GEOPHYSICAL RESEARCH LETTERS, VOL. 23, NO. 5, PAGES 459-462, MARCH 1, 1996

Initial results from the ICEMELT experiment: Body-wave delay times and shear-wave splitting across Iceland

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Abstract. We present results from the first stage of the ICEMELT broadband seismometer experiment designed to determine upper mantle structure beneath Iceland, a hotspot located on the Mid-Atlantic Ridge. Relative delays of teleseismic body waves across Iceland are in excess of 1 s for *P* waves and as large as 3 s for *S* waves. The patterns of *P* and *S* wave delays suggest a low-velocity anomaly in the upper few hundred kilometers beneath central Iceland, consistent with the signature of mantle upwelling beneath a hotspot. Shear-wave splitting measurements of the fast polarization direction ϕ and the delay time δt between the fast and slow shear waves have been obtained at several network stations. Splitting times range from 0.7 to 1.7 s, and fast directions are generally between N20°W and N45°W. While splitting times of this magnitude must be primarily signatures of the anisotropy of the Icelandic upper mantle, the directions of fast polarization are inconsistent with simple models of horizontally diverging flow either in the plate spreading direction or radially from the center of the hotspot. A hypothesis consistent with splitting data obtained to date is that the dominant contribution to upper mantle anisotropy is from the large-scale mantle flow field of the North Atlantic.

Introduction

Understanding the geometry of upwelling mantle flow and the characteristics of magma generation and transport beneath hotspots and mid-ocean ridges is of fundamental importance for topics ranging from the formative processes for the crust and lithosphere to the large-scale dynamics and chemical makeup of the mantle. Considerable insight into these issues has been gained from theoretical models coupled with constraints from topography, gravity, and heat flow, as well as petrological and geochemical information [e.g., *Ito and Lin,* 1995; *Feighner et al.*, 1995; *Menke and Sparks*, 1995]. The only means for resolving the detailed characteristics of upper mantle structure beneath hotspots and ridges, however, is through seismology, particularly through regional arrays of broadband, multi-component seismometers. The ICEMELT experiment in Iceland, a hotspot centered on the northern Mid-Atlantic Ridge, is the first regional broadband seismic experiment designed with such a motivation. We report here initial results from the first phase of that experiment, including new information on the relative delay times of teleseismic *P* and *S* waves and shear-wave splitting across Iceland.

There is reason to expect that many of the characteristics of mantle flow and melt segregation in the upper mantle beneath Iceland are amenable to measurement by seismic techniques. The direction-averaged seismic velocity and attenuation fields in the mantle are sensitive to temperature, bulk composition, and the volume fraction and distribution of retained partial melt; and the anisotropy of seismic wave speeds can provide a measure of flow-induced ordering of mantle olivine grains and the preferential orientation of melt volumes. Early studies by *Tryggvason* [1964] and *Long and Mitchell* [1970] showed that teleseismic *P* waves arrive at Iceland at least 1 s later than at stations in Greenland, Scotland, and Sweden and predicted by then-standard Earth models. More recent global tomographic models [e.g., *Zhang and Tanimoto*, 1993; *Grand*, 1994] indicate that the upper several hundred kilometers of the mantle beneath and immediately surrounding Iceland have lower than average shear wave velocities, but these models can resolve lateral structure only at scales of 500-1000 km and greater. *Tryggvason et al.* [1983] conducted a tomographic inversion of relative arrival times of teleseismic *P* waves recorded on an unevenly distributed network of short-period stations; they found a low-velocity anomaly in the upper 400 km beneath central Iceland which they identified with the site of upwelling underlying the Iceland hotspot.

Network Description

In the first phase of the ICEMELT experiment, the Carnegie Institution of Washington installed five portable broadband, three-component Streckeisen STS-2 seismometers in Iceland during 1993-94 (Figure 1). Each station includes a 16-bit Reftek 72A-06 data logger recording continuously at 10 samples/s and a GPS timing system, and all seismometers are sited on bedrock. The interstation distance is approximately 100 km. Three stations (BRE, KAF, and KLU) are located within farm buildings; Icelandic farmers assisted with their construction and also operate the instruments. AKUD is at a police station, the site of a permanent broadband seismic station (AKU) operated by DTM since 1972 [*Evans and Sacks*, 1979]. NYD is located in a remote area in a specially constructed underground vault. We also make use of data from the permanent Global Seismographic Network station BORG, in operation since August 1994. The network of portable instruments was expanded to 15 stations during the spring and summer of 1995 and will record data through 1996.

As on any oceanic island, microseismic noise in Iceland can

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Paper number 96GL00420
0094-8534/96/96GL-00420$03.00

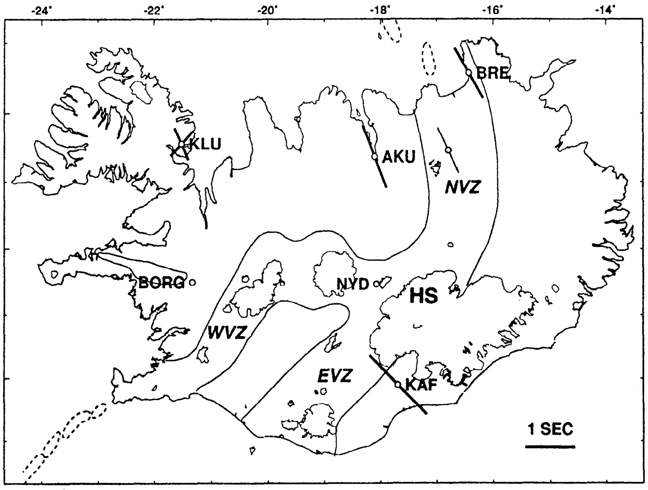

Figure 1. Distribution of seismic stations (circles) in Iceland during the first phase of the ICEMELT experiment. Also depicted are the areas of recent fissure and dike eruptions (bold lines), including the Northern, Eastern, and Western Volcanic Zones (NVZ, EVZ, and WVZ, respectively), and the postulated center of the Iceland hotspot (HS). Narrow lines outline glaciers and lakes. Segments of the Mid-Atlantic Ridge immediately north and south of Iceland are shown schematically by dashed lines. The direction ϕ of fast S-wave polarization and the delay time δt between fast and slow S waves is indicated at four stations. The delay time is linearly proportional to the length of the bar shown at each station (see scale). Records at KLU from different azimuths give apparently different results for ϕ; two possible solutions are shown. The splitting observation reported by *Menke et al.* [1994b] for the NVZ is indicated by the thin bar.

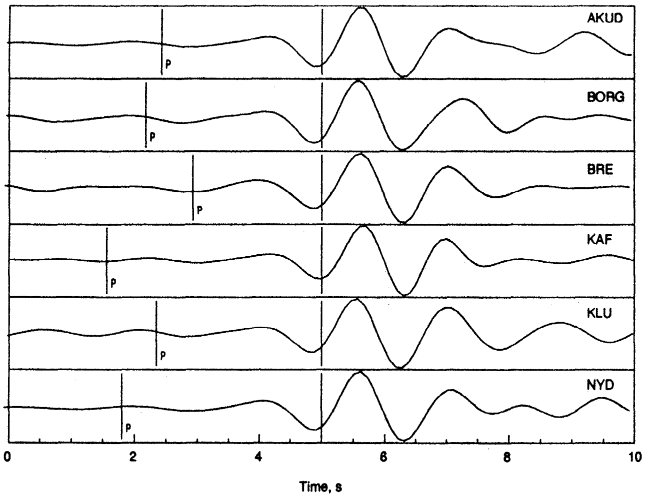

Figure 2. Example of P waveforms at six stations from the Kurile Islands earthquake of 9 November 1994 ($m_b = 6.1$) at a distance Δ of 71° from central Iceland. Waveforms have been bandpass-filtered from 0.5 to 1.0 Hz and are aligned according to the picks of the multi-channel cross-correlation method [*VanDecar and Crosson*, 1990]; the origin on the time axis is arbitrary. Prior to cross correlation, waveforms are multiplied by a tapered window of 3-s duration (15 s for S waves). The letter P denotes the P-wave arrival predicted by the *iasp91* model [*Kennett and Engdahl*, 1991]; relative travel time residuals are obtained from differences in these predicted times after waveform alignment.

limit the detectability and fidelity of recorded teleseismic waves. Signal-to-noise ratios are significantly poorer during winter months because of generally high storm-related noise. However, the azimuthal coverage of body waves from large ($m_b > 5.7$) teleseismic events is quite good in Iceland, and with a sufficient time window spanning periods of good local weather there are adequate sources of data with which to perform delay-time and shear-wave splitting analyses.

Body Wave Delay Times

Because of the generally high seismic attenuation beneath Iceland, teleseismic arrivals display little energy above about 1 Hz for P waves and 0.2 Hz for S waves. Waveforms of P waves bandpass filtered to 1-2 s and S waves filtered to 5-15 s are nonetheless well correlated across the network. We obtained relative delay times and estimates of their uncertainty with the multi-channel cross-correlation technique of *VanDecar and Crosson* [1990] (Figure 2). Prior to cross correlation, waveforms were windowed to isolate the direct arrival from crustal multiples. Residuals were corrected for epicentral distance by subtracting the predicted travel times for the *iasp91* structure [*Kennett and Engdahl,* 1991]. Measurements from multiple earthquakes within a restricted source region give a consistent pattern of travel time residuals, lending additional confidence to the observations.

Relative travel time delays are about 1 s for P waves (Figure 3) and as large as 2-3 s for S waves (Figure 4). These differences are too large to be due to crustal thickness variations. For instance, for lower crustal and upper mantle P wave velocities of 6.5-7 and 7.7 km/s, respectively [*Bjarnason et al.*, 1993], a ratio of P to S velocity of 1.8, and a representative angle of incidence of 20°, a 10-km variation in the thickness of the lower crust would introduce relative P and S wave residuals of only 0.1-0.3 and 0.2-0.5 s, respectively. Thus the relative delays in Figures 3 and 4 are primarily the result of upper mantle heterogeneity.

Data from a dozen well-recorded earthquakes analyzed to date all show the same basic pattern: For a variety of incoming azimuths, P and S waves that travel through the upper mantle beneath central Iceland are significantly delayed relative to waves at other network stations (Figures 3 and 4). The long-wavelength variation in the pattern of residuals with azimuth thus indicates that we are seeing primarily the effect of a low-velocity anomaly within the upper few hundred kilometers of the mantle located beneath central Iceland. A particularly diagnostic set of residuals is that shown for the *SKS* waves in Figure 3. Because at this distance range this phase arrives with upper mantle angles of incidence of 10° or less, the residuals depicted are approximately equivalent to differences in the one-way travel times through the upper mantle beneath each station; the *SKS* arrival at station NYD in central Iceland is up to 3.5 s later than at other stations in the network.

Shear Wave Splitting

Measurements of shear-wave splitting parameters, the fast polarization direction ϕ and the delay time δt, have been made from about twenty teleseismic shear phases for which the primary contribution to splitting is expected to come from the portion of the path beneath the recording station. These

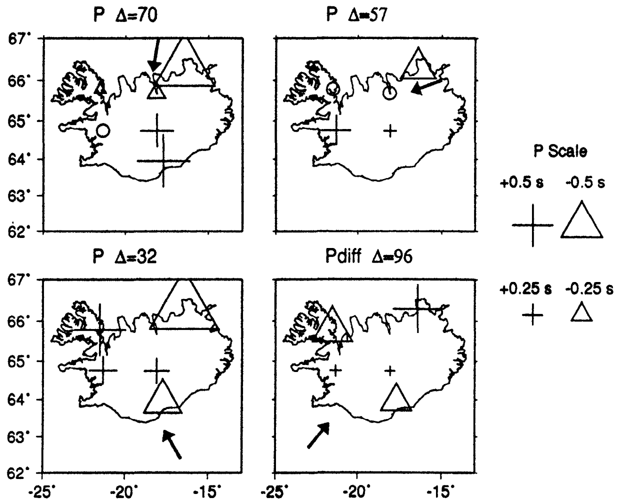

Figure 3. *P* wave residuals for direct and diffracted branches for selected events at the indicated epicentral distance; the azimuth of approach of incoming waves is indicated by the arrow. Residuals are relative to the average distance-corrected arrival time for each station set; positive residuals denote late arrivals; circles denote delays with absolute values less than 0.1 s. For all incoming azimuths, *P* waves that travel through the mantle beneath central Iceland are relatively late, consistent with a low-velocity anomaly in the upper few hundred kilometers beneath central Iceland.

phases include *SKS*, *PKS*, *SKKS* as well as direct *S* waves from deep-focus earthquakes. We have followed the method of *Silver and Chan* [1991], as modified by *Wolfe et al.* (manuscript in preparation), to solve for the best single set of splitting parameters at a station given waveforms from several events at different distances and back azimuths.

The results of the splitting analysis carried out to date are shown in Figure 1. We have obtained well-determined splitting parameters for stations AKU, BRE, and KAF. There remains some ambiguity in the direction of fast polarization at KLU, with two non-orthogonal directions possible on the basis of conflicting information from different sources. Splitting parameters are not yet well determined for NYD, which has been in operation for the shortest period. Delay times at the four stations analyzed all fall in the range 0.7-1.7 s. With the possible exception of KLU, the directions of fast polarization lie between N20°W and N45°W.

Discussion

We may compare our findings to date with those of earlier studies. The range in relative *P* wave delay times we observe, in excess of 1 s (Figure 3), compares well with the rms *P* wave residual of 0.5 s reported by *Tryggvason et al.* [1983], given the differences in geographic coverage and bandwidth between their network and the ICEMELT stations. On the basis of recordings from a teleseismic earthquake on a network of portable seismic stations deployed across the Northern Volcanic Zone (NVZ) spreading center segment as part of the active-source Faeroes-Iceland Ridge Experiment during 1994, *Menke et al.* [1994b] reported a variation in *P* wave residual of only 0.1 s across the spreading center, except that arrivals in the center of the Krafla volcano are delayed by 0.25 s relative to stations off the spreading axis. While the present ICEMELT network does not have the station density to resolve delay times across the NVZ, it is apparent from Figures 3 and 4 that the principal upper mantle signal in the delay times obtained to date arises from the difference in upper mantle structure beneath central Iceland and adjacent areas.

The relative delay times collected from this first phase of the ICEMELT experiment are still too sparse to provide well-constrained images of mantle structure. With the expansion of the network and a final interstation distance of 75 km or less, however, data of the sort depicted in Figures 3 and 4 will be well suited to tomographic inversions. We can anticipate that the principal anomaly to be imaged will be the low-velocity volume beneath central Iceland and that independent inversions for *P* wave and *S* wave velocity structure will provide a view of at least the upper reaches of the mantle upwelling zone of a vigorous hotspot in unprecedented detail. On the basis of the splitting observations, the possibility that the shear wave delays contain a contribution from mantle

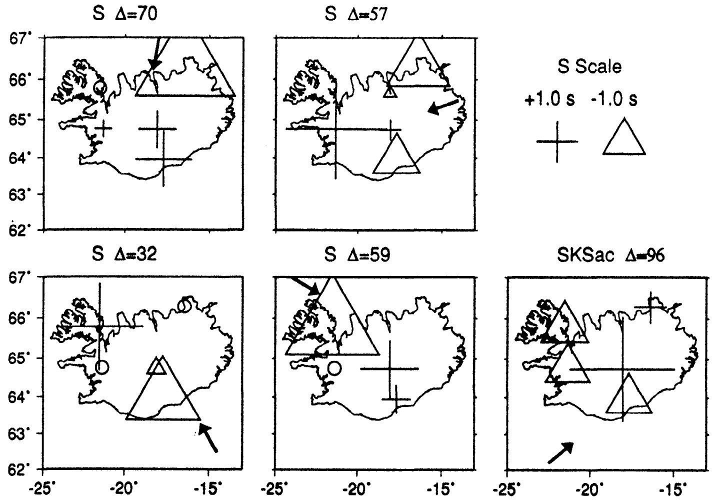

Figure 4. *S* and *SKS* wave residuals for selected events at the indicated epicentral distance; the azimuth of approach of incoming waves is indicated by the arrow. As with *P* waves, *S* waves that travel through the mantle beneath central Iceland are delayed. The magnitude of the delay for *S* and *SKS* phases is a factor of 2-3 greater than for *P* waves.

anisotropy must be explored. The good correspondence between patterns of *P* and *S* delays (Figure 3 and 4), however, suggests that the *S* wave travel times reflect primarily the structural heterogeneity of the Icelandic mantle.

We may also compare our splitting measurements with limited other data. *Menke et al.* [1994b] observed splitting, with a fast direction of N25°W and a delay time of about 1 s, for shear waves from a single deep-focus event recorded at their stations deployed across the NVZ. This polarization direction and delay time are in agreement with those we obtain, N20°W to N45°W and 0.7-1.7 s, respectively (Figure 1), with the possible exception of the fast polarization direction at KLU. As the contribution to shear-wave splitting from the crust is small, about 0.1-0.3 s in Iceland [*Menke et al.*, 1994a], the principal source of the splitting is the anisotropy of the upper mantle, produced by the lattice preferred orientation of upper mantle minerals (primarily olivine) or by the anisotropic distribution of magma.

The fast polarization directions obtained to date (Figure 1) rule out the geometrically most simple models for flow-induced alignment of mantle mineral grains or melt bodies, including patterns in which the direction of fast (or slow) polarization is either in the direction of plate spreading or radial to the center of hotspot upwelling. A consistent northwest-southeast orientation for fast shear wave polarization may be a signature of the long-wavelength pattern of upper mantle return flow driven by the motions of the plates. *Hager and O'Connell* [1979] show several models for such flow in which the predicted flow direction in the North Atlantic is north-south to northeast-southwest; departures from the simplifying assumptions made in constructing those models (e.g., only radial variations in viscosity, no superposed thermal convection) may account for the difference between the predicted flow direction and the S wave polarization directions in Figure 1. Under such an interpretation, the small differences in splitting parameters between stations could result from the superposition of patterns of lattice preferred orientation and melt distribution associated with upwelling and divergence at the hotspot and ridge sections with this larger scale mantle flow.

The pattern of shear wave splitting in Figure 1 is in contrast to observations at sites of continental rifting, where directions of fast shear wave polarization both normal to and subparallel to the trend of the rift have been reported [*Sandvol et al.*, 1992; *Gao et al.*, 1994]. It can be argued on the basis of regional patterns of splitting, however, that measurements at such sites are strongly influenced by the fabric of the underlying continental lithospheric mantle and need not reflect the flow patterns in the asthenosphere [*Silver,* 1996].

Conclusions

The first phase of the ICEMELT experiment has revealed large variations in *P* and *S* wave delay times across Iceland indicative of a pronounced low-velocity anomaly in the upper few hundred kilometers beneath central Iceland, consistent with the signature of mantle upwelling beneath the Iceland hotspot. Shear-wave splitting measurements of the fast polarization direction ϕ and delay time δt, in contrast, are inconsistent with simple models in which the fast (or slow) polarization directions are either radial to the hotspot center or oriented in the direction of plate spreading. The generally northwest-southeast direction of fast shear wave polarization observed thus far in Iceland may indicate that upper mantle flow is dominated by a larger-scale mantle circulation field in the North Atlantic. With the expansion of the ICEMELT network, we expect to record sufficient data both to conduct detailed tomographic imaging of the low velocity anomaly beneath central Iceland and to characterize more fully the nature and possible causes of the anisotropy of the Icelandic upper mantle.

Acknowledgments. We are grateful to Pall Einarsson for contributing logistical support, and to the several farmers who have graciously offered us access to their farms and assumed much of the task of station operation. We also thank Randy Kuehnel, Selwyn Sacks, Paul Silver, and John VanDecar for advice and assistance, as well as Martha Savage for constructive comments. This work was supported by the National Science Foundation under grant EAR-9316137.

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(Received August 8, 1995; revised November 22, 1995; accepted December 18, 1995)