SEISMIC IMAGING THROUGH BASALT FLOWS ON THE FAROE SHELF

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Introduction

Extrusive igneous rocks dominate the northwestern flank of the Faroe-Shetland Basin and the Faroe Shelf. They are more than 7 km thick on the Faroe Islands themselves, and extend some 150 km eastwards from the islands to feather out in the Faroe-Shetland Trough. Extrusive lavas pose a particular problem for seismic imaging through to the underlying, possibly prospective, sediments and basement structure. We show that by focusing on the production and recording of low-frequency seismic energy, improved sub-basalt images can be obtained. Another helpful approach for sub-basalt imaging is to record seismic data to very long offsets, which provide additional refractions and wide-angle reflections at angles approaching the critical angles. By using new processing techniques, these wide-angle arrivals can be used to identify deep reflections from the base of thick basalt sequences and the underlying structure. We illustrate these techniques using data from two novel surveys on the Faroes Shelf. The first is the Faroes Large Aperture Research Experiment (FLARE), acquired by the Amerada Hess Limited Partner Group. By using flip-flop firing from two seismic vessels, each towing streamers, profiles with offsets of up to 38,000 m were acquired. The second is the iSIMM (integrated Seismic Imaging and Modelling of Margins) profile, which extends 380 km across the northern Faroes Shelf and continent-ocean boundary (White *et al.* 2002) (Fig. 1).

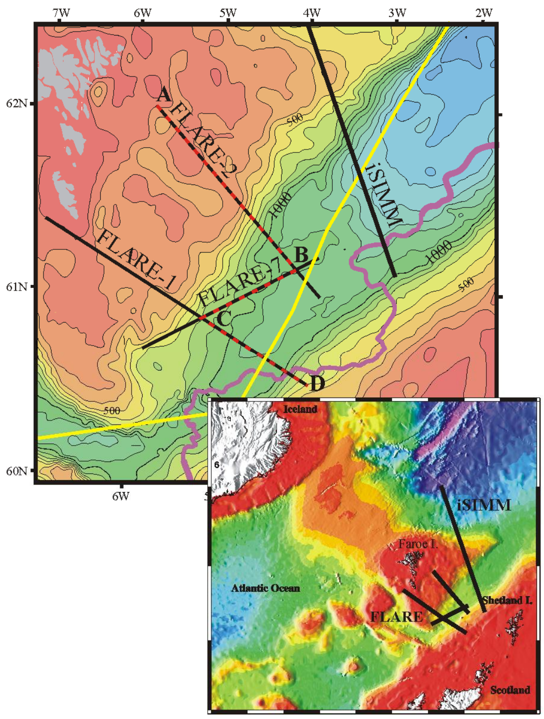

Fig. 1 Local and regional location maps with bathymetry: purple line marks SE limit of subsurface basalt flows.

The Requirement for Low Frequencies to Penetrate Basalts

Layered sequences of lava flows act as effective high-cut filters to seismic energy transmitted through them, so higher frequency energy is attenuated rapidly, and most reflections from sub-basalt horizons are rich only in the lower frequency energy. Effective seismic quality factors, Q, are typically as low as 25−35 for layered lava flows (Maresh *et al.* 2003; White *et al.* in press), which means that if we wish to see seismic reflections from beneath thick basalts, there is little alternative to using low frequencies.

With conventional airgun technology there are three main ways of producing frequencies with significant energy at low frequencies of c. 10 Hz. First is to use *big airguns,* both in individual chamber size and in large-volume arrays; second is to *tow the guns deep*, typically at c. 20 m; and third is to tune the airguns on the *bubble pulse* rather than the initial spike, as is conventionally done (Lunnon *et al.* 2003). Further improvement to the low-frequency response is obtained by also towing the receivers deep, and indeed the maximum improvement is obtained if the receivers are on the seabed: this can be achieved using bottom cables or ocean bottom seismometers (OBS), with the added advantage with seabed recording of having geophones for direct recording of shear waves.

Long-Offset Acquisition and Processing

Acquisition of long offset data provides considerable additional information outside the water wave that is useful for sub-basalt imaging. Diving waves provide good velocity control on the deep subsurface, useful both for direct characterization of lithology, and also for improved imaging by pre-stack depth migration (PSDM). The step-back in diving waves caused by low velocity material underlying basalts provides an excellent method of mapping the presence of sub-basalt sediments (White *et al.* 1999). Wide-angle reflections increase in amplitude as they approach the critical angle, so arrivals such as the base-basalt reflection may be identified at wide angles, whereas at conventional shorter offsets it generally has a low amplitude and is often overprinted by multiples. The larger offsets also offer increased moveout and improved velocity resolution, and the long-offset arrivals outside the water wave can be separately identified and migrated back to normal incidence, then superimposed on the near-offset PSDM, as has been done for the FLARE profiles shown in Fig. 2 (from White *et al.* 2003).

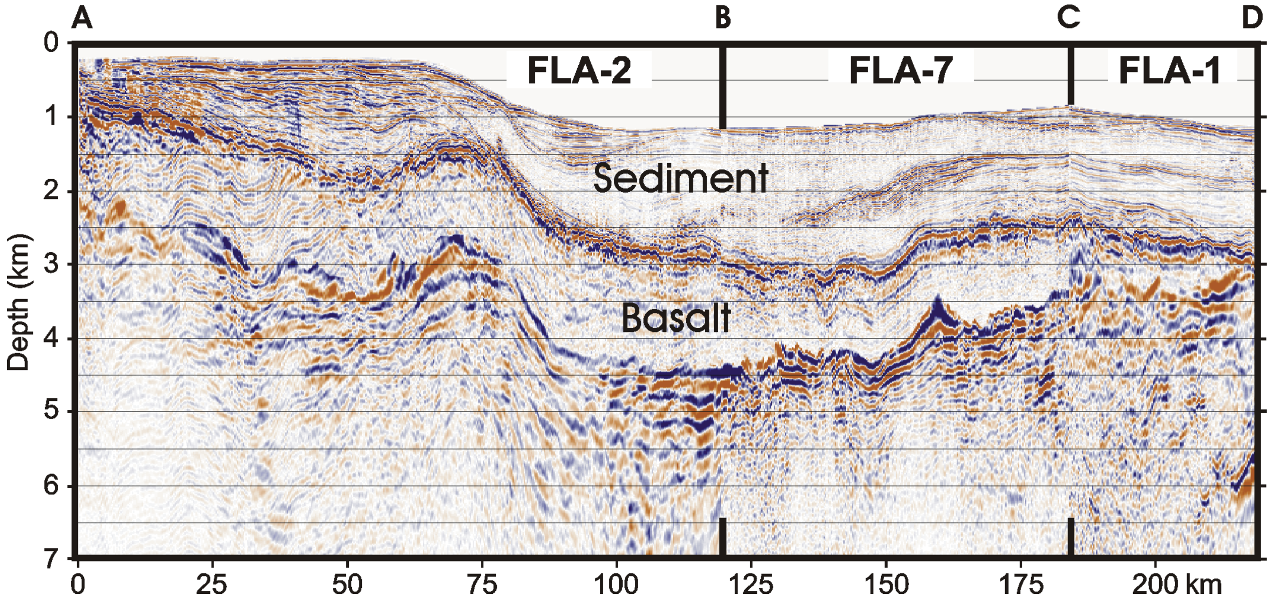

Fig. 2 Unfolded seismic section, highlighting the top and base of the basalt flows from FLARE lines 1, 2 and 7 (red dashes on Fig. 1), crossing the feather edge of the basalt flows beneath the Faroe-Shetland Trough.

Long-offset data can be recorded either by using multiple passes of two seismic ships, as for the FLARE profiles (White *et al.* 1999), or by using a long streamer − 12,000 m in the case of the iSIMM profiles. Along the iSIMM profile, good wide-angle seismic arrivals were also recorded by 85 OBS from the entire crust and into the upper mantle out to ranges beyond 140 km. In the iSIMM project the advantages of long-offset streamer data with their high spatial sampling and fixed OBS data which provide better control on the deep structure and on converted waves were combined by recording both types of data along the same profile.

Examples of Sub-Basalt Imaging in Faroes Region using Wide-Angle Profiles

The iSIMM reflection profile extends from the stretched crust of the Faroe-Shetland Trough, across the continental block of the Fugloy Ridge, over the volcanic continent-ocean transition and onto the oceanic crust of the Norwegian Sea (Fig. 3). Extrusive igneous rocks dominate much of the section, although everywhere covered by post-rift sediments. The oceanic crust consists entirely of igneous rock; the continent-ocean transition exhibits extensive extrusive and intrusive lower-crustal igneous rocks, while the basaltic flows that are prominent on the Faroe Islands themselves flow across the continental hinterland toward the Faroe-Shetland Trough. We show enlargements of two representative sections in Figs. 4 and 5.

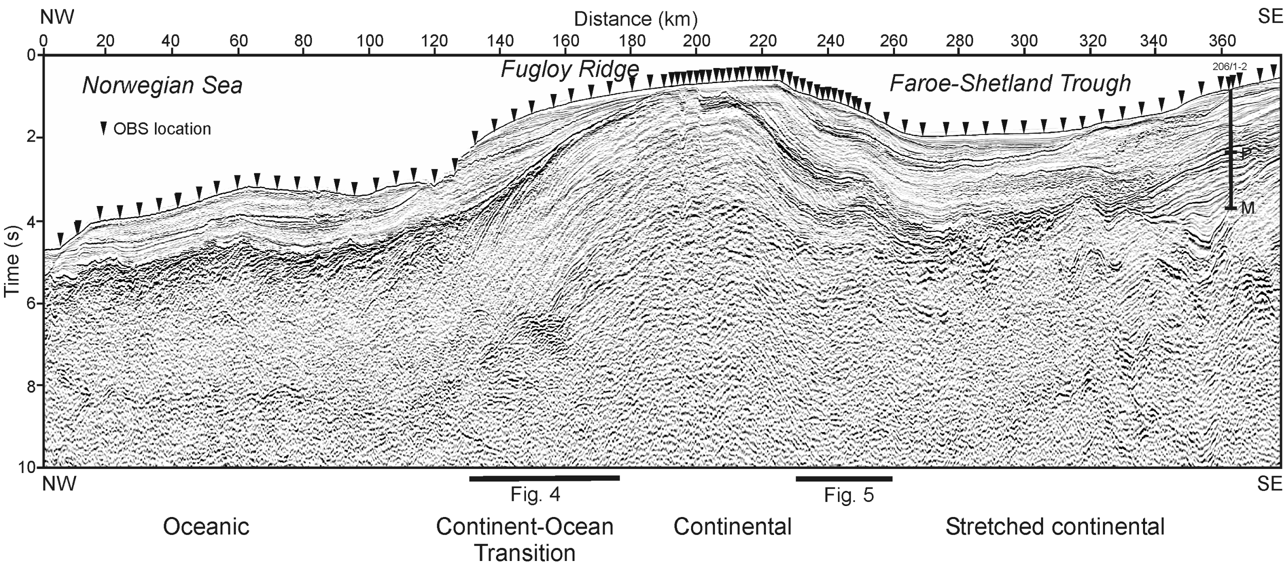

Fig. 3 Squash-plot of entire iSIMM profile (see Fig. 1 for location), showing location of hole 206/1-2, and of OBS (triangles). P and M mark the tops of the Paleocene and Maastrichtian layers.

Continent-Ocean Transition: The most prominent feature of the volcanic rocks on the continental margin are the convex-upward, seaward dipping reflectors (SDRs) illustrated in Fig. 4. The SDRs are formed by the massive and rapid extrusion of basalts which accompanied continental breakup in the early Tertiary, as a result of interaction between rifting and the thermal anomaly caused by the underlying mantle plume (White and McKenzie 1989). Individual reflectors are coherent over lateral distances of 20 km or more and the SDRs attain a maximum thickness of 4 km adjacent to the oldest oceanic crust, thickening rapidly from the continental (SE) to the oceanic (NW) part of the continent-ocean transition. The lower part of the continental crust below the SDRs, some 15 km thick, is marked by extensive, strong reflectivity. The region of the lower crust with strong reflectivity coincides with abnormally high seismic velocities (above 7.2 km/s) found from wide-angle OBS analysis. These velocities are markedly higher than the seismic velocities found in the equivalent portion of lower crust under the adjacent British mainland, and are interpreted as due to the intrusion of mantle-derived magmas during continental breakup (White and McKenzie 1989). The primitive picritic magmas, rich in iron and magnesium, intruded into the lower crust, differentiated to produce the less dense, and so more buoyant

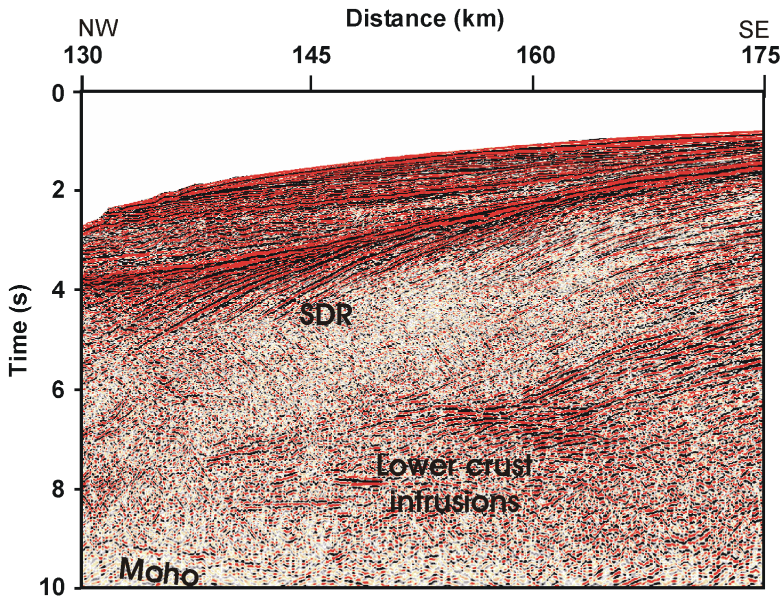

Fig. 4 Section of profile crossing the SDR sequence on the continent-ocean transition (see Fig. 3 for location). The SDRs are interpreted as lava flows extruded near sea level from the developing Atlantic rift and flowing landward over the hinterland; the strong lower-crustal layering is coincident with high-velocities, representing lower-crustal intrusions; the sharp Moho reflection shallows markedly from continental (SE) to oceanic (NW) crust.

tholeiitic basalt lavas that were extruded to form the SDRs, leaving behind the denser (and higher seismic velocity) residue in the lower crust. Petrological models suggest that the volume of residual melt left in the lower crust is likely to be two or three times the extruded volume, which is consistent with the relative thicknesses of lower crust intrusions and extruded SDRs on this margin. A strong, well-defined reflector interpreted as the Moho discontinuity at the base of the crust shallows steeply from the continental to the oceanic crust.

Flank of the Faroes-Shetland Trough: The style of extrusive Paleocene volcanic rocks which flowed toward the continental hinterland (which experienced little or no stretching during the Tertiary continental breakup), is quite different from that found at the continent-ocean transition. The lavas, produced in the volcanically active Atlantic rift to the northwest of this location, flowed up to 150 km landward across a partly sediment-filled landscape toward the Faroe-Shetland Trough, thinning as they flowed. Where they reached the paleo-shoreline, they produced strong, southeastward dipping, sigmoidal reflectors within the basalt sequence. The sigmoidal reflections move upward and southeastward across the section as the lavas progressively built outward, pushing the coastline eastward (Kiørboe 1999). Strong sub-horizontal layering below the sigmoidal reflectors probably represents early hyaloclastites and lava flows from the first phase of volcanic activity in the Faroes region, while the equally strong layering above the top of the sigmoidal reflectors is interpreted as due to late lava flows crossing the entire region, capped by the ubiquitous Balder Ash. Sedimentary layers, probably intruded by sills, and faulted basement rocks of presumed Cretaceous age underlie the basalts.

Detailed velocity analyses play an important part in the interpretation. The Balder Ash which overlies the basalt flows is predominantly a sedimentary deposit, and exhibits a strong velocity gradient from typical unconsolidated sediment at the top to weathered basalt at the base. Beneath the bottom of the basalt sequence, velocity inversions inferred from the long-offset wide-angle data show the presence of sediments over which the early basalts flowed (Spitzer *et al.* 2004 and submitted).

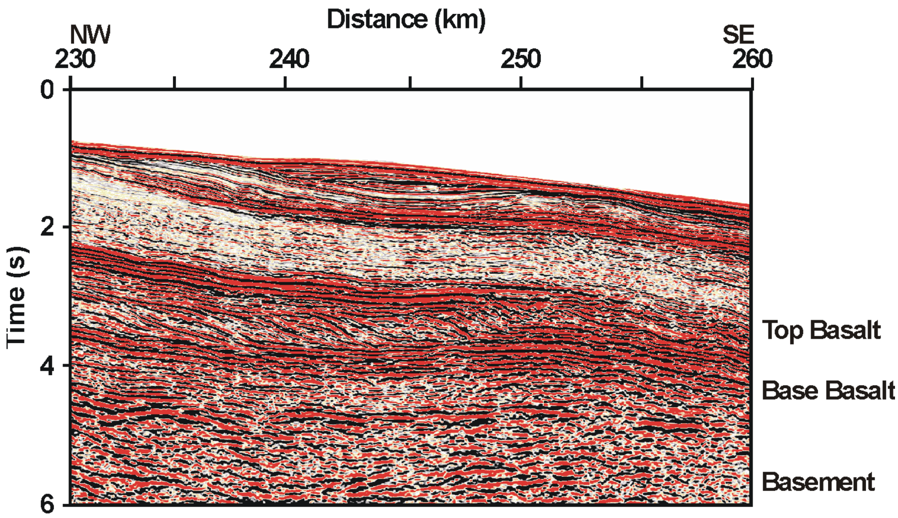

Fig. 5 Section of migrated seismic profile crossing the basalt escarpment on the NW flank of the Faroe-Shetland Trough (see Fig. 3 for location). Strong sigmoidal foresets are well imaged within the basalt sequence between 3−4 s two-way travel time: these are interpreted as the paleo-coastline in this region when the lavas were extruded.

Conclusions

Significant improvements to intra- and sub-basalt seismic imaging can be made by careful attention to tuning the source and receiver characteristics so as to optimise the low-frequency response. In the Faroes area, this is shown by the high-quality iSIMM profiles in Figs. 3−5. The recording of complementary long-offset arrivals further provide significant new data, because it is then possible to use the refracted and wide-angle reflected energy outside the water-wave cone both to constrain the velocity distribution in the sub-surface for better pre-stack depth migration, and also for direct imaging using the high-amplitude wide-angle reflections as demonstrated with the FLARE data in Fig. 2. Although the migrated wide-angle reflections are of great value in showing which arrivals are from the base of the basalt, and from deeper in the section, their low frequency content and the large angles at which reflections occur (and therefore the large size of the Fresnel zones), means that they have much poorer resolution than do reflections from closer to normal incidence. So for interpretation purposes it is best to use both a conventional migrated image, together with the composite image that contains the separately identified and migrated high-amplitude wide-angle arrivals which allows us to identify which arrivals are from the deep horizons of interest.

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