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Ambient noise tomography reveals basalt and sub-basalt velocity structure beneath the Faroe Islands, North Atlantic

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ABSTRACT

Ambient noise tomography is applied to seismic data recorded by a portable array of seismographs deployed throughout the Faroe Islands in an effort to illuminate basalt sequences of the North Atlantic Igneous Province, as well as underlying sedimentary layers and Precambrian basement. Rayleigh wave empirical Green's functions between all station pairs are extracted from the data via cross-correlation of long-term recordings, with phase weighted stacking implemented to boost signal-to-noise ratio. Dispersion analysis is applied to extract interstation group travel-times in the period range 0.5–15 s, followed by inversion for period-dependent group velocity maps. Subsequent inversion for 3-D shear wave velocity reveals the presence of significant lateral heterogeneity (up to 25%) in the crust. Main features of the final model include: (i) a near-surface low velocity layer, interpreted to be the Malinstindur Formation, which comprises subaerial compound lava flows with a weathered upper surface; (ii) a sharp velocity increase at the base of the Malinstindur Formation, which may mark a transition to the underlying Beinisvørð Formation, a thick laterally extensive layer of subaerial basalt sheet lobes; (iii) a low velocity layer at 2.5–7.0 km depth beneath the Beinisvørð Formation, which is consistent with hyaloclastites of the Lopra Formation; (iv) an upper basement layer between depths of 5–9 km and characterized by *S* wave velocities of approximately 3.2 km/s, consistent with low-grade metamorphosed sedimentary rocks; (v) a high velocity basement, with *S* wave velocities in excess of 3.6 km/s. This likely reflects the presence of a crystalline mid-lower crust of Archaean continental origin. Compared to previous interpretations of the geological structure beneath the Faroe Islands, our new results point to a more structurally complex and laterally heterogeneous crust, and provide constraints which may help to understand how continental fragments are rifted from the margins of newly forming ocean basins.

1. Introduction

The crustal structure of the continental block on which the Faroe Islands (Fig. 1) sits is poorly understood, largely due to the presence of thick Tertiary basalt sequences of the North Atlantic Igneous Province at the surface that hinder controlled-source seismic imaging methods (e.g. Maresh et al., 2006). The region is of particular interest for: i) examining magma-assisted break-up of continents (e.g. Kendall et al., 2005), due to its proximity to the ocean-continent boundary; and ii) locating offshore hydrocarbon prospects within the Faroese sector of the Faroe Shetland Basin, since they are expected to occur both in layered basalt flows (including hyaloclastites) and in sediments between the base of basaltic sequences and the top of Precambrian crystalline basement. The onshore thickness of the basalts, the presence of sub-basalt sediments and the depth and lateral variation of the underlying crystalline basement, however, are largely unconstrained. In this study, we use data from a 12-station temporary seismic array and apply the passive seismological method of ambient noise tomography to construct a 3-D shear wave velocity model for the uppermost ~15 km beneath the Faroe Islands. Through interpretation of lateral and depth variations in velocity structure, we are able to delineate for the first time the extent and internal properties of the basalt pile, together with the structural configuration of the underlying layers.

1.1. Geology of the Faroe Islands

The Faroe Islands Basalt Group (FIBG) (Fig. 1) was emplaced during Paleocene and Eocene times and formed part of the North Atlantic Igneous Province (NAIP) magmatism (Upton, 1988; Waagstein, 1988; Saunders et al., 1997; Meyer et al., 2007), which was emplaced via subaerial volcanism during the separation of Greenland and Eurasia. The FIBG areal extent is at least 120,000 km^2 within the NE Atlantic region and it is exposed throughout the ~1400 km^2 surface area of the 18 main islands that comprise the Faroe Islands (Passey and Jolley,

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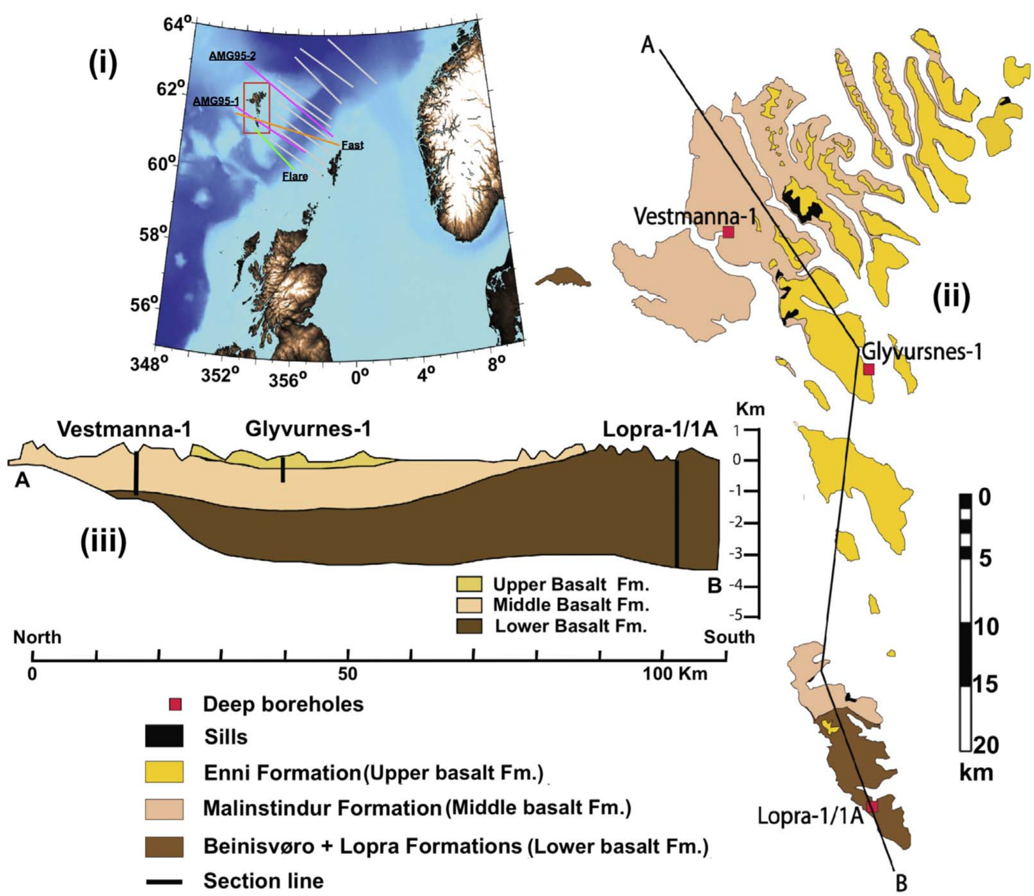

Fig. 1. Faroe Islands location and geology. i) Regional topographic and bathymetric map showing the location of the Faroe Islands (red rectangle) in the North Atlantic. ii) Simplified surface geology map and iii) north–south geological cross-section showing the main units of the Faroe Islands Basalt Group (FIBG). ii) and iii) modified from Waagstein (1988). In grey lines are shown the lineaments while in color lines are shown the main refraction studies mentioned in the paper. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

2008) (Fig. 2). Post-emplacement subsidence is a likely explanation for the origin of the present-day FIBG dip of $< 4^{\circ}$ in an E-SE direction (Andersen, 1988) and its stratigraphic thickness totals at least ~6.6 km (Rasmussen and Noe-Nygaard, 1969, 1970; Waagstein, 1988; Passey and Bell, 2007; Passey and Jolley, 2008).

The FIBG consists of basalt lava flows with minor volcaniclastic (sedimentary and pyroclastic) lithologies, and the major formations from base to top are: 1) Lopra Formation: at least ~1.1 km thick and composed of volcaniclastic lithologies, mainly hyaloclastites (Ellis et al., 2002; Waagstein and Andersen, 2003; Passey and Jolley, 2008); 2) Beinisvørð Formation: ~3.25 km thick laterally extensive, subaerial basalt sheet lobes topped by an erosional surface (Passey and Bell, 2007); 3) Malinstindur Formation: < 1.4 km thick subaerial compound lava flows with a weathered upper surface (Passey and Bell, 2007); 4) Enni Formation: > 900 m thick subaerial compound lava flows and sheet lobes (Passey and Jolley, 2008). Sub-vertical dykes have intruded most levels of the basalt, along with irregular and saucer-shaped sills (Hansen et al., 2011). Erosion may have removed at least a few hundred metres of the Enni Formation, assuming it was uniformly distributed with an original thickness of 1.0–1.5 km (Waagstein, 1988; Andersen et al., 2002).

The FIBG rocks exposed on the Faroe Islands are presumed to either rest atop pre-Cretaceous (Brewer and Smythe, 1984) sedimentary rocks or Lewisian crystalline basement. Seismic refraction experiments revealed offshore sedimentary sequences that reach thicknesses of: i) a few kilometres but appear to pinch out towards the Faroe Islands (Richardson et al., 1999); ii) 7–8 km offshore and 3–4 km beneath the Faroe Islands (Raum et al., 2005); or iii) less than 1 km beneath central regions and up to 3 km beneath northern and southern parts of the Faroe Islands (White et al., 2003). Ambiguity remains due to multiple ways of interpreting a sub-basalt layer with a *P*-wave velocity of 5.2–5.7 km/s and the possible contamination of sub-basalt sedimentary rocks with igneous sill intrusions (Richardson et al., 1999; England et al., 2005; Raum et al., 2005). Lewisian basement rocks are exposed in East Greenland and Shetland Islands (Stoker et al., 1993) and it is therefore expected that Archaean to Proterozoic age Lewisian metamorphic rocks comprise the crystalline basement beneath the Faroe Islands. This is most likely underlain by stretched Archaean continental crust that could be thickened and/or intruded by magmatic material (Bott et al., 1974; Richardson et al., 1998; Raum et al., 2005).

1.2. Previous geophysical and borehole studies

Regional refraction and wide-angle reflection profiles have been acquired to investigate the crustal structure to the north-east, east and south-east of the Faroe Islands (Fig. 1). It is widely agreed that the velocity structure most likely represents crystalline crust with a continental composition (Bott et al., 1974; Richardson et al., 1998, 1999; Smallwood et al., 1999; Raum et al., 2005). Moho depths along these profiles vary between 17 and 35 km, while estimates of crustal thickness beneath the Faroe Islands are either 21–32 km (through extrapolation onshore from the seismic profiles) or 27–38 km (described as ~30 km) from an onshore seismic refraction study (Bott et al., 1974).

A map of basalt and sub-basalt sedimentary layer thickness beneath the Faroe Islands and surrounding area, compiled from published wide-angle seismic data, indicates that basalt thickness is consistently 5.5–6.0 km across the majority of the Faroe Islands apart from 4.5 to 5.5 km and 3.5–4.5 km beneath the southern islands of Sandoy and Suðuroy, respectively (White et al., 2003). Sub-basalt sediment thickness was estimated to be ≤1.5 km beneath the central Faroe Islands, increasing to 2–3 km in north-eastern and southern parts. A more recent seismic profile showed evidence for a 2–3 km thick low velocity sub-basalt Mesozoic sedimentary layer (Raum et al., 2005). The geophysical properties of key layers included in published models of Faroe Islands