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Seismic imaging of a hot upwelling beneath the British Isles

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ABSTRACT

The Iceland plume has had an important influence on vertical motions in the North Atlantic. The convecting mantle in this region contains a large-scale low-velocity seismic anomaly, which correlates with a long-wavelength gravity high and bathymetric feature. This suggests that an arm of plume material has extended, or is extending, from Iceland, in a direction perpendicular to the Mid-Atlantic Ridge. Here we present the results of a detailed teleseismic traveltimes study that reveals the high-resolution morphology of this low-velocity anomaly beneath the British Isles. Our images provide insights into the nature of plume-lithosphere interactions. The low-velocity anomaly imaged in this study correlates geographically with a region of high gravity anomalies and high topography that was associated with Paleogene magmatism and phases of epeirogenic uplift during the Cenozoic Era. There is evidence that the distribution of British earthquakes is also related to the low-velocity anomaly. The low-velocity anomaly is interpreted to represent hot material from the original Iceland plume head that became trapped beneath thinned regions of lithosphere ca. 60 Ma.

Keywords: plume-lithosphere interactions, North Atlantic Igneous Province, seismic tomography.

INTRODUCTION

Inversions of surface and body wave data for the upper-mantle structure of the North Atlantic Ocean (e.g., Marquering and Snieder, 1996; Bijwaard et al., 1998) have imaged a long-wavelength, slow-velocity anomaly in the mantle beneath the North Atlantic, centered at Iceland. This irregularly shaped slow anomaly extends down to the transition zone beneath Iceland (Wolfe et al., 1997; Foulger et al., 2000) with one prong extending laterally as far as the British Isles and Norway. The seismic anomaly is supported by a long-wavelength gravity high, also centered at Iceland and with similar lateral extent. There is evidence from southern Norway for a correlation between low seismic velocity anomalies, gravity anomalies, and Neogene uplift (Rohrman et al., 2002).

There is significant circumstantial evidence that the British Isles prong is associated with active upwelling. A region encompassing these islands underwent several phases of regional uplift and denudation during the Cenozoic Era. Denudation of ~3 km is coincident with a region of Paleogene magmatism (Rowley and White, 1998). This magmatic activity forms part of the North Atlantic Igneous

Province, consisting of synchronous magmatism over a large region of the North Atlantic (White and McKenzie, 1989). Geochemical evidence collected from rocks in the British Cenozoic Igneous Province (BCIP), which forms part of the North Atlantic Igneous Province, shows evidence of high $^3\text{He}/^4\text{He}$ ratios, consistent with their origin of a deep mantle upwelling (Stuart et al., 2000), assuming a conventional mantle model. The seismicity of the British Isles also provides evidence of the continuing tectonics associated with the hot upper mantle, the uplift it causes, and the weakened crust. Bott and Bott (2004) attempted to bring some of these disparate data sets together into a single dynamic framework. To this date, a high-resolution tomography image of the upper mantle below the region has been lacking. The goal of this paper is to determine whether there is seismic tomographic evidence for a “fingerprint” of the hot upwelling in the upper mantle beneath the British Isles.

METHODS AND RESULTS

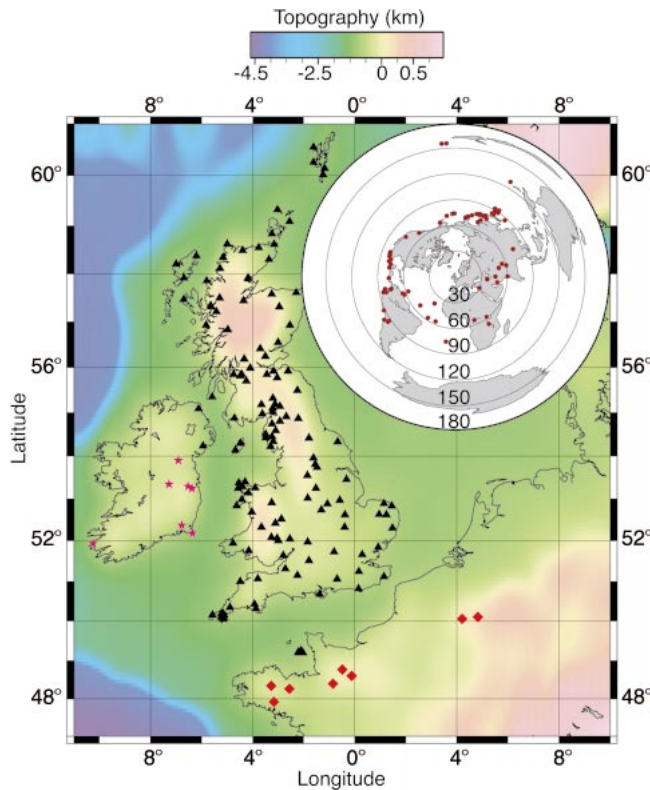
Seismic data come from a total of 148 stations (Fig. 1). The density of seismic stations for such an aseismic region is unprecedented and comparable with more active regions, e.g., California. We determined ~10,000 P-wave teleseismic relative arrival times for 81 events using a cross-correlation procedure (VanDecar and Crosson, 1990). These events are well distributed with both back-azimuth and epicen-

tral distance with respect to the seismic array (Fig. 1). A good distribution of events is crucial because the resolution of teleseismic tomography is essentially a function of the density of crossing ray paths. The initial standard deviation of the data set is 0.25 s. The standard deviation of noise in the data set is estimated to be 0.02 s, based on the mean standard deviation of residuals associated with each trace (for further explanation see VanDecar and Crosson, 1990).

We parameterize the velocity structure of the upper mantle beneath the British Isles using splines under tension constrained at 33,396 nodes. Such a scheme allows for smooth velocity variation, essential for three-dimensional (3D) ray tracing, while still allowing relatively local structure. An optimal parameterization scheme for resolution of the 3D upper-mantle velocity distribution is determined using sensitivity tests. The inversion algorithm used (VanDecar, 1991) allows us to simultaneously solve for velocity perturbations and event statics, which account for event mislocations and 3D structure outside the region of interest. Each trace is weighted in the inversion scheme by the mean standard deviation of residuals associated with that trace (VanDecar, 1991). Since there is no resolution of crustal structure, due to the absence of crossing rays at shallow depths, we compensate for the effect of the crust on the teleseismic relative arrival times using an a priori crustal correction. Crustal thicknesses (Chadwick and Pharaoh, 1998), sedimentary basins, and topography are incorporated into a 3D crustal-velocity model using the method of Waldhauser et al. (2002). Traveltimes are forward modeled through the crustal model (for every event-station pair used in the tomography) using a finite difference algorithm (Vidale, 1988). The resultant traveltimes are then subtracted from the total recorded traveltimes prior to the 3D inversion. In addition, we have computed crustal corrections using station static terms to absorb relative travel-time delays due to the crust (VanDecar, 1991; Arrowsmith, 2003) and found similar results. Because the system of equations is underdetermined, the 3D inversion is regularized by minimizing first and second spatial derivatives. The method of conjugate gradients

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Figure 1. Map showing locations of seismic stations. Black triangles represent British Geological Survey seismic stations, purple stars represent Dublin Institute for Advanced Studies seismic stations, and red diamonds represent Laboratoire de Détection et de Géophysique seismic stations. Background color scale shows long-wavelength topography. Inset: Azimuthal projection is centered on British Isles, which shows locations of earthquakes used in this study. Red circles show location of events; concentric circles mark angular distances every 30° from center of UK. Note that all events occur at $30^\circ < \Delta < \sim 100^\circ$, with exception of three core-phase events (2 PKP, 1 PkiKP).

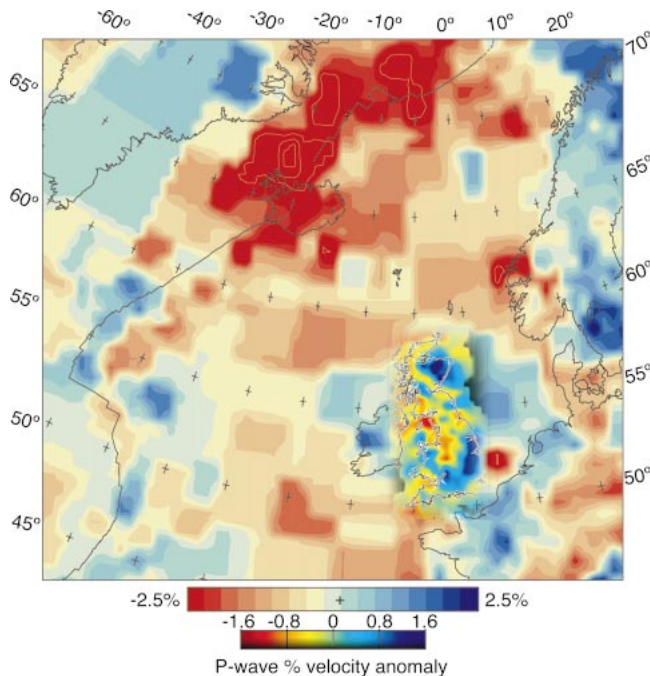


(Scales, 1987) is used to solve the resultant linear equations. Nonlinearity is addressed by iteratively performing 3D ray tracing and linear inversion until the solution converges. Our final velocity model fits 87.5% of the initial data variance. We choose smoothing parameters to avoid fitting more than 92% of the data, since this would result in us fitting spurious noise.

Absolute P-wave arrivals are consistently

late compared with predicted arrival times from the IASP91 Earth model (Kennett and Engdahl, 1991), indicating that the mantle beneath the British Isles is generally slow relative to IASP91. Therefore, while slow-velocity anomalies in our model represent real slow anomalies compared with the global average, fast anomalies may not necessarily represent fast mantle. In the derived 3D velocity model, we image $\pm 2\%$ velocity anomalies at

Figure 2. Three-dimensional P-wave velocity model at depth of 100 km superimposed on global model of Bijwaard et al. (1998). Colors in Bijwaard et al. (1998) model, and in our velocity model, are scaled according to top and bottom color bars, respectively. Area of British Isles is above edge of broad-scale low-velocity anomaly in mantle beneath North Atlantic, centered at Iceland plume. Resolution of Bijwaard et al. (1998) model is highly nonuniform, but low-velocity anomaly is also observed in surface wave studies (Marquering and Snieder, 1996) and is backed up by large-scale regional gravity high.



depths of 50–250 km (Figs. 2 and 3; see Data Repository Fig. DR1¹). Low-velocity anomalies are observed beneath western Scotland, the Irish Sea, and western England. High velocities are observed beneath eastern Scotland and southeast England. The resolution of upper-mantle velocity structure is assessed using a sensitivity test. We construct a synthetic velocity model and forward model arrival times using 3D ray tracing and the same source and receiver locations as in the real inversion. The results (Figs. DR2 and DR3; see footnote 1) suggest that the lateral resolution of the velocity anomalies should be considered reliable.

DISCUSSION

A limitation with teleseismic tomography is the depth resolution of velocity anomalies. Most ray paths are subvertical, and therefore anomalies tend to become smeared vertically. In order to interpret anomalies we need to determine if they originate in the crust, in the lithospheric mantle, or in the convecting mantle. We can rule out the crust as being the origin for the velocity anomalies since the effect of the crust on the teleseismic wave fronts is compensated for as an a priori correction in the inversion procedure. It is more difficult to determine if the origin of the anomalies is in the lithospheric mantle or the convecting mantle. We argue that the origin of the anomalies is more likely to be in the convecting mantle, based on the magnitudes of anomalies. There is evidence that anomalies observed in this study are not caused by compositional anomalies in the lithosphere as their magnitudes are $\pm 2\%$, and are more likely to be larger in reality due to the regularized inversion (see amplitude reduction in the synthetic tests; Figs. DR2 and DR3 [see footnote 1]). The most plausible hypothesis is that the velocity anomalies imaged at depths of 50–300 km are caused by thermal upwellings in the asthenosphere. Velocity anomalies at shallow depths (~ 50 km) may be smeared anomalies from deeper depths, or may represent lithosphere that has been heated by the underlying hot asthenosphere. However, the anomalies are unlikely to be entirely lithospheric in origin and must involve an asthenospheric component, based on their high magnitudes.

Velocity anomalies show a good geographical correlation with long-wavelength gravity anomalies (Fig. 3). Low-velocity anomalies and high-gravity anomalies span western Britain and the Irish Sea, while high-velocity

¹GSA Data Repository item 2005066, Figures DR1–DR3, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

anomalies and low-gravity anomalies span eastern Britain. There is also a crude correlation with topography, whereby western Britain has generally higher topography than eastern Britain (Figs. 1 and 3). However, there are some important exceptions, including eastern Scotland and the Irish Sea. The British Isles, however, is a region that underwent phases of significant epeirogenic uplift in the Cenozoic Era, with a maximum in the Irish Sea of ~ 3 km (Rowley and White, 1998). The region of maximum uplift, and subsequent denudation, correlates very well with the low-velocity anomaly in the Irish Sea and western Britain. The majority of British earthquakes may also be related to the low-velocity anomaly. Earthquakes are concentrated around the edges of the low-velocity anomaly (Fig. 3). There is a good correlation with Paleogene igneous centers (Fig. 3), whereby igneous centers are associated with low-velocity anomalies. Dike swarms follow the NW-SE trend of the low-velocity anomalies, but are not always located directly above them.

An interpretation of the low-velocity anomalies in terms of a hot, low-density upwelling in the uppermost mantle underlying Britain could explain the numerous correlations that we observe. Low-velocity anomalies, high-gravity anomalies, high topography, the epeirogenic uplift that occurred in the Cenozoic, and Paleogene magmatism are all indicative of an upwelling in the upper mantle. Furthermore, such an upwelling may be the cause of the majority of British earthquakes, many of which have poorly understood origins. Available earthquake focal mechanisms suggest that the earthquakes are caused by tensional loading stress in all directions, which would be consistent with their cause being an upwelling in the upper mantle (Bott and Bott, 2004).

The interpretation of a low-velocity anomaly in the asthenosphere beneath the British Isles as the fingerprint of a hot upwelling in the mantle raises an important question: why does the low-velocity anomaly still correlate geographically with an area of Cenozoic magmatism and uplift? Since 60 Ma the British Isles have drifted toward the north. If rigid plates are decoupled from the convecting mantle, regions of Cenozoic magmatism and uplift should no longer directly overlie their causative mantle upwellings. One possible explanation is that the lithosphere and the top 100–200 km of the asthenosphere beneath the British Isles have remained coupled for the past 60 m.y. The degree to which the lithosphere and asthenosphere are coupled remains a subject of some debate. A second explanation is that the low-velocity anomalies represent hot material from a mantle upwelling that has ponded beneath relatively thin regions of

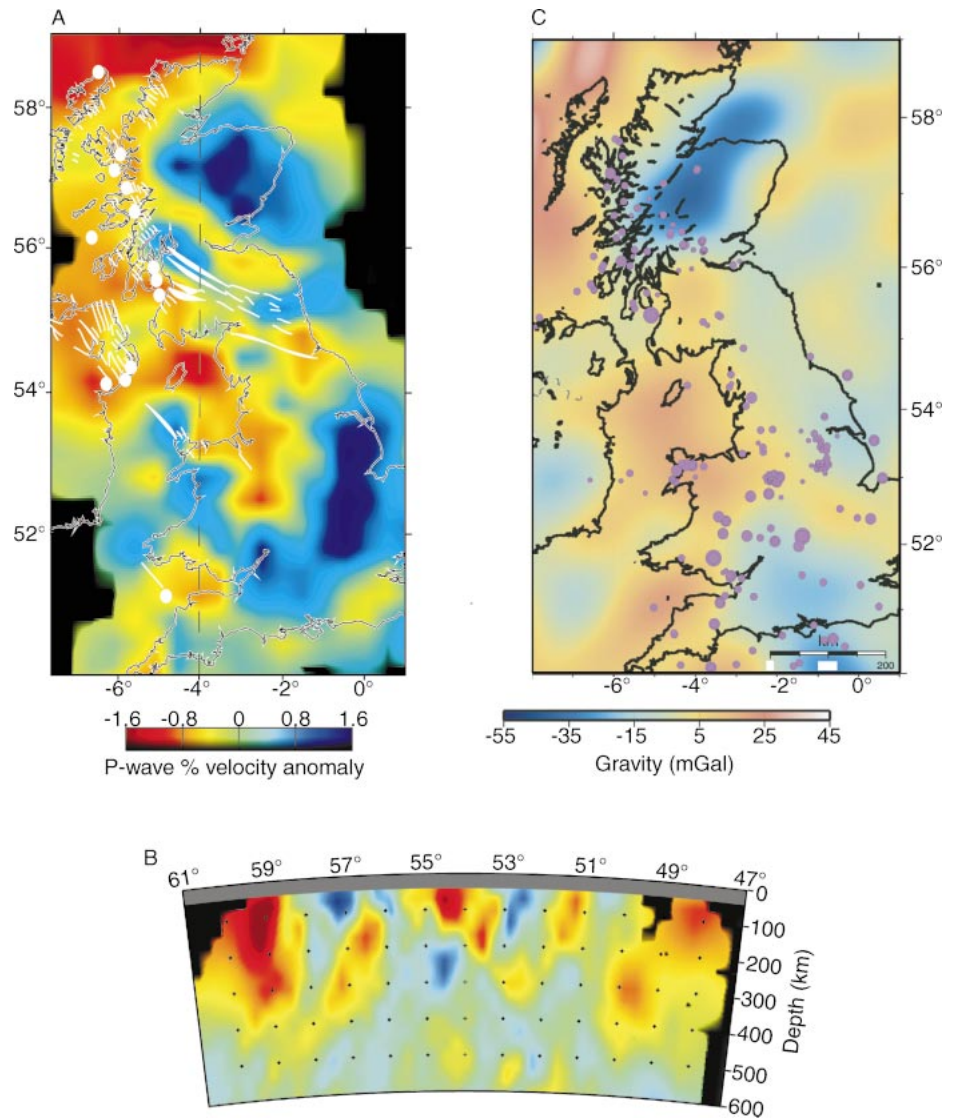


Figure 3. A: Horizontal slice through three-dimensional P-wave velocity model at depth of 100 km. White circles and lines show locations of Paleogene igneous centers and dike swarms, respectively. Paleogene volcanics composing British Cenozoic Igneous Province contain high $^3\text{He}/^4\text{He}$ ratios, indicative of deep mantle source (Stuart et al., 2000). Scale fades to black in regions of model where ray coverage is poor. Dashed black line shows transect of cross section shown in B. **C:** Long-wavelength, free-air gravity map for British Isles. There is clear geographical correlation between regions of low velocity in mantle and regions of high gravity anomalies. Purple circles denote locations of earthquakes occurring in British Isles during 10 yr period, from 1991 to 2001.

lithosphere (thin spots). Sleep (1997) and Thompson and Gibson (1991) suggested that Paleogene uplift in the Irish Sea and the intrusion of the BCIP were caused by plume material from Iceland that flowed laterally beneath the lithosphere and became ponded beneath lithosphere thin spots. Such a pond of hot material would result in local uplift and denudation, and would remain trapped beneath the lithosphere in the same location relative to the surface. Approximately 300–400 m of Paleogene uplift occurred in the Irish Sea (McKenzie and Bickle, 1988). Sleep (1997) showed that this suggests that ~ 50 – 66 km of plume material was trapped beneath the litho-

osphere. The time gap between the end of active subsidence of Mesozoic basins and the onset of Paleogene magmatism was ~ 80 m.y. (Thompson and Gibson, 1991). Locally thinned lithosphere rethickens by conductive cooling in the same way as oceanic plates thicken away from spreading centers (Turcotte and Schubert, 1982). By using a thermal diffusivity for the upper mantle of $10^{-6} \text{ m}^2\text{s}^{-1}$ (Sleep, 1997), a thinning of the lithosphere-asthenosphere boundary by 75 km for 150-km-thick lithosphere would take ~ 100 m.y. to rethicken (Turcotte and Schubert, 1982). For such a region, ~ 34 km of thinning would remain after 80 m.y. The length of time it takes

for the lithosphere to rethicken is dependent on the amount of thinning and the lithosphere thickness. However, it is plausible that Mesozoic sedimentary basins in the Irish Sea and British Isles were regions of thinned lithosphere in the Paleogene.

The two hypotheses for explaining the correlation between low-velocity anomalies in the asthenosphere, and areas of Cenozoic magmatism and uplift, reconcile low-velocity anomalies in terms of either present-day or ancient convective processes. In the case of lithosphere-asthenosphere coupling, low-velocity anomalies would represent hot upwellings that are part of the active convection system. If low-velocity anomalies represent hot material from the Iceland plume head that has become ponded beneath thin spots, the low-velocity anomalies would represent the thermal remanence of a convection process that occurred ca. 60 Ma. The low-velocity anomalies exhibit a maximum contrast of 1.5%, relative to normal mantle beneath the British Isles. For a typical pyrolite mantle composition, the observed velocity variations can be produced by a thermal anomaly of ~200 °C (Carmichael, 1982). This estimate for the magnitude of the thermal anomaly is approximate, as the magnitudes of the anomalies are relatively poorly resolved (compared to their locations) and are a function of the amount of smoothing we have used in regularizing the inversion. However, for a temperature contrast of ~200 °C in the asthenosphere, the mantle should be crossing the dry solidus, and we would expect some partial melt (Hirschmann, 2000). Therefore, the low-velocity anomalies may be caused by a combination of thermal anomalies and partial melt.

CONCLUSIONS

We have computed the first high-resolution seismic model of the upper mantle beneath the British Isles. Our robust new images reveal the presence of significant seismic velocity anomalies at depths of 50–250 km. By observing low velocities directly beneath regions of high-gravity anomalies, high topography, regions of epeirogenic uplift, and the locations of British earthquakes, we present convincing evidence that crustal epeirogenic uplift is a consequence of mantle convection. There is significant evidence that the upwelling beneath Britain is related to the Iceland plume. Our findings provide further insight into the

nature of interaction of the Iceland plume with the North Atlantic, in a region distant from the plume axis.

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