Difficulties in Seismically Imaging the Icelandic Hotspot

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Abstract

The locations of volcanic islands may be controlled by thin or extending parts of the lithosphere over a partially molten asthenosphere (*1, 2*), by edge effects near the boundaries of thick cratonic lithosphere (*3*), or by narrow jets of hot mantle rising from deep within the mantle (*4-6*). Many hotspots are found on or near ridges, at lithospheric discontinuities, or in extensional environments, so high resolution seismic images are required to determine whether it is lithospheric structure, stresses in the lithosphere, or the deep mantle that is the controlling factor for the location of active volcanoes. In this study, we perform a simple experiment in which we use basic geometrical arguments and idealized experimental parameters in order to understand the resolution of tomographic images of the upper 400 km of the mantle under Iceland. Our results indicate that a narrow, deep seated mantle plume is not required in order to explain the observed travel time delays. Results of tomographic inversions are often viewed as unique; however, recent seismic studies of the Icelandic Hotspot have illustrated the non-unique nature of these models.

The geometry of plumes in laboratory and computer simulations is a narrow cylinder capped by a bulbous head that flattens beneath the lithosphere, giving an overall mushroom shape to the upwelling (*7-9*). Deep mantle upwellings are also expected to broaden beneath the 650 km endothermic phase change. On the other hand, the geometry of upwellings driven by

plate divergence or by lateral changes in lithospheric thickness are expected to be focused at the surface toward the thin or extending regions. Iceland is in a particularly complex region, different from other volcanic islands, because it is located on a very slowly spreading ridge in the youngest, narrowest part of the Atlantic Ocean and is bounded by thick cratonic lithosphere. The separation of thick cold cratonic lithosphere will generate a deep upwelling which focuses toward the surface to fill in the newly formed gap. Passive steady-state upwellings, such as those found at mature ridges away from thick cratonic lithosphere, will exhibit a similar geometry but will not have as deep of an expression. Ribe et al. (*10*) showed that a hot, narrow, rising plume underneath Iceland would produce a bathymmetric signature that is inconsistent with observations (*11*) and suggested that the anomaly must be cooler and wider than would be expected from a hot rising plume. Using seismic methods, it is theoretically possible to distinguish between a narrow plume upwelling, passive effects due to plate divergence, and dynamic upwelling between two cratons; however, distinguishing between these three scenarios is problematic with real data.

Using data from a regional broadband seismic experiment (ICEMELT), Wolfe et al. (*12*) produced three dimensional tomographic images of the mantle beneath Iceland which show a Acone shaped≅ low velocity zone beneath the island that is approximately 150 km wide at the surface and is inferred to extend to at least 400 km depth. They suggest that this low velocity zone is the expression of a plume that is rising from deep within Earth=s mantle. However, this Acone shaped≅ geometry is not consistent with published images of plumes that suggest the existence of a cylindrical plume conduit which feeds a broadening plume head in the uppermost

mantle (*7-9*). The Acone shaped≅ tomographic appears to be defined by the cone of incoming rays, and most of the rays are traveling nearly vertically in the upper 400 km beneath Iceland. Because of the lack of crossing rays, the structure described might be explained by the smearing out of a shallow (<200 km depth) low velocity anomaly instead of the effect of a deep mantle plume.

This is the well known parallax problem and is not unlike the problems encountered when a light is shone on an object and one attempts to reconstruct the shape of the object from the shadow it forms on the wall. For instance, a disc, a sphere, an ellipsoid, a cone, and a cylinder will all cast a circular shadow on the wall when oriented in the proper way. The only way to determine the three dimensional shape of the object is to observe the shadow when the light source is shone on the object at many different angles. We show that the uniqueness and resolution problem encountered when imaging the Icelandic mantle is due to the geometry of the experiment and the lack of crossing ray information. Other tomographic studies in areas near hotspots have found that it is impossible to distinguish between a shallow anomaly in the upper 200 km of the mantle and a narrow deep seated plume. In a recent study of the Yellowstone Hotspot, Saltzer and Humphreys (*13*) found that both scenarios fit their tomographic inversion results equally well.

We perform simple tomographic resolution tests in which we calculate idealized synthetic delay times for S-waves through a variety of velocity anomalies in the upper 400 km of the mantle, and then invert these delays for structure in order to understand how well these anomalies may be resolved in a tomographic inversion. Raypaths from sources and receivers

along the two dimensional profile discussed in Wolfe et al. (*12*) were calculated to determine the ray coverage, number of ray crossings, and angle of ray crossings along this cross section of the model (figure 2a). The sources and receivers used in this calculation are shown in red in figure 1a and 1b. The sources in light red are the earthquakes that occurred further than 90 degrees from Iceland. This profile is a Abest case scenario≅ because it contains the widest range of source to receiver offsets of any profile in the data set, and thus it contains the best ray crossing information. We expect this cross-section to provide an upper bound on the resolution of the full 3D analysis because it has more constraints per degree of freedom than the full model. In addition, all of the possible source – receiver combinations were used in our calculations which gives a very optimistic resolution estimate. Slightly less than half of the possible S-wave source receiver combinations in the ICEMELT experiment (*12*) yielded useful data in which accurate travel time measurements could be made. Figure 2a shows that most of the rays in the upper 400 km of this model are nearly vertically incident, and most of the angles between crossing rays are small.

For the resolution tests, we cast a model with a cartesian grid which has a spacing of 50 km in the horizontal direction and a spacing of 25 km in the vertical direction. To simplify the resolution tests, it is assumed that the raypaths are straight lines in the upper 400 and that the cartesian grid is a good approximation to a spherical earth in the region of interest. A pseudo hit count map for the tests is shown in figure 2b. There is a strong correlation between figure 2b and tomographic inversion results along this profile, and this illustrates the biased nature of the result of the inversion.

A narrow deep low velocity anomaly (figure 3a1) and a broader shallow low velocity anomaly (figure 3b1) were used as starting models in the resolution tests. After synthetic travel time delays were calculated through both of these models along the profile in question, the delay times were inverted for structure. A generic SIRT (Simultaneous Iterative Reconstruction Technique) algorithm was used for this inversion (*14*), and the results are shown in figure 3a2 and figure 3b2. Elements in which there is no ray coverage are black. The large amount of vertical smearing shown in the images in figure 3 indicates that the depth resolution of this dataset is very poor. The inversions performed in each resolution test yield results which satisfy the synthetic travel time delays equally well, and as a result of the experimental parameters, it is impossible to distinguish between these two quite different models by performing tomographic inversions. This experiment, therefore, cannot distinguish among the different hypotheses proposed for Iceland.

Various authors have attempted to constrain the depth extent and shape of proposed plumes by analyzing PdS conversions, waves converted from P to S at seismic discontinuities at depths d below the receiver, in areas near hotspots. Shen et al. (*15*) showed that P660s-P410S differential times in Iceland are less than predicted, which indicates a fast or thin transition zone in this region. They conclude that their observations are most consistent with a hot narrow plume originating from the lower mantle; however, they are not able to rule out the possibility of a larger regional anomaly because the area southeast of Iceland remains unmapped by their techniques. Shen et al. (*15*) observe a relatively narrow zone of anomalous P660S-P410S differential times, and their preferred model is that of a narrow plume which travels unimpeded, with no change in shape, through the transition zone. However, numerical modeling has shown

that plume conduits are expected to broaden just below the endothermic phase change at 660 km and to narrow as they enter the low viscosity region of the upper mantle (*16-18*). In addition, Vinnik et al. 1997 (*19*) looked at PdS conversions for hotspots on the Pacific Plate and found no evidence for thin transition zone under known hotspots. Chevrot et al. (*20*) analyzed PdS conversions from over 80 stations and 9 locations near hotspots, including Iceland, and they concluded that there was no correlation between transition zone thickness and location of hotspots on a global scale.

Recent tomographic studies in Iceland have yielded varied results. Bijwaard and Spakman (*21*) published a tomographic model of a low velocity anomaly below Iceland which extends from the core-mantle boundary to the surface. Their model suggests that the imaged structure is very complex with numerous lateral branches. The plume head in their model encompasses the entire upper mantle of the North Atlantic Region. However, regional tomographic studies in Iceland (*12, 22*) have confirmed the existence of a low velocity anomaly with a diameter less than that of the island. Pritchard et al. (*22*) suggest that the velocity anomaly in the upper mantle beneath Iceland actually narrows with depth in a cross section perpendicular to the Mid-Atlantic Ridge as opposed to broadening with depth like the cone shaped anomaly of Wolfe et al. (*12*). They also show an anomaly that is elongated in a N-S direction along the ridge axis at depth as opposed to the axially symmetric model of Wolfe et al. (*12*). The model of Ritsema et al. (*23*) shows a broad upper mantle anomaly and no lower mantle anomaly. Varying experimental parameters, assumptions, geometry, number of crossing rays, and inversion techniques have clearly had a major effect on the results of these different tomographic inversions.

It is evident that the problems involved in resolving vertical structure in the mantle beneath Iceland is greatly limited by two factors – the small aperture of the seismic array as a result of the limited dimensions of the island, and the near vertical incidence of rays in the upper 400 km - caused by a relative lack of seismicity close to Iceland and the decision to only use sources greater than 30 degrees away from the receiver array. These same factors limit the effectiveness of seismically imaging other oceanic hotspots because of the generally small diameter of ocean islands and because of the relative lack of sizeable earthquake sources within the ocean basins. The ray crossing information and thus the resolution of such images could be increased by expanding the aperture of the array by using ocean bottom seismometers, by using events within 30 degrees of the island as opposed to limiting the data to teleseismic events, and by including travel times from phases such as SS, sS, ScS, etc. in the inversion as was done by Pritchard et al. (*22*). Results of tomographic inversions are often treated as unique; however, in the case of the Icelandic mantle, several groups have obtained very different results by using different assumptions, inversion techniques, and data sets. These discrepancies highlight the non-unique nature of seismic tomography and point out the importance of performing a series of inversions with varying parameters in order to determine a robust solution to a given tomographic problem.

Figure Captions

Figure 1. a) Location of the seismic instruments used in the ICEMELT experiment. The yellow line marks the location of the cross section shown by Wolfe et al. (*12*), and the cross section used for all the calculations in this study. The receivers used in our 2D calculations are shown in red on this figure. b) Location of the earthquakes recorded during the ICEMELT experiment. The sources used in this study are shown in red (sources beyond 90 degrees are shown in light red), and the azimuth of our 2D profile is again shown in yellow. All possible source – receiver combinations are used in our calculations which gives an upper bound on resolution.

Figure 2. a) Plot showing all the rays used for the calculations in this study. Most of the rays are nearly vertically incident, and there is very little ray crossing information at depth, especially in the SW side of the model. d) This figure shows the cumulative ray length for each element in our model, and can be thought of as a pseudo hit count. This image bears a strong resemblance to tomographic inversion results along this profile, illustrating the biased nature of the inversion results. PREM is the reference model that is used in all calculations in this study (*24*).

Figure 3. a1-a2) Tomographic resolution test for a narrow plume model as suggested by Wolfe et al. (*12*). b1-b2) Tomographic resolution test for a broader anomaly within the upper 200 km of the mantle. Both of these starting models yield similar results in the

inversion, and both models explain the synthetic travel time delays equally well. Thus, it

is impossible to distinguish between these two models by performing tomographic

inversions.

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