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Earth and Planetary Science Letters 214 (2003) 143–151
EPSL
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Seismological evidence for a mid-mantle discontinuity beneath Hawaii and Iceland

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Received 7 November 2002; received in revised form 4 June 2003; accepted 18 June 2003

Abstract

Receiver functions derived from body waves recorded in Iceland and on the Hawaiian Islands reveal a seismic velocity discontinuity at about 1050 km depth beneath the two regions of presumed mantle upwelling. The waveforms of the converted phases from the mid-mantle discontinuity indicate a velocity increase with depth. The lack of consistent scattering found in recent systematic searches for seismic boundaries in the middle mantle argues against a globally continuous, sub-horizontal mineralogical phase transition near 1000 km depth. The sense of the velocity change at the mid-mantle discontinuity beneath the two hotspots is consistent with geodynamic models in which the mantle has distinct chemical reservoirs and the material beneath the compositional boundary in these areas is more silicon-rich than the overlying mantle, although the possibility of a yet-unknown phase transition particular to mantle plume material cannot be ruled out.

Keywords: mantle discontinuities; transition zones; mantle composition; Iceland; Hawaii

1. Introduction

The presence and nature of mid-mantle discontinuities have potentially important implications for the dynamics of the mantle. Seismic discontinuities in the lower mantle can be indicative of mineralogical phase transformations [1] or changes in chemical composition [2–4]. The depths of mineralogical phase transformations provide information on the temperature and composition of the mantle, while any compositional stratification would reflect the integrated history of mantle convection and differentiation. Mantle layering has been a topic of debate for decades. The early view that distinct mantle chemical reservoirs and convective regimes lie above and below the seismic discontinuity at 660 km depth has been rendered untenable by tomographic images of slabs sinking deep into the lower mantle [5] and by the inference of a lower mantle origin for prominent mantle plumes [6]. To account for distinct geochemical reservoirs in a manner consistent with seismic tomography, several recent geo-

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doi:10.1016/S0012-821X(03)00349-2

dynamic models have placed a boundary between compositionally differing mantle layers in the lower mantle [2–5].

Lateral variations in the depth, velocity contrast, and sharpness of a mid-mantle discontinuity can be important clues to the nature of the discontinuity. Mineralogical phase transformations, for a homogeneous mantle, are global features, and their depths vary systematically with temperature according to the thermodynamics of the transformations. In some geodynamic models [2,3], the depth to a mantle compositional boundary having a small intrinsic density contrast shoals at upwelling regions and deepens near downwelling regions. If the chemical differences between ocean island basalts and mid-ocean ridge basalts are the product of distinct mantle reservoirs, compositional boundaries are unlikely to be uniform globally in compositional or seismic structure. Mantle convection may cause compositional boundaries to be variously sharp or diffuse and strongly tilted or locally sub-horizontal.

The global extent of mid-mantle discontinuities is still poorly understood. Several recent studies have identified seismic discontinuities at depths of 900–1700 km in subduction-zone regions [7–13] using S-to-P conversions at mantle discontinuities beneath zones of deep earthquakes. The distribution of deep earthquakes and dense seismic networks has limited the geographic extent of such studies. From precursors to SS, which have more even global coverage but relatively poor resolution [14], Deuss and Woodhouse [15] reported a continuous spectrum of reflectors in the uppermost lower mantle. The geographic distribution of these reflectors nonetheless remains unclear. Le Stunff et al. [16] identified a precursor to P′P′ from a mid-mantle discontinuity near 1200 km depth beneath southern Africa. Overall, however, little detailed work has been done to determine the nature of lower-mantle discontinuities beneath regions of mantle upwelling or other areas far from subduction zones.

In this paper, we employ radial receiver functions to document shear waves converted from compressional waves at seismic discontinuities near 1050 km depth beneath Hawaii and Iceland, two regions of presumed upwelling. Our results

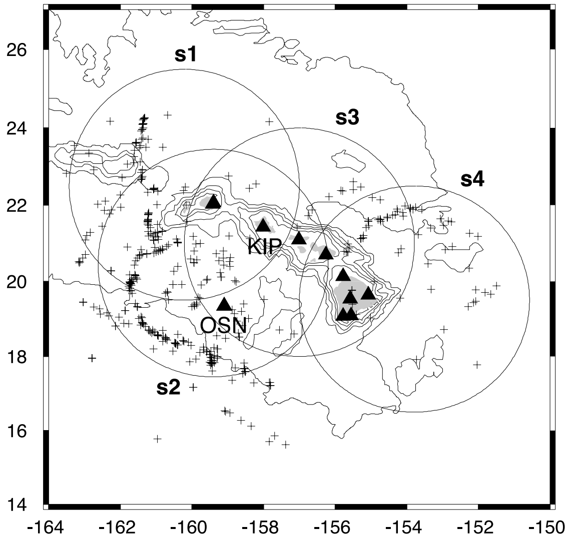

Fig. 1. Locations of broadband seismic stations (triangles) on the Hawaiian swell and piercing points of P-to-S conversions at 1050 km depth (crosses). KIP and OSN denote the GSN station and the OSN ocean-bottom seismometers, respectively. Circles outline the patches within which receiver functions were gathered and stacked.

demonstrate that seismic discontinuities in the uppermost lower mantle can be mapped with receiver function analysis. This method can potentially expand significantly the areas where mid-mantle discontinuities can be discerned. The detection of the 1050-km discontinuity beneath the two prominent hotspots has interesting potential implications for the nature of mantle layering and its manifestation in upwelling regions.

2. Mid-mantle discontinuities beneath Hawaii and Iceland

To search for evidence of deep structure beneath the Hawaiian hotspot, we made use of teleseismic body waves recorded by a temporary network [17] of seven broadband stations on the Hawaiian Islands (Fig. 1). Additional earthquake records from the Global Seismic Network (GSN) station KIP and the Ocean Seismic Network (OSN) Pilot Experiment [18] were included (Fig. 1). We inspected traces of earthquakes at epicentral distances between 30° and 95° and selected

593 seismograms having noise levels (defined as the standard deviation of the values on the radial component in an 80-s window before the P arrival) less than 0.1 times the amplitude of the direct P wave on the vertical component. After the PP arrival was deleted from the seismograms, radial receiver functions were calculated [19] and arrivals were identified as S energy converted from incident P energy at a given depth *d* (or P*d*s). In the deconvolution for receiver functions, the Gaussian width factor (0.3, equivalent to low-pass filtering at 0.13 Hz) was used to suppress the high levels of microseisms at ocean island stations. To improve the quality of the signal, we gathered and stacked receiver functions having P*d*s paths that pierce the same patch at a given depth in the mantle [6,20] (Fig. 1). The size of the patches is comparable to the width of the Fresnel zone in the uppermost lower mantle for a converted phase with a dominant period of ∼15 s. An *n*th-root ($n = 2$) stacking process [21] was used to suppress random noise further and to enhance coherent signals.

The stacked receiver functions reveal an arrival 105–110 s after the initial P wave (Fig. 2a). Stacking by ray parameter, a function of incidence angle, reveals that the arrival has a moveout consistent with that of a P-to-S conversion near ∼1050 km depth (Fig. 2b). We denote this phase as P1050s hereinafter. Stacking along moveout curves for reverberations from shallower discontinuities [22] reduces the amplitude of this phase (Fig. 2a) as well as those of converted phases from the discontinuities near 410 and 660 km depth (P410s and P660s, respectively), confirming that the later phase is not a reverberation. Stacking along a range of moveout curves normalized by the P*d*s moveout demonstrates that the amplitudes of all identified P*d*s phases generally decrease away from the P*d*s moveout.

To estimate the depth of this mid-mantle discontinuity, we applied corrections for velocity anomalies in the upper 400 km from the average delay of the observed P410s and P660s times relative to their predicted arrival times from the iasp91 global model [23]. Because the Clapeyron slopes of the phase changes associated with the 410- and 660-km discontinuities are comparable

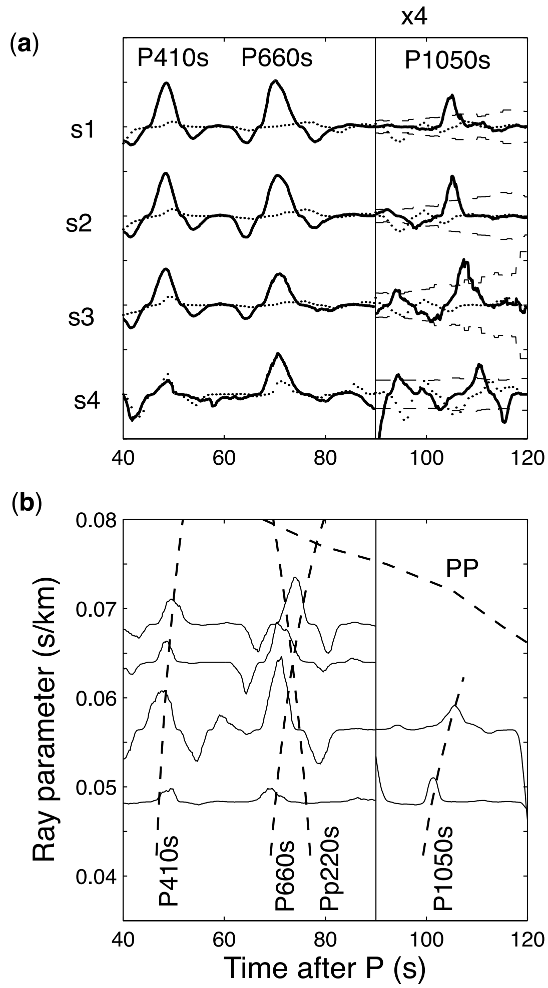

Fig. 2. (a) Stacked receiver functions from the Hawaiian region showing the P1050s phase about 105–110 s after the P arrival. The labels (s1–s4) correspond to the patches shown in Fig. 1. The time series after 90 s has been amplified by a factor of 4. Dashed lines are 95% confidence limits estimated using a bootstrap method [37]. Receiver functions stacked along the first-order reverberation moveout [22] (dotted lines) are shown for comparison. (b) Receiver functions from s1 and s2 stacked by ray parameter. The ray parameter of each stack is the average of 80 receiver functions sorted by ray parameter. Dashed lines indicate the moveout curves for PP, P410s, P660s, P1050s, and the reverberation from a hypothetical discontinuity at 220 km depth (Pp220s). A 3-s delay, attributed to velocity heterogeneity in the shallow mantle, has been added to the moveout curves for P410s, P660s, and P1050s to improve the match to the waveforms.

in magnitude but opposite in sign [24], the effect of the topography of the transition-zone discontinuities on the correction to the P1050s time is modest and neglected here. The apparent depth of the mid-mantle discontinuity increases by about 50 ± 20 km from the western part of the Hawaiian swell (∼1050 ± 20 km) to the eastern part (Figs. 1 and 2).

To conduct a similar search for the Iceland hotspot region, we used the same data selection criteria and obtained 2843 receiver functions from teleseismic earthquake records (Fig. 3) collected in two broadband seismic experiments in Iceland [25,26]. Previous studies of the discontinuity structure beneath Iceland have shown that the upper-mantle transition zone is thinner than the global average beneath central and southern Iceland but is of normal thickness beneath surrounding areas [6,27]. The thinner-than-normal transition zone, which has an east–west dimension of less than 300 km, has been interpreted as evidence for anomalously high temperatures in the transition zone, consistent with the presence of a mantle plume originating at greater depth [6]. The southern boundary of the transition-zone thickness anomaly remains to be mapped.

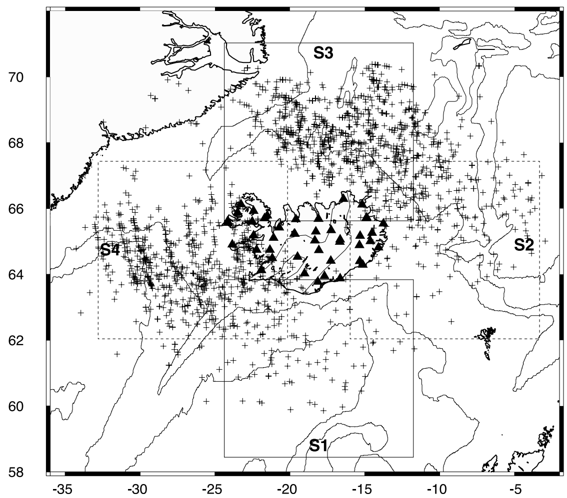

Fig. 3. Locations of broadband seismic stations in Iceland (triangles) and the piercing points of P-to-S conversions at 1050 km depth (crosses). Boxes outline the patches within which receiver functions were gathered and stacked.

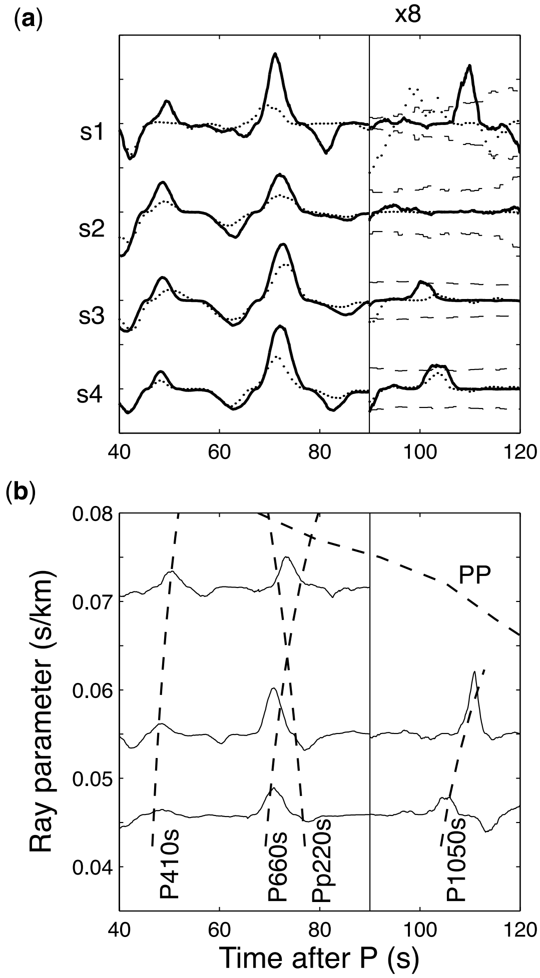

Fig. 4. (a) Stacked receiver functions from Iceland. The labels (s1–s4) correspond to the patches shown in Fig. 3. The time series after 90 s has been amplified by a factor of 8. (b) Receiver functions from s1 stacked by ray parameter. A 4-s delay, attributed to velocity heterogeneity in the upper mantle, has been added to the moveout curves for P410s, P660s, and P1050s to improve the match to the waveforms. The misfit between the arrivals and the moveout curves likely reflects variations in the depth of the discontinuities. See Fig. 2 for additional explanation.

The stack of receiver functions having P*ds* phases that pierce the patch of mantle beneath southern Iceland displays an arrival 110 ± 1 s after P (Fig. 4a). As with the P1050s phase beneath Hawaii, stacking along moveout curves for reverberations from shallow discontinuities (Fig. 4a)

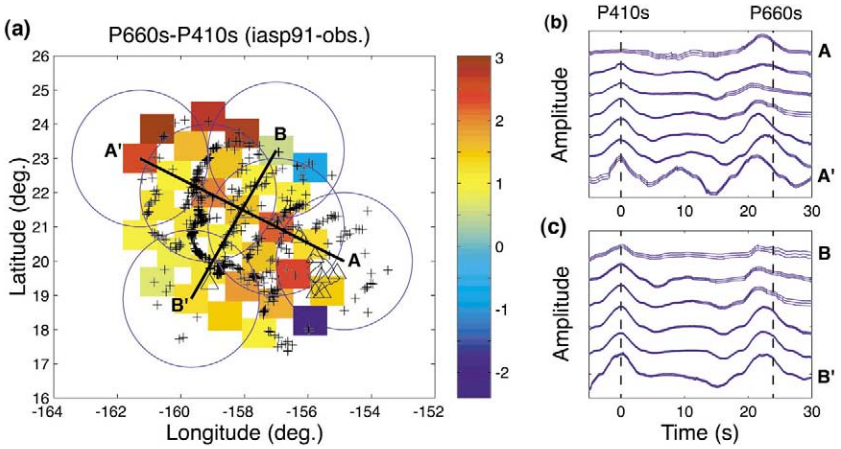

Fig. 5. (a) Map view of the difference between the observed P660s–P410s differential times and the values predicted for the iasp91 model [23] shows a broad transition-zone thickness anomaly. Red and yellow colors indicate significantly smaller differential times (thinner mantle transition zone) than in iasp91, while blue colors denote normal or greater-than-normal differential times. A 1-s change in differential time is equivalent to about a 10-km change in transition-zone thickness. Circles with a radius of 2° indicate the boundaries of a few of the overlapping patches used in stacking. (b) Waveforms of stacked receiver functions, and their 95% confidence limits, along the profile AA′ in panel a. The traces are aligned on the P410s arrival time determined by bootstrap [37] and weighted linearly by the amplitude of the waveform of the converted phase. The top trace has an anomalously weak P410s phase and is shifted using the P410s time of the second trace. The vertical lines mark the values predicted for the iasp91 model. (c) Waveforms of stacked receiver functions along the profile BB′ in panel a.

and other moveout curves reduces the amplitude of the identified phase. The moveout of the phase is consistent with a P-to-S conversion from a seismic discontinuity near 1120 ± 20 km depth (Fig. 4b). Stacking for other nearby patches of mantle, however, does not yield any phase significantly above the noise level in the time window 90–120 s after P (Fig. 4a). The number of receiver functions in these stacks varies from 510 to 1220, substantially greater than for the Hawaiian stacks. The absence of a significant mid-mantle phase in these stacks is therefore attributable to a lack of coherent signals rather than higher noise levels in the stacks. The fact that the mid-mantle discontinuity is resolvable only beneath southern Iceland, where the transition zone is anomalously thin and hot [6,27], suggests a spatial correlation between the mid-mantle discontinuity and thinning of the mantle transition zone. If the discontinuity is also present beneath surrounding areas, its non-detectability would have to be the result of lesser sharpness of, or greater relief on, the discontinuity that prevents coherent stacking of converted phases.

The correlation between a significant P1050s phase and a reduction in transition zone thickness also holds for Hawaii. In contrast to the transition-zone structure beneath Iceland, the transition zone beneath Hawaii (Fig. 5) is anomalously thin over a broad (> 500 km wide) region along the island chain (> 700 km long). Our transition-zone thickness results generally confirm earlier observations [18,28].

As with the waveforms of the transition-zone converted phases, the positive amplitude of P1050s (Figs. 2 and 4) indicates a velocity increase with depth at the 1050-km discontinuity. The apparent amplitude of P1050s is approximately four and eight times less than the amplitudes of P660s beneath Hawaii and southern Iceland, respectively. Estimation of the true amplitude of P1050s is hindered by uncertainties in relief on the 1050-km discontinuity within each patch and the non-linear stacking process. Nonetheless, the observation of the converted phase requires that the velocity transition at the 1050-km discontinuity occurs over a depth interval less than ~50 km, half the wavelength of the converted phases at the dominant period of ~15 s.

3. Nature of mid-mantle discontinuities

The mid-mantle discontinuities beneath the study areas and the reflector identified near 1200 km depth beneath southern Africa [16], another site of presumed mantle upwelling, suggest that mid-mantle discontinuities are not unique features of subduction regions.

Given the spatial correlation between the identification of a P1050s arrival and thin transition zone, it is reasonable to hypothesize that both features are related to elevated temperatures associated with mantle upwelling beneath Hawaii and southern Iceland. Because of thermal conduction, however, it is unlikely that elevated temperature alone can maintain a sub-horizontal seismic velocity boundary at 1050 km depth sufficiently sharp to generate converted phases.

Observations of mid-mantle discontinuities to date do not support the idea of a globally continuous mineralogical phase transition near 1000 km depth, but they are broadly consistent with the notion of compositionally distinct reservoirs in the lower mantle. The seismic scatterer observed in the lower mantle (1400–1600 km deep) to the east of the Mariana and Izu-Bonin subduction zones is characterized by a steep dip, a large velocity contrast, and a sharp velocity transition, properties suggestive of a chemical origin rather than a temperature heterogeneity or a phase transformation [10]. In other parts of the western Pacific, where mid-mantle discontinuities have been identified in the depth range 900–1100 km [7,8,12,13,15], tomographic studies have found that high-velocity subduction-zone anomalies are deflected at the 660-km discontinuity or several hundred kilometers below [29]. From a detailed study of a mid-mantle discontinuity beneath the Indonesia arc, it was found that the depth variation in the discontinuity appears to be correlated with the location of sub-horizontal high-velocity anomalies in tomographic models [8]. Waveform analysis reveals a velocity increase at the discontinuity, similar to the velocity change at the mid-mantle discontinuities beneath the Hawaiian and Iceland hotspots. This result rules out the possibility that the discontinuity is the bottom limit of the high-velocity anomalies [8]. The correlation between the discontinuity and overlying high-velocity anomalies has instead been suggested to result from a geodynamic boundary at 1100 km depth or shallower that resists slab penetration [8,29]. The frequency dependence of the converted phases at the discontinuity beneath the Indonesia arc can be explained by a sharp velocity change with a transitional thickness less than 5 km and a velocity jump of about half that of the 660-km discontinuity. The sharpness of the velocity transition again suggests that the discontinuity is unlikely to be purely thermal in origin.

If the mid-mantle reflectors observed beneath the Indonesia arc and elsewhere represent a mineralogical phase boundary in a compositionally homogeneous mantle, such a feature would be global in extent and would occur at a depth that varies systematically with temperature according to the thermodynamics of the phase transformation. There is, however, no systematic correlation between the depth of mid-mantle discontinuities observed to date and sites of inferred upwelling and downwelling (and thus mantle temperature). Furthermore, recent systematic searches for seismic boundaries in the middle mantle [13,30] have not yielded consistent scattering in this depth range, leading to the suggestion that lateral variations in the depth and detectability of mid-mantle discontinuities may be substantial. This inference argues against a global, sub-horizontal discontinuity having a significant and sharp velocity contrast near 1000 km depth. The lack of resolvable P-to-S conversions in regions of Iceland with normal transition-zone thickness provides additional evidence against a sub-horizontal discontinuity near 1000 km depth in the normal lower mantle. It is thus unlikely that the 1050-km discontinuity observed beneath Hawaii and southern Iceland and the mid-mantle reflectors detected beneath subduction regions represent a phase transition of global extent. We cannot exclude the possibility, however, that the mid-mantle discontinuities observed beneath these regions are associated with yet-unknown phase transitions particular to mantle plume material and subducted lithosphere.

Lateral variations in the depth and detectability of mid-mantle discontinuities may reflect compositional boundaries in the lower mantle. The characteristics of the 1050-km discontinuity observed beneath Hawaii and Iceland are broadly consistent with some geodynamic models having distinct chemical reservoirs in the lower mantle [2–5]. The increase in velocity with depth at the 1050-km discontinuity is opposite to the prediction of models with iron enrichment in the underlying mantle, but it is consistent with models in which the underlying mantle is enriched in silicon, i.e. an increase in the ratio of $(Mg,Fe)SiO_3$ in the perovskite structure to magnesiowüstite [2]. A silicon-rich lower-mantle body may be difficult to detect tomographically, because changes in seismic velocities caused by silicon enrichment can be partially offset by increases in temperature [2]. At a chemical boundary, compositional effects can create a velocity contrast at the boundary, whereas thermal conduction tends to equalize temperature across the boundary. By this scenario, mantle plumes can originate at the thermal boundary layer at the interface between compositionally distinct reservoirs. In experimental simulations of a compositionally layered mantle [3], plumes tend to form at sites where the compositionally denser layer domes upward to produce a relatively shallow and sub-horizontal upper surface, a geometry that might be expected to generate coherent P-to-S converted phases over a resolvable area. The differences between Iceland and Hawaii in the lateral dimensions of both the transition-zone thickness anomalies and the resolvable mid-mantle discontinuity may be the result of a relatively greater variation in the depth of the compositional boundary beneath Iceland and a consequently stronger focusing of hot mantle rising from the associated thermal boundary layer.

If mid-mantle discontinuities beneath the hotspots and near western Pacific subduction zones are boundaries between chemically distinct mantle reservoirs, there are potentially important implications for mantle dynamics. Two types of models, not mutually exclusive, invoke plumes rising from a boundary between mantle reservoirs. The first type of model involves a global lower-mantle layer denser than upper mantle material at the same pressure and temperature [2,3,5]. The depth to the compositional boundary shoals at upwelling regions and deepens near subduction zones [2,3]. This type of model fits some of the seismic constraints, including the stopping of slab penetration seen in some mantle tomographic images [5] and body-wave scattering from discontinuities east of the Marianas region [9,10], which occurs several hundred kilometers deeper than the mid-mantle discontinuities beneath upwelling regions. However, this type of model fails to explain mid-mantle discontinuities observed beneath the western Pacific in the depth range 900–1100 km [7,8,12,13,15] and the lack of mid-mantle discontinuities beneath western North and South America [30]. In the second type of model [4,31], compositionally denser mantle material accumulates in piles in the lower mantle, two of which may correspond to the large-scale low-velocity anomalies imaged tomographically beneath Africa and the south Pacific [32–34]. This second type of model is consistent with the interpretation that slabs penetrate to the core–mantle boundary in some regions (e.g. [33]) and that the low-velocity anomaly in the lower mantle beneath southern Africa is steep- and sharp-sided [35]. Such models further imply that each accumulated pile of comparatively dense lower-mantle material may have had a unique convective history and consequently a distinctive composition [36], seismic velocity, and mid-mantle discontinuity. Lateral variations in the depth and detectability of mid-mantle discontinuities appear to be more consistent with the second type of model, although a global layer with a strongly variable boundary transition would also fit most observations.

4. Conclusions

From teleseismic body waves recorded in Iceland and on the Hawaiian Islands, we identified P-to-S conversions from seismic discontinuities near 1050 km depth beneath the two regions of presumed upwelling. The results demonstrate that seismic discontinuities in the uppermost lower mantle can be mapped with receiver function analysis, and therefore the areas where mid-mantle discontinuities might be discerned can be expanded significantly. Our findings and an earlier observation of a mid-mantle discontinuity beneath southern Africa [16] suggest that mid-mantle discontinuities are not unique features of subduction regions. The waveforms of the converted phase from the 1050-km discontinuity beneath southern Iceland and Hawaii indicate a velocity increase with depth at the discontinuity. There seems to be a correlation between a significant P1050s phase and a reduction in transition zone thickness.

Recent systematic searches for seismic boundaries in the middle mantle have shown substantial lateral variations in the depth and detectability of mid-mantle discontinuities [13,30]. This inference argues against a global, sub-horizontal discontinuity having a significant and sharp velocity contrast near 1000 km depth. The lack of resolvable P-to-S conversions in the mid-mantle in regions of Iceland with normal transition-zone thickness provides additional evidence against the possibility that the observed 1050-km discontinuity beneath the Hawaiian and Iceland hotspots represents a mineralogical phase transition of global extent.

Lateral variations in the depth and detectability of mid-mantle discontinuities appear to favor geodynamic models in which intrinsically dense mantle material accumulates in distinct piles in the lower mantle [4,31], although a global lower-mantle layer that displays a strongly variable boundary structure is also possible. The increase in velocity with depth at the 1050-km discontinuity observed beneath southern Iceland and Hawaii suggests that the mantle beneath the compositional boundary in these areas may be enriched in silicon. The differences between Iceland and Hawaii in the lateral dimensions of both the transition-zone thickness anomalies and the resolvable mid-mantle discontinuity may reflect a relatively greater variation in the depth of the compositional boundary beneath Iceland and a consequently stronger focusing of hot mantle rising from the associated thermal boundary layer.

Acknowledgements

We thank the participants in the ICEMELT, HOTSPOT, and OSN experiments. Adriana Kuehnel, Randy Kuehnel, Emile Okal, Raymond Russo, and Paul Silver were involved in the installation and operation of the broadband seismic stations on the Hawaiian Islands. We thank John Vidale and two anonymous reviewers for helpful comments. This work was supported by the U.S. NSF.***[SK]***

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