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Asthenospheric channeling of the Icelandic upwelling: Evidence from seismic anisotropy

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Abstract

Two end-member geometries, radial flow and ridge-channeled flow, have been proposed for the dispersion of material upwelling beneath Iceland. Seismic anisotropy provides information on mantle flow, and therefore has the potential to discriminate these two geometries. In this study, we combine the HOTSPOT and SIL datasets (39 stations) and select 28 events for teleseismic shear-wave splitting analysis. Splitting results in central and eastern Iceland show 1–2 s splitting times with an average NNW–SSE orientation of the fast splitting direction and an anti-clockwise rotation of fast axes from east to central Iceland. In western Iceland, smaller splits with more N–S orientations are observed. Since crustal splitting times in Iceland are 0.1 s to 0.3 s, our delays of up to 2 s indicate a mantle source. Both the lack of dependence of the splitting parameters on event back azimuth and the observations of null splits for events where the back azimuth is parallel or perpendicular to the fast splitting directions (observed using other events) suggest that one layer of anisotropy dominates beneath Iceland. While both high stress plus enriched water content and melt-rich layers can result in a 90° rotation of the fast splitting direction with respect to the flow direction, we interpret our fast axis orientation as pointing in the direction of flow as the magnitude of stress is low and the amount and geographical extent of melt are likely small beneath Iceland. The observed anisotropy pattern beneath Iceland is inconsistent with radial flow away from the upwelling. Instead we propose a ridge-channeled flow model in which there is horizontal flow of material away from the upwelling axis beneath southeast Iceland toward the southern end of the Kolbeinsey Ridge and the northern end of the Reykjanes Ridge, both of which are west of the upwelling. This geometry is similar to the ridge perpendicular flow predicted for off-ridge hotspots towards the ridge. We hypothesize that upwelled material then feeds ridge parallel asthenospheric channels beneath the North Atlantic Ridge. Our interpretation is thus consistent with generation of V-shaped ridges by channeling of upwelling material down the Reykjanes and Kolbeinsey ridges.

Keywords: Iceland; mantle upwelling; seismic anisotropy; shear-wave splitting; asthenospheric channeling

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1. Introduction

Iceland is a hotspot located on the North Atlantic Ridge, with the Reykjanes Ridge to the south and the Kolbeinsey Ridge to the north. This special location makes Iceland an ideal place to study the interactions between hotspot upwelling and mid-ocean ridge processes. Seismic studies show the presence of a low velocity anomaly extending vertically through the upper mantle, which has been interpreted as a high temperature buoyant upwelling centered beneath southeast Iceland [1–4]. Surface observations such as the broad high topography of the Reykjanes Ridge, which is much smoother and lacks the segmentation of typical slow-spreading ridges [5,6], and the thicker crust of Iceland up to six times that of normal oceanic crust [7,8] also suggest that the uppermost mantle is relatively high temperature producing large volumes of melt. This influence of the Iceland upwelling extends down the Kolbeinsey and Reykjanes ridges to the north and south of Iceland. A V-shaped pattern of bathymetry and gravity anomalies, interpreted as representing the passage of melting anomalies along the ridge away from Iceland, is observed along both the Reykjanes Ridge [9,10] and on the eastern side of the Kolbeinsey Ridge (the lack of symmetry of the western side is probably due to the fact that the V-shaped ridge gravity signal has been attenuated by the gravity signal caused by up to 4 km of overlying sediments shed from Greenland [11]). Geochemical signatures show that both the Reykjanes Ridge and the Kolbeinsey Ridge are affected by the Iceland upwelling [12–14]. The Kolbeinsey Ridge is less affected than the Reykjanes Ridge, and might be modified by upwelling beneath Jan Mayen in addition to Iceland [13–15]. All these observations are generally taken as indicators of the existence and spatial influence of the Icelandic upwelling. While they are consistent with a whole-mantle plume, global tomography studies do not support the continuation of the upper mantle low velocity anomaly down into the lower mantle [16–18]. We therefore use the term “upwelling” instead of “plume”.

Various models have been proposed for the interaction between the Icelandic upwelling and the North Atlantic Ridge based on the above observations, via either along-axis melt transport [19,20] or large-scale asthenospheric flow [21–26]. Estimates of upwelling flux and crustal generation rates imply that the bulk of upwelling material flows away from the region without participating in melting processes beneath Iceland [1]. A key question is how does this upwelling material disperse in the North Atlantic asthenosphere? This remains enigmatic not only to Iceland, but to other plume–ridge systems [27]. Two geometries have been suggested: radial flow and ridge-channeled flow. Vogt [10] first discussed both radial and channeled flow and subsequent studies have generally supported one of these two end-member models. In radial flow, material spreads out in all directions away from the upwelling axis [25,28,29], whereas in channeled flow, upwelling material feeds asthenospheric channels below the spreading axis [19,21–23,26].

New constraints are needed to test and distinguish between these two geometries. Seismic anisotropy provides information about mantle strain; constraints on anisotropic structure beneath Iceland therefore have the potential to elucidate mantle flow geometries in the region. In previous anisotropy studies [30,31], the splitting observations in Iceland fall into two groups: in eastern Iceland the average splitting direction is NNW–SSE, and in western Iceland the average splitting direction is rotated clockwise to N–S [31] or NNE–SSW [30]. Bjarnason et al. [30] interpret their teleseismic shear-wave splitting results as the consequence of shear between the North American or Eurasian plate and background mantle flow, concluding that mantle flow is in a northward direction. Li and Detrick [31] also interpret their shear-wave splits as being the result of background mantle flow. In addition, they constrain anisotropy using Rayleigh waves and conclude there are two layers of anisotropy above 100 km in western and central Iceland, and SKS splitting is primarily caused by flow deeper than 100 km. This interpretation reconciles the departure of their surface wave results from splitting results and also implies that the Iceland upwelling and its interaction with the Mid-Atlantic Ridge are not sensed by or does not dominate shear-wave splitting.

In this study, we present new SKS and SKKS splitting data from the HOTSPOT and SIL networks. We use these measurements to constrain the flow of Icelandic upwelling material. The increased number of stations used provides the most detailed map of splitting observations across Iceland thus far. After constraining the depth of the anisotropy, and considering