter away from the structure—indicating that this large ULVZ is the sole feature of its kind in a broad region of D′ along the Mid-Atlantic Ridge on either side of Iceland. Indeed, for azimuths further away from the ULVZ (e.g., paths marked in blue in fig. S6A, and all paths in fig. S6, B and C), which sample D′ as far as five times the diameter of the ULVZ to the north of it (fig. S6B) and two times to the south of it (fig. S6A), we found no evidence for postcursors that could be associated with another similar ULVZ.

The quasi-axisymmetric shape of this ULVZ, its location at the root of the Iceland plume as imaged tomographically (15), and its large diameter, commensurate with the width of the plume higher up in the lower mantle (15), imply a close dynamical link between the ULVZ and the plume. This suggests that the ULVZ most likely involves partial melting (6, 22, 23). The ULVZ would be confined to the hot base of the plume (24, 25), and its borders may mark the transition between a partially molten zone and the solid surroundings. A compositionally distinct, solid ULVZ of low-viscosity material (26, 27) could possibly be shaped similarly by plume dynamics; however, this would necessitate explaining how a heterogeneous solid blob of the right size could be swept right into the plume root and not elsewhere. The shear velocity reduction of 23%, as argued in previous
studies (6, 28), is compatible with a melt fraction of 10 to 20% by volume, although our data cannot provide further constraints, because they are insensitive to P velocity reduction and density. Although our approach cannot directly constrain the density within the ULVZ, it has been argued that melt in D′ would be denser than the surrounding solid (6), and the stability of hot spots through substantial geological time requires the presence of denser-than-average material at the roots of the corresponding mantle plumes (24, 25, 29).

The large ULVZ that we imaged may not be representative of all ULVZs (30). However, its unique occurrence in an extended region of the core-mantle boundary, combined with previous observations and modeling of a similar ULVZ at the base of the Hawaiian plume (31) and a “mega” ULVZ beneath Samoa (32), is striking. This suggests the existence of a specific class of large ULVZs formed at the roots of broad plumes associated with major, presently active hot spots (35). Such ULVZs may be the clearest manifestation of thickening of an otherwise likely very thin (kilometer-scale), partially molten layer (31, 32) (Fig. 4) that is enriched in iron and therefore denser than its surroundings. This layer may represent an interaction zone between mantle and core (7), which could be the source of isotopic anomalies of ancient origin observed at this and other hot spots (33, 34). Evidence for such a thin layer has been suggested from fine-scale local seismic studies in the Pacific (31) and elsewhere (32). Other ULVZs not associated with the broad plumes imaged tomographically may also mark local hills in this layer caused by smaller, hotter upwelling instabilities in the LLSVPs (Fig. 4). The denser-than-average part of the LLSVPs may be limited in height to the locations of these ULVZs, which may explain why recent travel-time and normal-mode studies that do not have much sensitivity to the last 100 km at the base of the mantle can explain the long-wavelength structure of the LLSVPs by lateral variations in temperature alone (35, 36). This poses the question of how exactly one should define the height of a LLSVP. LLSVPs are often described as large piles of compositionally distinct material (12, 37, 38), but they may actually be the long-wavelength expression of a bundle of plumes (25, 39), anchored in a thin dense layer with high topography at its top (Fig. 4).

Our results should provide guidance for further modeling of the thermal history, mineralogy, and present-day dynamics at the very base of the mantle. Further characterizing the fine-scale structure of the bottom 50 km of the mantle—and, in particular, detection of ULVZs at the root of other broad mantle plumes—would be facilitated by the deployment of new large-aperture broadband arrays, especially on the ocean floor, to increase illumination of the vicinity of the core-mantle boundary. This needs to be combined with the development of waveform imaging techniques that can target specific objects of limited extent at short enough periods, with realistic computational resources (40).

REFERENCES AND NOTES

17. Materials and methods are available as supplementary materials.

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SUPPLEMENTARY MATERIALS

www.sciencemag.org/content/357/6349/393/suppl/DC1
Materials and Methods
Figs. S1 to S13
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**Iceland's molten roots**

Major hot spot plumes are responsible for basaltic ocean island chains such as Hawaii. Yuan and Romanowicz used seismic tomography, which constructs an x-ray–like picture of Earth's interior from seismic waves, to show that the root of Iceland's hot spot plume is partially molten. The partially molten region is located near Earth's core-mantle boundary and has been challenging to image with geophysical methods. This approach may be applicable to other hot spots with similar areas of melts or other enigmatic regions in the lower mantle.

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