Assessing the depth resolution of tomographic models of upper mantle structure beneath Iceland

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[1] Earlier inversions of body wave delay-time data recorded during the ICEMELT portable broadband experiment imaged a cylindrical plume-like low-velocity anomaly extending to at least 400 km depth beneath Iceland, but the depth extent of the anomaly resolvable by tomography has recently been called into question. We have performed several additional resolution tests to evaluate the depth resolution of tomographic models of the Icelandic upper mantle. The distribution of paths of body waves recorded by ICEMELT can distinguish among three different types of models: (a) a wide and shallow anomaly, (b) a narrow and deep anomaly, and (c) a narrow and shallow anomaly. While tomographic models contain an element of nonuniqueness, these tests illustrate that the depth resolution of passive seismic experiments spanning subaerial Iceland is adequate for distinguishing among alternative geodynamic models. *INDEX TERMS:* 7218 Seismology: Lithosphere and upper mantle, 8180 Evolution of the Earth: Tomography, 8121 Tectonophysics: Dynamics, convection currents and mantle plumes

1. Introduction

[2] Iceland, one of the most thoroughly studied hotspots, has been suggested to be the manifestation of an upwelling mantle plume [*Morgan*, 1971]. The Iceland hotspot generates a broad topographic high, thicker than normal crust, and a pronounced geochemical anomaly that extends along the adjacent Reykjanes Ridge [e.g., *Schilling*, 1973; *White et al.*, 1995]. These observations have been shown to be geodynamically consistent with the plume hypothesis [*Ribe et al.*, 1995; *Ito et al.*, 1996]. While initial geodynamic models favored a relatively cool and wide plume, later models incorporating a rheology that depends on water content showed that the observations could be equally well satisfied with a hot and narrow plume [*Ito et al.*, 1999].

[3] The upper mantle beneath Iceland also displays a strong seismic anomaly. *Tryggvason et al.* [1983] imaged a narrow low-velocity region in the mantle down to 400 km depth using relative *P* wave travel times across the local Iceland seismic network. This pattern has been confirmed and better defined for both *P* and *S* waves from tomographic inversions of delay times recorded by networks of portable broadband seismometers [*Wolfe et al.*, 1997; *Foulger et al.*, 2000; *Allen*, 2001]. Although the tomographic models do not resolve structure below about 400 km depth, localized thinning of the transition zone beneath Iceland is consistent with the plume extending to at least 670 km depth [*Shen et al.*, 1998]. Global tomographic models have revealed a larger-scale low-velocity anomaly near Iceland, although results differ on whether the seismic anomaly is confined to the upper mantle or extends into the lower mantle [*Bijwaard and Spakman*, 1999; *Ritsema et al.*, 1999]. In addition, a localized ultra-low velocity zone has been detected at the core-mantle boundary beneath Iceland and has been suggested to be the source region for the Iceland mantle plume [*Helmberger et al.*, 1998]. These observations are consistent with a plume that extends at least as deep as the base of the mantle transition zone and possibly as deep as the core-mantle boundary.

[4] In any study, it is important to consider the possibility of alternative models, and many Earth science problems are subject to an element of non-uniqueness inherent when using surface observations to constrain deep structures. Whether the Iceland upper mantle seismic anomaly represents a deep mantle plume has recently been questioned by *Keller et al.* [2000] who suggest that the anomaly could alternatively reflect a shallow asthenospheric source. In particular, on the basis of tomographic resolution tests, *Keller et al.* [2000] argued that the tomography experiment we performed [*Wolfe et al.*, 1997] with data from the ICEMELT broadband experiment [*Bjarnason et al.*, 1996] cannot distinguish between a shallow and broad anomaly (400 km in diameter and restricted to depths less than about 200 km) and a narrow (100 km radius) and deeper anomaly.

[5] There are several reasons why the tests performed by *Keller et al.* [2000], however, do not adequately represent the resolution of the ICEMELT data set. First, *Keller et al.* [2000] carried out only a two-dimensional analysis along a single profile using a small subset of the ICEMELT wave paths, rather than performing tests with the full three-dimensional path distribution. Second, they assumed that the wave paths are straight lines in the Icelandic upper mantle, whereas actual paths have curvature. Third, their inversion and regularization procedure differed from that of the ICEMELT study, which will affect the weighting of the data and the smoothness of the resulting models. Finally, *Keller et al.* [2000] made no mention of solving for station terms or earthquake relocations, both of which were incorporated in the inversions of the ICEMELT data.

[6] In this paper, we therefore revisit the question of the depth resolution of our previous models. In contrast to the conclusions of *Keller et al.* [2000], we find that the ICEMELT data can distinguish between shallow and deep plume models.

2. Resolution of Tomographic Models

[7] Imaging the Icelandic upper mantle by tomographic inversion of data from the ICEMELT experiment [*Bjarnason et al.*, 1996; *Wolfe et al.*, 1997] followed the method of *VanDecar et al.*

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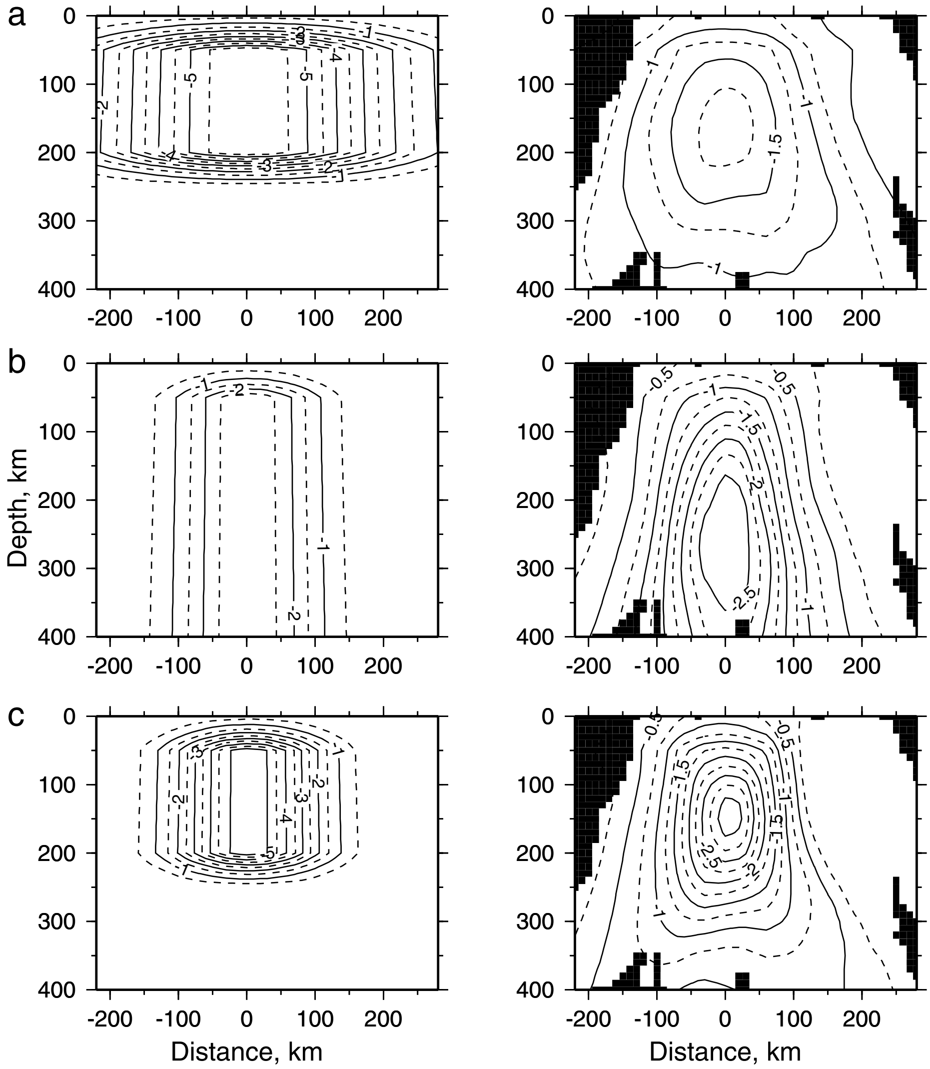

Figure 1. Resolution tests of low-velocity anomaly models beneath Iceland using the ICEMELT *P* wave path set. Vertical cross sections are shown through the center of the model along a line from 63°N, 20.2°W, to 67°N, 15.2°W, a profile oriented similar to the vertical cross section in Figure 2 of *Wolfe et al.* [1997]. The synthetic input models are shown in the left column (0.5% contour interval), and the results of inverting synthetic data to which 0.03-s rms gaussian noise has been added are displayed in the right column (0.25% contour interval). The velocity perturbations shown are relative variations across the modeled volume; absolute velocities are unconstrained. Regions with sparse ray coverage are tiled black. Note that ICEMELT data can distinguish between shallow and deep plume alternatives. See text for further information.

[1995]. *P* and *S* wave delays were independently inverted to solve for three-dimensional velocity structure, earthquake relocations, and station terms by means of a robust nonlinear, regularized scheme. Because these types of problems are underdetermined, this method searches for the minimum-structure model required to satisfy the data by minimizing spatial gradients and roughness. The inversions incorporated relative arrival times of 601 *P* waves from 86 earthquakes (including 12 earthquakes with core phases) and 560 *S* wave times from 78 earthquakes (including 13 earthquakes with core phases). The earthquakes employed in the study are well distributed in azimuth around Iceland. The dominant seismic wavelengths are about 10 km for the *P* waves and 50–75 km for the *S* waves. The seismic velocity grid used for inversion contains an outer and interior boundary, as shown in Figure 1 of *Wolfe et al.* [1997], and the model extends from 0 to 1000 km depth. The best resolution is obtained within the interior boundary and at depths above 400 km, within which we confine our interpretation. Because the station spacing is about 75 km and incidence angles of teleseismic waves steepen in the shallowmost mantle, there are no crossing wave paths above about 100 km depth. Velocity structure is thus poorly constrained at these shallow depths, although the station terms account in part for the integrated differences in mantle structure above 100 km depth as well as the effects of crustal thickness variations and differences in station elevation.

[8] Here, we conduct resolution tests in which a known synthetic anomaly is used to calculate synthetic travel times with the ICEMELT wave paths, gaussian noise (with root-mean square amplitude of 30 ms for *P* waves and 100 ms for *S* waves) is added, and the synthetic data are inverted. All parameters are set to the same values used for the inversion of ICEMELT observations. Figure 1 shows sample seismic resolution tests using the *P* wave set for three different models: (a) a wide, shallow low-velocity anomaly with a maximum absolute amplitude of 6% for *P* waves and 12% for *S* waves, a 200-km radius (defined by the region at which the perturbation drops below $1/e$ of the maximum ampli-

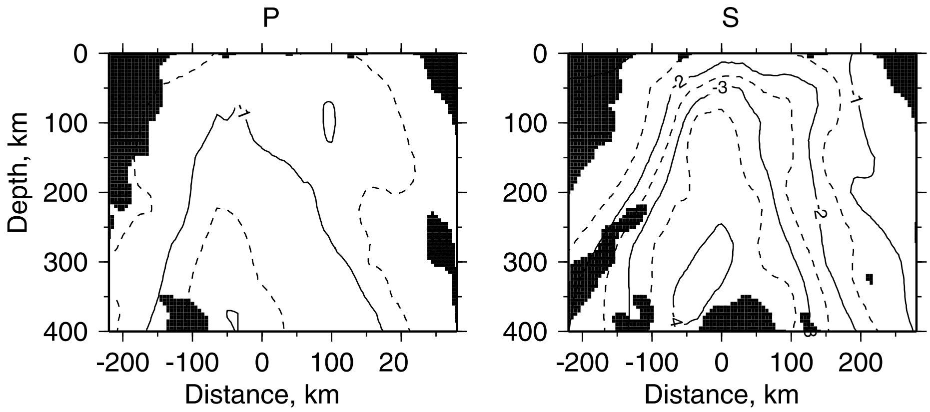

Figure 2. The solutions obtained by inverting ICEMELT data for velocity perturbations. Vertical cross sections of velocity perturbations are shown (0.5% contour interval) through the center of the ICEMELT *P* and *S* wave models along a line from 63°N, 20.2°W, to 67°N, 15.2°W. Note that both models increase in amplitude with depth. See *Wolfe et al.* [1997] for further information.

tude), and a depth range of 50 to 200 km, (b) a narrow, deep low-velocity anomaly with a maximum amplitude of 3% for *P* waves and 6% for *S* waves, a 100-km radius, and a depth range of 50 to 675 km, and (c) a narrow, shallow low-velocity model with a maximum amplitude of 5.5% for *P* waves and 11% for *S* waves, a 100-km radius, and a depth range of 50 to 200 km. These models are constructed using a horizontally decaying cylindrical gaussian over the indicated depth interval, multiplied by a vertically decaying gaussian above and below this depth range having a decay constant of 25 km. The model center is fixed at 64.75°N, 18°W, in central Iceland. Model (a) is similar to the one that *Keller et al.* [2000] has asserted fits the ICEMELT data set, while model (b) is more similar to that found by *Wolfe et al.* [1997] by direct inversion of the ICEMELT data. The amplitudes of the synthetic models are chosen to have a similar initial root-mean-square residual (~0.4 s for *P* waves and ~1.5 s for *S* waves) so that there will be an equal signal-to-noise ratio among models and all synthetic models produce a recovered anomaly with an amplitude of about 2% for *P* waves and 4% for *S* waves, equal to the amplitudes of the anomalies imaged by inversions of ICEMELT data. Only the results from the *P* wave tests are shown here, but the resolution of *S* wave models is similar.

[9] Lateral variations in the recovered model fades toward the surface, which is the result of the station terms absorbing structure above ~100 km depth where there are no crossing wave paths. As shown in Figure 1, the depth resolution is excellent for the narrow, shallow plume model (Figure 1c), with the amplitude decaying rapidly below 200 km depth. The depth resolution is not as good for the wide plume model (Figure 1a), which decays more slowly below 200 km. This difference reflects the fact that structure having a horizontal scale comparable to the aperture of the seismic experiment (~400 km) will be more poorly resolved than structure of smaller horizontal extent and centered interior to the seismic network. The amplitudes in Figure 1a are poorly reconstructed because relative delay-time tomography is sensitive only to the velocity variations beneath, and slightly outside of, the seismic network, and the inversions are insensitive to any one-dimensional (radial) velocity deviations from the starting Earth model. However, ICEMELT data can distinguish between the narrow deep model (Figure 1b) and a wide shallow model (Figure 1a). By 400 km depth, the amplitude of the recovered anomaly in Figure 1a has decayed to ~50% of its maximum value whereas the amplitude of the recovered anomaly in Figure 1b is more nearly constant over the depth interval ~150 to 400 km. It is noteworthy that the recovered ICEMELT images (Figure 2) [*Wolfe et al.*, 1997] do not contain a shallow maximum anomaly that decays in magnitude with depth as would be produced by a structure similar to that of Figure 1a. We also conducted resolution tests with models similar to Figure 1b, but with a maximum depth extent of only 400 km. In those cases, the recovered images are similar to that in Figure 1b, except the amplitude of the maximum anomaly decays more rapidly for depths greater than 300 km.

[10] For simplicity, our resolution tests have been restricted to linear modeling, where wave paths are from a one-dimensional global Earth model in both the forward problem and the inversion. We conducted a sample resolution test for the model of Figure 1a where synthetic delay times were calculated by three-dimensional ray tracing. We find that the recovered pattern from a linear inversion using the nonlinear set of synthetic data is equivalent to that shown in Figure 1a, although the amplitude of the imaged anomaly is slightly reduced, as would be expected from the effects of ray bending around a low-velocity region. Furthermore, the iteration for nonlinearity in the inversion of ICEMELT data produced only minor changes in the shape and position of the plume-like anomaly. Our conclusions are thus not sensitive to nonlinear effects.

3. Discussion

[11] While there is an element of nonuniqueness in the Iceland tomographic problem, these simple tests show that a shallow, broad anomaly should be distinguishable from a deep, narrow anomaly with the ICEMELT data. The lack of a decaying shallow anomaly (Figure 1a and 1c) in the ICEMELT images [*Wolfe et al.*, 1997] indicates that shallowly confined models are not favored. The possibility of a shallow low-velocity anomaly can also be tested with an independent set of observations. *Allen* [2001] analyzed Love waves recorded by the HOTSPOT network, a set of broadband portable stations deployed subsequent to ICEMELT, and compared mantle structural models derived from these records with body-wave tomography images obtained from inversions of a combination of HOTSPOT and ICEMELT data, as well as observations from permanent short-period and broadband stations in Iceland. The body-wave delay times were corrected for crustal thickness variations using a crustal model derived from the combined inversion of local Love wave observations, S_n arrivals, refraction measurements, and receiver function measurements. This correction improves the resolution of shallow upper mantle structure. *Allen* [2001] found that lateral variations in the shallow upper mantle derived from Love waves corroborate the lateral variations obtained from body wave tomography, and that the generally low velocities in the shallow upper mantle, interpreted as a plume head, do not remove the need for a deeper, cylindrical low-velocity anomaly beneath central Iceland to satisfy body-wave delay times.

[12] There have been four studies of the upper mantle structure beneath Iceland from local recordings of teleseismic body waves [*Tryggvason et al.*, 1983; *Wolfe et al.*, 1997; *Foulger et al.*, 2000; *Allen*, 2001]. To first order, all of these studies resolve a low-velocity anomaly beneath central Iceland that extends to at least 400 km depth, despite important differences among the studies in data sets, data processing procedures, and inversion schemes. For example, two studies made use of hand-picked data [*Tryggvason et al.*, 1983; *Foulger et al.*, 2000] and parameterized velocity variations with uniform blocks. The studies of *Wolfe et al.* [1997] and *Allen* [2001], in contrast, employed cross-correlation measurements of delay times and similar grid inversion schemes with smoothing constraints. An important difference in *Allen* [2001] work is that he corrected the delay-time data for shallow structure using independently derived crustal thickness maps and found that the cylindrical low-velocity anomaly is confined to 200–400 km depth.

[13] The resolution tests reported here, together with the broad consistency of independent inversions of distinct data sets, argue strongly for a plume-like upper mantle anomaly rather than a shallow asthenospheric anomaly as the source of the observed pattern of *P* and *S* delay times across Iceland. While on-land experiments are capable of distinguishing among several classes of geodynamic models for this region, future experiments using ocean-bottom as well as land seismometers would nonetheless provide an increased aperture important both for constraining longer-wavelength structure and for imaging to greater depths.

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