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The Iceland–Jan Mayen plume system and its impact on mantle dynamics in the North Atlantic region: Evidence from full-waveform inversion

Florian Rickers *, Andreas Fichtner, Jeannot Trampert

Department of Earth Sciences, Utrecht University, Budapestlaan 4, 3584 CD, Utrecht, The Netherlands

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ABSTRACT

We present a high-resolution S-velocity model of the North Atlantic region, revealing structural features in unprecedented detail down to a depth of 1300 km. The model is derived using full-waveform tomography. More specifically, we minimise the instantaneous phase misfit between synthetic and observed body- as well as surface-waveforms iteratively in a full three-dimensional, adjoint inversion. Highlights of the model in the upper mantle include a well-resolved Mid-Atlantic Ridge and two distinguishable strong low-velocity regions beneath Iceland and beneath the Kolbeinsey Ridge west of Jan Mayen. A sub-lithospheric low-velocity layer is imaged beneath much of the oceanic lithosphere, consistent with the long-wavelength bathymetric high of the North Atlantic. The low-velocity layer extends locally beneath the continental lithosphere of the southern Scandinavian Mountains, the Danish Basin, part of the British Isles and eastern Greenland. All these regions experienced post-rift uplift in Neogene times, for which the underlying mechanism is not well understood. The spatial correlation between the low-velocity layer and uplifted regions suggests dynamic support by low-density asthenosphere originating from the Iceland and Jan Mayen hotspots. Our model further suggests a lower-mantle source for the Iceland and Jan Mayen hotspots. Two distinguishable low-velocity conduits are imaged, connecting the upper-mantle anomalies beneath Iceland and Jan Mayen into the lower mantle. Both conduits are tilted to the South-East, reflecting the westward motion of the Mid-Atlantic Ridge. The location of the imaged Iceland conduit is in agreement with the observation of a locally thinned transition zone south of Iceland from receiver function studies.

1. Introduction

The North American and Eurasian continental margins are drifting apart since the onset of ocean spreading in the North Atlantic about 55 Ma ago. The continental breakup went along with the eruption of large amounts of magma within a short geological time (White and McKenzie, 1989). Following the breakup, the magma production rate along the Mid-Atlantic Ridge remained locally unusually high. This resulted in the formation of Iceland (Fig. 1), which is part of an extensive bathymetric and gravimetric high observed over much of the North Atlantic (Jones et al., 2002). To the South-West of Iceland, the elevation decreases gradually along the Reykjanes Ridge towards the Charlie-Gibbs Fracture Zone. In contrast, the Kolbeinsey Ridge to the North of Iceland remains at a relatively constant, high elevation until it encounters the Jan Mayen Fracture Zone. The Jan Mayen Islands are another centre of increased magma production, possibly related to a separate hotspot. However, existing global and regional seismic models cannot resolve individual hotspots in this region (e.g. Ritsema et al., 1999; Ritsema and Allen, 2003; Bijwaard and Spakman, 1999; Grand, 2002; Pilidou et al., 2005; Legendre et al., 2012).

Considerable (kilometre-scale) post-rift uplift in Neogene times (Fig. 1) is documented on the continental shelves surrounding the North Atlantic (see summaries in e.g. Japsen and Chalmers, 2000; Doré et al., 2002; Carminati et al., 2009). Uplifted regions include, among others, the southern and northern Scandinavian Mountains in western Scandinavia (Rohrman et al., 1995; Redfield et al., 2005), part of the British Isles (George, 1966; Green, 1989; Japsen, 1997; Duncan et al., 1998; Hall and Bishop, 2002; Holford et al., 2008), the Danish Basin (Japsen et al., 2002, 2007), eastern Greenland (Mathiesen et al., 2000; Johnson and Gallagher, 2000) and Svalbard (Vågnes and Amundsen, 1993). Deep cratonic roots, which could isostatically balance the additional topography, are lacking beneath these regions. The mechanism for the uplift is debated (e.g. Rohrman and van der Beek, 1996; Ebbing and Olesen, 2005; Holford et al., 2008; Pascal and Olesen, 2009; Ebbing et al., 2012). A connection to the Iceland hotspot is supported by the tomographic study of Weidle and Maupin (2008), who image

* Corresponding author. Tel.: +49 173 8321531.
E-mail addresses: florian.rickers@gmail.com (F. Rickers), A.Fichtner@uu.nl (A. Fichtner), J.A.Trampert@uu.nl (J. Trampert).

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a low-velocity finger extending beneath the lithosphere to the southern Scandinavian Mountains. Beneath parts of the British Isles, Arrowsmith et al. (2005) image low velocities, and Davis et al. (2012) find a negative correlation between crustal thickness and topography. Both of these studies indicate dynamic support, which they suggest to be related to low-density material from the Iceland hotspot. Scaled long-wavelength gravity maps (Jones et al., 2002) indicate that parts of Britain, southern Scandinavia and eastern Greenland are presently experiencing dynamic support related to the Iceland hotspot.

Morgan (1971) proposed that the localised, long-lived magmatism of hotspots could be caused by mantle plumes. They are envisioned as narrow, hot upwellings originating from the core-mantle boundary. In the case of Iceland, a possible mantle plume would be interacting with a spreading ridge, and might have weakened the continental lithosphere prior to continental breakup. The mantle plume hypothesis found widespread acceptance, but unambiguous seismic evidence for the continuation of upper-mantle low-velocity anomalies into the lower mantle beneath Iceland is still sparse.

Some global tomographic models show broad and relatively weak low-velocity structures in the lower mantle below Iceland (e.g. Bijwaard and Spakman, 1999; Ritsema et al., 1999; Zhao, 2004), which cannot be interpreted with certainty as continuous plume structures. Several studies attempted to image the mantle below Iceland using array data recorded on Iceland (Tryggvason et al., 1983; Wolfe et al., 1997; Foulger et al., 2001; Allen et al., 2002; Bjarnason et al., 2002; Delorey et al., 2007). While all these models agree on the presence of low velocities in the uppermost mantle, results are contradictory in deeper mantle regions. Keller et al. (2000) showed that the limited array aperture used in such studies does not permit unique constraints on the depth extent of the Iceland anomaly. Using receiver functions, Shen et al. (1998, 2002) imaged a locally thinned transition zone below Iceland, indicative for elevated temperatures which could possibly be caused by a hot plume. Other studies, however, imaged a flat transition zone using similar methods (Du et al., 2006).

Hwang et al. (2011) find that simple cross-correlation travel-time measurements are not suited to extract lower-mantle plume information from seismic data. Rickers et al. (2012) come to the same conclusion and explain it with the fact that such methods do not account for diffraction effects in seismic wave propagation, which are strong in the case of small-scale heterogeneities.

The lack of unambiguous evidence for a lower-mantle plume below Iceland leaves the possibility of a different mechanism producing the increased magma volumes. Such a mechanism could be fertile, old crust in the upper mantle, being overridden by the Mid-Atlantic Ridge (Foulger et al., 2001; Foulger and Anderson, 2005; Foulger, 2012).

The need for an improved tomographic model of the whole North Atlantic region, covering the upper and at least part of the lower

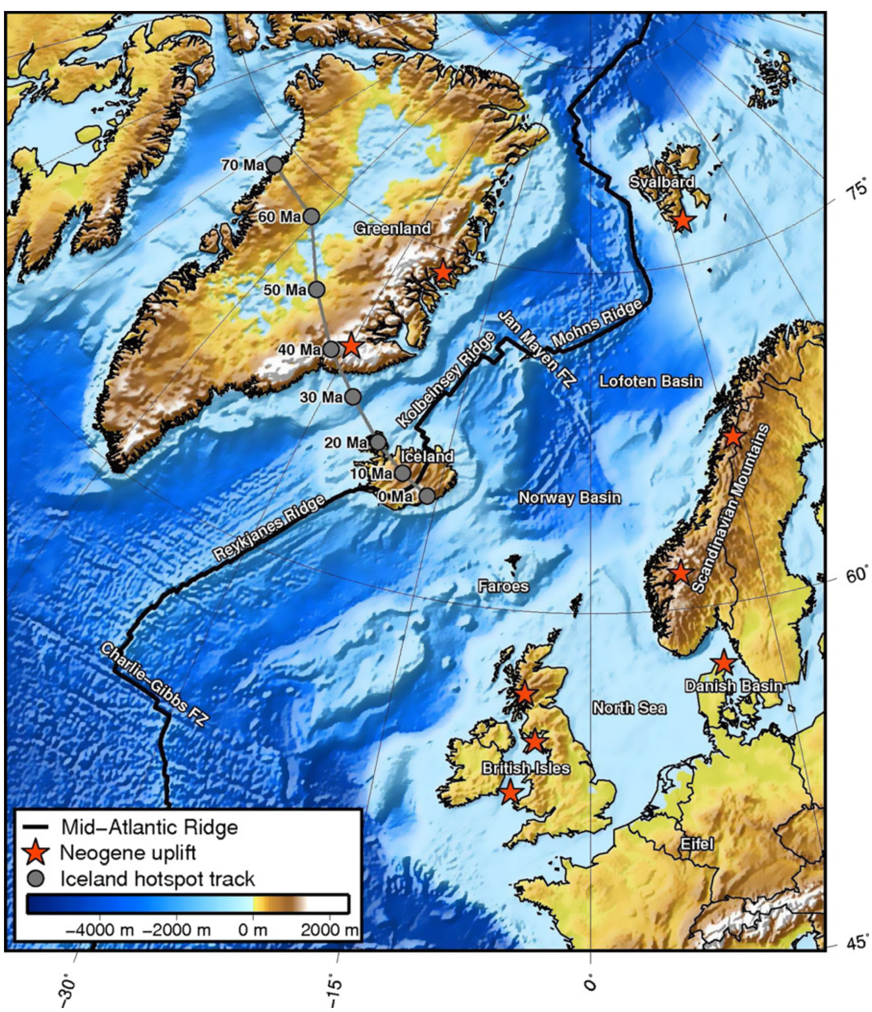

Fig. 1. Bathymetry and topography of the North Atlantic region. The black line indicates the Mid-Alantic Ridge, the grey dots represent the reconstructed Iceland hotspot track between 70 Ma and today (Lawver and Müller, 1994). Red stars indicate a (non-complete) selection of regions where Neogene uplift is documented (after Japsen and Chalmers, 2000; Japsen et al., 2007; Holford et al., 2008, and references therein). FZ is used as abbreviation for Fracture Zone. (For interpretation of the references to colour in this figure caption, the reader is referred to the web version of this article.)