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Imaging and regional distribution of basalt flows in the Faeroe-Shetland Basin

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ABSTRACT

We demonstrate that the use of long-offset seismic data allows wide-angle reflections and diving waves to be recorded, and that these can be used in conjunction with prestack depth migrations to constrain and to image the base of the basalt flows and the underlying structure in the Faeroe-Shetland Basin. Crustal velocity models are built first by inverting the traveltimes of the recorded reflections and diving waves using ray-tracing methods. Finer details of the velocity structure can then be refined by analysis of the amplitudes and waveforms of the arrivals. We show that prestack depth migration of selected wide-angle arrivals of known origin, such as the base-basalt reflection, using the crustal velocity model, allows us to build a composite image of the structure down to the pre-rift basement. This has the advantage that the wide-angle first-arriving energy must be primary, and not from one of the many multiples or mode-converted phases that plague near-offset seismic data. This allows us to 'tag' these primary arrivals with confidence and then to identify the same arrivals on higher-resolution prestack migrations that include data from all offsets. Examples are drawn from the Faeroe-Shetland Basin, with a series of regional maps of the entire area showing the basalt depths and the thickness of the basalt flows and underlying sediment down to the top of the pre-rift basement. The maps show how the basalts thin to the southeast away from their presumed source west of the present Faeroe Islands, and also show the extent to which the structure of the pre-rift basement controls the considerable variations in sediment thickness between the basement and the cap formed by the overlying basalt flows.

BACKGROUND GEOLOGY

The Faeroe-Shetland Basin was formed by a series of rift episodes, including major rifting during the Permo-Triassic, the Cretaceous and possibly also the Jurassic (Duindam and van Hoorn 1987; Earle, Jankowski and Vann 1989). The development of the basin was strongly influenced by the magmatic events of the North Atlantic Tertiary Igneous Province and break-up of the North Atlantic (White and McKenzie 1989; Barton and White 1997). Extensive magmatism during 63–54 Ma was expressed through development of igneous centres such as those on Skye, Mull and the Faeroe Islands, and also included the intrusion of sill complexes in the Faeroe-Shetland Basin (Ritchie and Hitchen 1996; Naylor *et al.* 1999).

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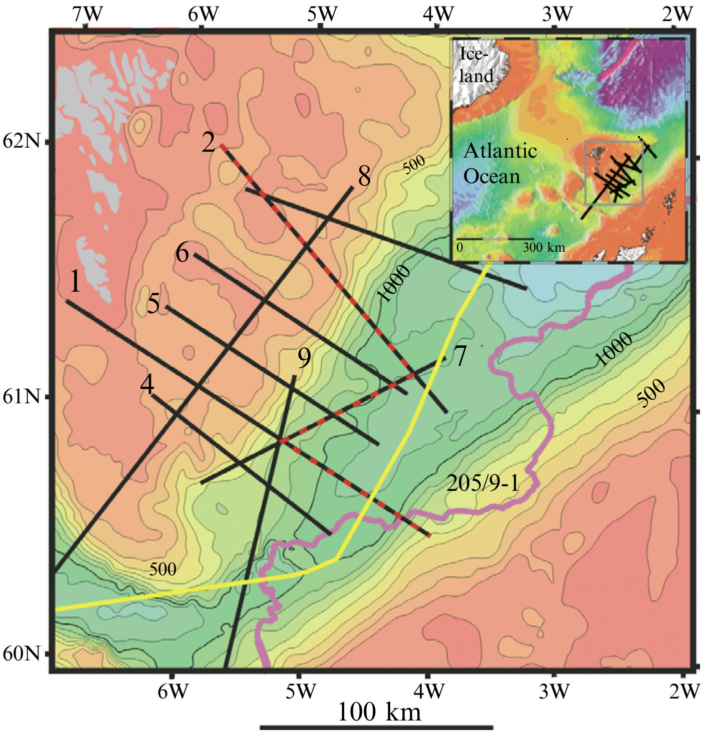


Figure 1 Map showing location of long-offset two-ship profiles of the FLARE project used in this paper, constructed using the same profiles as for the maps shown in Fig. 11, and using the same projection. The purple line marks the southeastern limit of Tertiary basalt flows. The yellow line marks the boundary between UK and Faeroes waters. Bathymetric contours every 100 m, with heavier contour at 1000 m. Profiles 1 and 2 used three passes of the two ships to achieve maximum offsets of 38 000 m; profiles 4–9 used a single pass with maximum offsets of 18 000 m. Red dashes mark the location of the composite seismic profile in Fig. 7. The inset shows the location of the survey area on the northwest European continental margin, and highlights the edge of the 30–35 km thick igneous crust of the Iceland-Faeroe Ridge formed above the Iceland mantle plume as the North Atlantic opened. Black lines mark the locations of all 12 FLARE profiles.

Extrusive igneous rocks dominate the northwestern flank of the basin. Flood basalts created at the time of break-up between the Faeroe Islands and east Greenland extend over 250 000 km^2 (Andersen 1988; Waagstein 1988; Larsen *et al.* 1999), at least 40 000 km^2 of which lie in the Faeroe-Shetland Basin (Naylor *et al.* 1999). The flood basalts flowed eastwards and southwards from their source in the main rift zone west of the present Faeroe Islands, decreasing in total thickness from more than 7 km on the Faeroe Islands (Richardson *et al.* 1998, 1999) to zero some 150 km away, midway across the Faeroe-Shetland Basin (Fig. 1). From studies of their outcrop in the Faeroe Islands and from subsurface sampling by the Lopra and Vestmanna drillholes, the Tertiary basalts have been divided into three distinct units, the Lower, Middle and Upper Series. The Lower Series were extruded during approximately 62–61 Ma, and comprise about half the total thickness. The Middle and Upper Series were emplaced after a hiatus (Fig. 2), during which time 10 m of lacustrine shales and coals accumulated.

Regionally, both the sediment supply and the availability of accommodation space within the Faeroe-Shetland Basin through the Palaeocene and Eocene were controlled primarily by the proto-Iceland plume beneath the lithosphere. The Palaeocene lavas of the Tertiary Igneous Province were extruded across this basin, so there is a complex and intimate link between the rifting, subsidence, sedimentation and igneous histories.

In the Early Palaeocene, sedimentation in the basin was controlled by the underlying end-Cretaceous fault-induced topography (Ebdon *et al.* 1995). Submarine fans first filled the basin-floor deeps, then progressed to onlap and eventually also to cover the basin-floor highs. This system developed into a period of deep-water fan sand progradation, attributed by White and Lovell (1997) to enhanced erosion and base-level changes caused by uplift of the shelf and hinterland by the proto-Icelandic mantle plume. The highest Palaeocene sedimentation rates in the basin were reached in the Upper T35 to T36 interval (Jolley, Clarke and Kelley 2002), with input of a series of major fans such as the Kintail Fan (Ebdon *et al.* 1995) into the basin from the south and west. The T36 Kettla Tuff (Fig. 2), above the Kintail fan, is a prominent seismic reflector, which is sparsely offset by faults, indicating the termination of the Palaeocene phase of rift development.

Following the deposition of the Kettla tuff, an abundant supply of clastic material, derived from the uplifted Scottish Highlands, built two major progradational packages out across the basin, i.e., the Lamba and Flett Formations

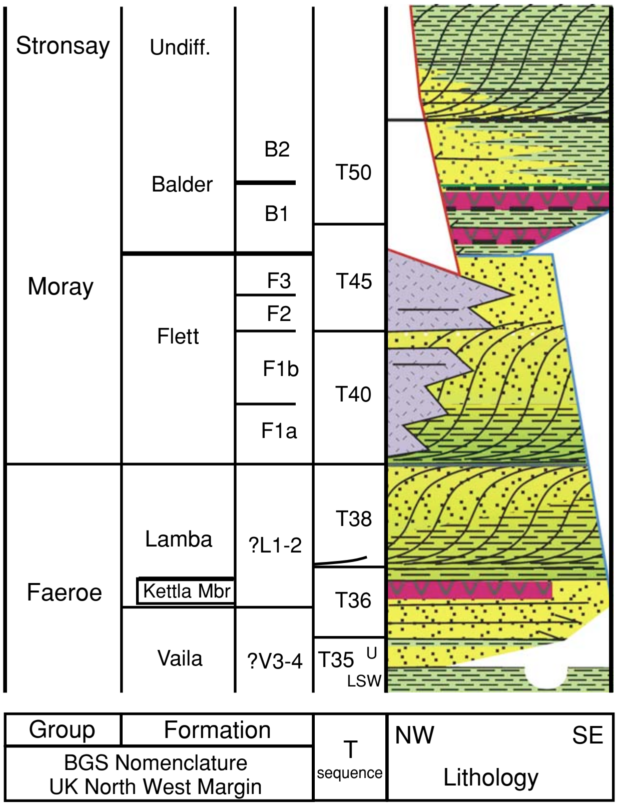


Figure 2 Summary of a section of the stratigraphy around the basalt in the Faeroe-Shetland Basin, showing the timing of the main early Tertiary igneous phases (modified after Ebdon *et al.* 1995; Knox *et al.* 1997; Stoker 1999). Extrusive basalts are shown in blue, tuffs in red with 'V' symbols, sandstones in yellow, and shales in green.

(Fig. 2). Clinoforms 500 m high in the Lamba Formation and at least 300 m high in the Flett Formation indicate the palaeo-water depth and show the scale of the depositional systems. The major extrusive igneous activity, which generated the Lower Basalt Series, commenced during deposition of the Flett Formation (Fig. 2). Sediments within and equivalent to the oldest lavas allow them to be placed within the T40 sequence (Jolley *et al.* 2002).

Igneous activity continued during the T45 interval (Fig. 2) with the extrusion of the Middle and Upper Series of lavas in the Faeroe Islands (Waagstein 1988; Jolley *et al.* 2002). While subaerial lava flows have been proved as far southeast as well 205/9-1 (Fig. 1), to the north the lavas encountered marine conditions and major hyaloclastite wedges built out into the basin (Kiørboe 1999; Ritchie, Gatliff and Richards 1999).

The end of the T40s interval is characterized by the culmination of a major uplift event and development of a regional unconformity, which forms the base to the Balder Formation. The Balder Formation itself progressively onlaps the top basalt surface to the northwest as marine transgression proceeded, and deep marine conditions were re-established across the basin in the Lower Eocene. This dramatic rise in base level is tentatively attributed by Smallwood and Gill (2002, pers. comm.) to removal of asthenospheric thermal support from the Faeroe-Shetland region as anomalously hot asthenospheric mantle flowed into the developing zone of continental rifting to the west of the Faeroe Islands. A suite of sills in the centre of the basin, intruding section as young as the Palaeocene T30s, is thought to have been intruded mainly around the time of the Balder Formation (Smallwood and Maresh 2002).

Overall, the Eocene and following periods were dominated by post-rift thermal subsidence. This general subsidence during the Cenozoic was punctuated by several periods of both local and regional uplift (Nadin, Kusznir and Cheadle 1997). A number of compressional events formed inversion structures in the Faeroe-Shetland Basin between the late Palaeocene and the Miocene, events that are now reflected in the shape of the top basalt surface (Boldreel and Andersen 1993). As we show later, these inversion events, which produced structures such as the Munkagrunnar Ridge, are also visible in the relief of the base of the basalt flows.

PROBLEMS IN IMAGING THROUGH BASALTS

On a large scale, the basalt flows in the Faeroe-Shetland Basin tend to be subhorizontal and well layered, although with notable exceptions where the flows spilled across the palaeo-coastline. The steep palaeo-slopes near the coast not only produced an escarpment in the basalts that persists today in the subsurface, but also led to the generation of hyaloclastite breccias and complex foresets where the basalts flowed into the sea (Andersen 1988; Kiørboe 1999; Naylor *et al.* 1999). The seismic reflection profiling technique is good at imaging subhorizontal structures, and much less good at imaging steeply dipping or complex geometries. However, as the apertures (maximum offsets) of streamer data have increased steadily through the past two decades, and as computer processing power has become available to deal with raypaths that are more complex than straight segments (prestack migration techniques), so the profiling methodology has been able to image increasingly complex structures.

Although the extrusive basalt flows in the Faeroe-Shetland Basin are generally subhorizontal on a large scale, there are often large physical property variations within individual flows and sometimes locally rugged small-scale relief on the tops of flows. The strong layering and local rugged relief may cause some or all of the strong internal multiples, forward and back scattering of the incident energy, multiple mode conversion, anisotropy, absorption, geometrical spreading and low-pass filtering of the energy that propagates through a stacked layer of basalt flows. The main variations in the physical properties occur within individual flows: often the bottom of a flow is rubbly, where molten rock has flowed across and chilled against the underlying rocks. The interior of a basalt flow, which cools slowly, is usually the most homogeneous portion and exhibits the highest seismic velocities (Planke and Eldholm 1994). The upper part often has seismic velocities reduced by 1000 m/s or more, due to its higher porosity and weathering. The amount of weathering depends, among other factors, on the time interval between successive flows. In the Faeroes area the basalts were mainly subaerial and the climate subtropical, so soil horizons often developed between flows.

With flow thicknesses an order of magnitude, or more, smaller than the seismic wavelength, reflections are rarely seen off individual flows: rather, the seismic response depends on the complex interactions of reflections off multiple flow units (e.g. Planke and Eldholm 1994; Smallwood, White and Staples 1998). In the specific case of the Faeroe basalts, synthetic sections representing multiple flows show that the reflectivity pattern varies between the Lower, Middle and Upper Series Basalts, which each have distinctively different average flow thicknesses and properties.

Two of the consequences of the strongly layered internal structure of stacked basalt flows, which themselves have large physical property variations at their tops and bases, are that there is a lot of energy conversion between compressional- and shear-wave modes, and that many internal peg-leg multiples are generated (Longshaw, Sunderland and Horn 1998). Multiples may be generated both from within the layered basalt flows and from bounces between the top or base of the basalt section and other sedimentary or sea-floor interfaces. These multiples can be extremely hard to disentangle from primary energy, especially where the converted shear waves have moveout velocities similar to those of the primary sediment arrivals from above and below the basalt layers, as they often do. However, the converted shear-wave arrivals may also be helpful in imaging because, given the right circumstances and provided they can be identified correctly, they may provide an additional image of horizons beneath the interface where the mode conversion occurred.

SOME SOLUTIONS FOR IMAGING THROUGH BASALTS: LONG-OFFSET DATA

One aid in imaging through basalts is to record seismic arrivals at longer offsets than is normal in seismic reflection profiling, and much of this paper will be devoted to demonstrating the use of long-offset seismic data from the Faeroes Large Aperture Research Experiment (FLARE), which was acquired by the Amerada Hess Limited Partner Group. By using flip-flop firing from two seismic vessels, each towing streamers, offsets up to more than 38 000 m were recorded on three profiles shot in 1996 (White *et al.* 1999), and offsets up to 18 000 m were recorded on a further nine profiles acquired in 1998.

Recording data to large offsets brings two major advantages. First, it allows diving waves (often called refractions) and wide-angle reflections that have been returned from within the basalt layer to be recorded (Fig. 3). Conventional seismic-profiling techniques have traditionally muted the arrivals outside the water-wave cone before further processing, because they do not stack along hyperbolic, or nearly hyperbolic, trajectories, as do the near-offset reflections. The wide-angle arrivals therefore pollute a conventional near-offset stack. However, the traveltimes and amplitudes of the wide-angle arrivals carry a considerable amount of information on the velocities and the thickness of the basalt layer, so are useful in building a model of the velocity structure (Fliedner and White 2001b). We find that velocities for the subsurface basalts in the Faeroe-Shetland Basin are consistent with those measured from borehole logs of drillholes through correlative basalts on the Faeroe Islands (Nielsen, Stefánsson and Tulinius 1984; Kiørboe and Petersen 1995).

Where the seismic velocity increases with depth, the first-arriving energy at any given offset is always a primary arrival. Since we have noted that multiples are a major problem in contaminating the seismic image, and may be extremely difficult to identify, let alone to remove, the knowledge that a particular wide-angle arrival must be primary is of great importance. Furthermore, if we can use the first-arriving energy in constructing our subsurface model, there is the obvious advantage that it is not contaminated by signal-generated noise from earlier returns, which means that it produces a cleaner image.

The second major advantage of using data from large offsets is that, for most reflectors, the amplitude of the reflection

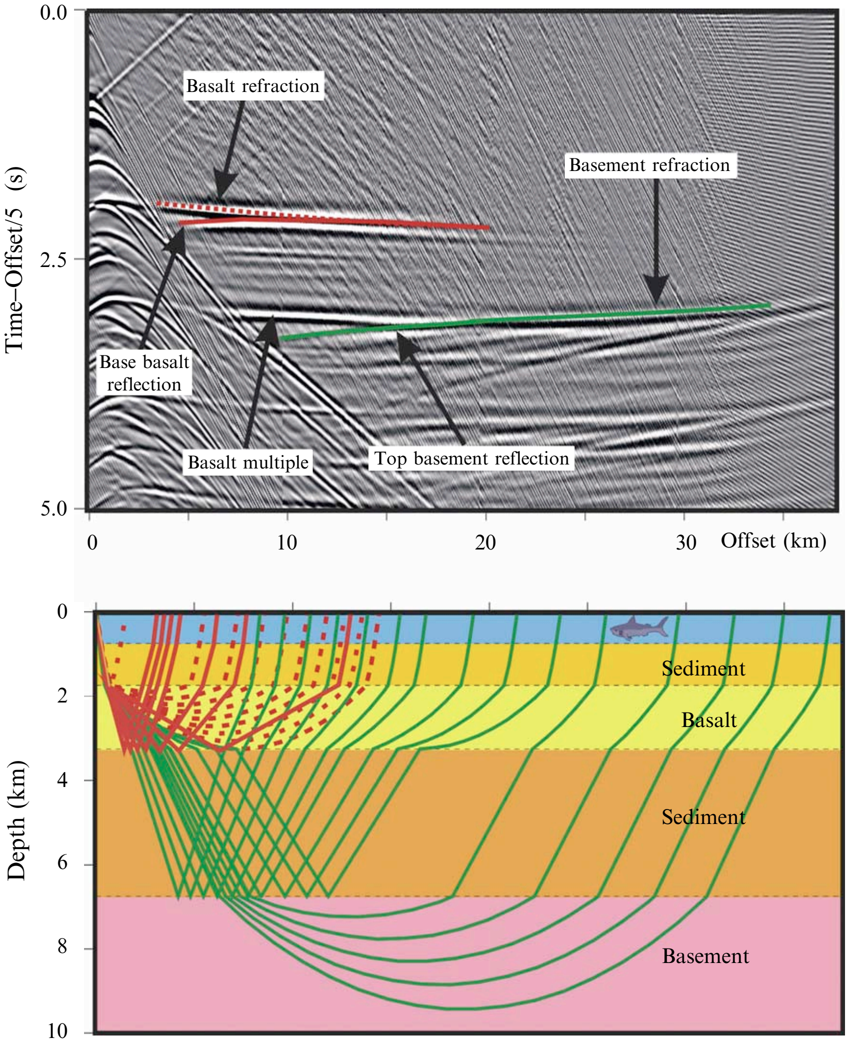


Figure 3 Synthetic seismogram calculated using the full waveform reflectivity response (Fuchs and Müller 1971), showing the main arrivals and corresponding raypaths that constrain the thickness and velocity of the basalt and of the sub-basalt sediment. Broken red rays are diving waves through the basalts and solid red rays are reflections off the base of the basalts. Green rays are diving waves through the basement and reflections off the top of the basement. Note the step-back of about 1 second in first arrivals visible at an offset of about 20 km, caused by the low-velocity sediments lying beneath the high-velocity basalt flows. Traveltimes are reduced with a linear moveout of 5 km/s.

increases as the angle of incidence increases towards the critical angle. So with longer offsets, the angles of incidence increase, and arrivals that are weak at small angles of incidence (small offsets) may become stronger. This is particularly helpful, for example, in identifying wide-angle reflections off the base of a basalt layer (e.g. Fig. 3).

However, long-offset data have some shortcomings. One is that the long travelpaths mean that the higher-frequency components of the waveform tend to be absorbed, so that the frequency content of the long-offset data is lower than that of shorter-offset data, with a concomitant reduction in its ability to resolve fine detail. Another factor is that the further the distance over which the energy travels, the larger will be the errors introduced by incorrect velocity models used in migrating the arrivals back to normal incidence. As larger offsets are considered, the influence of vertical-to-horizontal anisotropy in the propagation velocities also becomes more significant, so it becomes increasingly important to know not only the vertical and lateral variations in velocity, but also the anisotropic components of these velocities.

There are three main ways of recording data to large offsets. One is to use fixed receivers on the sea-bed, in which case it is feasible to use three-component seismometers in addition to hydrophones. This carries the additional advantages of the possibility of removing the water multiple by separating the upgoing and downgoing waves (Amundsen and Reitan 1995), and that converted shear waves can be detected directly, without having to rely on a second converting interface to mode convert the energy back to P-waves. The disadvantage of using fixed sea-bed receivers is that it is difficult to produce an image over an extended profile. It is possible to use dragged arrays on the sea-floor to extend the profile length, but this is expensive and rarely done, and it is difficult to acquire long profiles in this way.

The second, and most obvious, way to record to larger offsets is to use longer hydrophone streamers. Streamer lengths have increased from a typical 2400 m in the 1970s to a routine 6000 m and up to 12 000 m for specialist profiles by the end of the 1990s. Along with the increase in streamer length has arisen a need to know the shape of the streamer, because the effects of wind and currents can cause considerable deflections of very long streamers away from the sail line. However, the technology for recording the streamer position has improved from the use of simple magnetic compasses at discrete points along the streamer, to differential Global Positioning Satellite (DGPS) control at the front and tail, and real-time monitoring of the shapes of multiple towed streamers by acoustic cross-bracing (McBarnet 2001).

The third way of acquiring large-offset data, which is unconstrained by the streamer length available, is to use a second seismic acquisition ship steaming at a fixed distance behind a lead seismic acquisition vessel to synthesize a super-long streamer. These two-ship techniques were first developed in academia (Stoffa and Buhl 1979; Buhl, Diebold and Stoffa 1982), but have also been used commercially. In their simplest form, a second ship steams as close as possible to the tail of the streamer on a lead ship, and shooting is only from the lead ship. The maximum offset is then the sum of the lengths of the streamers on the two ships. Another method is to fire sources alternately from either ship (White *et al.* 1999), allowing synthetic streamers of any arbitrary length to be produced by making multiple passes with the two ships at different separations. In the FLARE profiles, offsets of more than 38 000 m were achieved by making three successive passes along the same profile of two seismic vessels shooting alternately (see fig. 3 of White *et al.* 1999). The disadvantages of the flip-flop shooting is that the fold of cover is halved, that there may be mismatches in the waveforms if the two sources are not identical, and that streamer feathering may compromise the 2D assumption.

In the following sections we discuss the way in which the velocity structure for the Faeroe-Shetland Basin was built up and then used to produce seismic images, which were interpreted to generate maps of the basalt and sub-basalt layers beneath the Faeroes Shelf using both conventional and long-offset data.

TRAVELTIME MODELLING

Techniques for determining the velocity structure of the shallow sediments overlying the basalts have been well developed for conventional single-ship profiling, assuming hyperbolic moveout of sedimentary reflections. We use these methods for the sediments from the sea-bed down to top-basalt, which in the Faeroes region are all Palaeocene or younger. For the FLARE profiles, velocities were picked manually along each separate profile and conventional processing of the near-offset (0–6000 m) data was applied to produce images of the section down to the top of the basalt (e.g. Fig. 4 from FLARE-1). For the regional mapping using a grid of 2D profiles and some 3D surveys, a regional velocity compilation was made to facilitate depth conversion of all the profiles (Smallwood 2002).

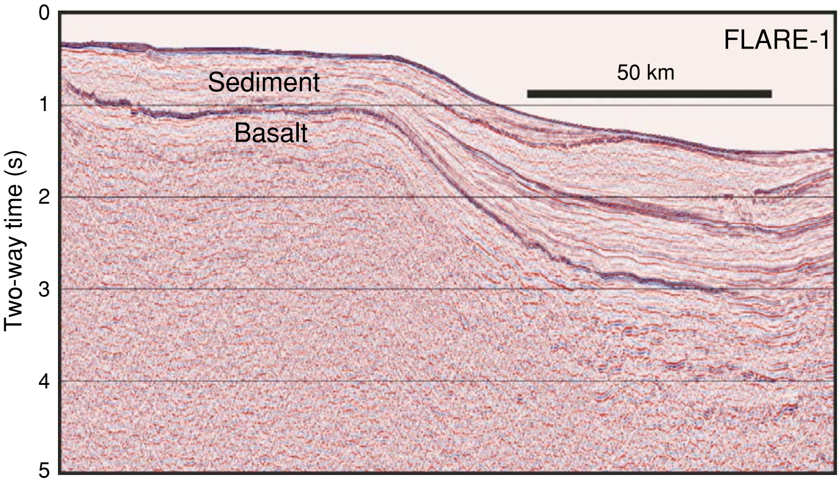


Figure 4 Conventional near-offset processing of 0–6000 m data from FLARE-1 (for location see Fig. 1). Compare with image including prestack depth migration of long-offset arrivals shown in Fig. 7(a).

For the deeper structure, the variations of traveltime with offset of both reflections and diving waves picked manually from a subset of every tenth shot gather were used to create 2D velocity models along each of the FLARE profiles. The ray-tracing program RAYINVR (Zelt and Smith 1992) was used to invert the traveltimes and thus to build the velocity models. These velocity models delineate the extent and thickness of basalt flows on the Faeroes Shelf, together with lower-velocity sediments that lie beneath them and, in some places, strong reflections off the top of the underlying basement (Fruehn, Fliedner and White 2001). Thus they provide a first look at the gross structure (e.g. Richardson *et al.* 1998, 1999), which we subsequently refine by migration of all the data. The shots from several of the profiles were recorded to ranges greater than 50 km using three-component land stations on the Faeroe Islands, and these enabled Moho reflections to be recorded (Richardson *et al.* 1998). Although the Moho reflections only constrain small portions of the profile, the additional constraints from gravity measurements enable the crustal thickness to be extrapolated regionally (Smallwood, Towns and White 2001).

The shallow sediments are mainly clastic Tertiary sediments with velocities mostly lower than 3.0 km/s. There is an abrupt increase in seismic velocity at the top of the basalt flows with basalt velocities being well constrained by the first-arrival diving waves (broken red rays on synthetic gather in Fig. 3 and region inside red polygon on real gather from FLARE-1 in Fig. 5a). Reflections off the top of the deeper basement and diving waves through the basement (green rays, Fig. 3, and region inside green polygon, Fig. 5a) form strong arrivals at offsets usually in excess of 10 km (Fig. 3); this highlights the usefulness of long-offset data, since these phases are only recorded as first arrivals at large offsets. The amplitude of reflections generally increases towards the critical distance, so the wide-angle reflections here have large amplitudes at bigger offsets. It is these arrivals that enable us to build a good velocity model of the deep structure.

The presence of a low-velocity zone beneath the basalt flows is indicated by the step-back of first arrivals at large offsets. In the example supergather, shown in Fig. 5(a), the basalt thickness is about 1 km, and the basalt diving ray terminates at about 13 km offset because the velocity gradient in the basalt layer is such that diving rays cannot penetrate deeper into the basalt without going through its base (broken red lines, Fig. 3). The range at which the basalt diving wave terminates depends primarily on the basalt thickness and its vertical velocity gradient (Fliedner and White 2001b). In reality, because the energy travels as waves, the amplitude of the basalt diving wave does not drop abruptly to zero at the far offsets, but decreases more gradually to beneath the background noise level. It is also possible for low-velocity sediments to be present beneath a thick high-velocity basalt layer without a step-back in the traveltimes of the first arrivals appearing on the wide-angle gathers, depending on the combination of velocities, velocity gradients, basalt thickness, local structure and maximum offset recorded.

The velocity in the sediments beneath the basalts is difficult to determine directly. The amplitude-versus-offset behaviour of the base-basalt arrivals may provide constraints on the underlying velocities (Fliedner and White 2001b), but often other information has to be used. In the case of the Faeroe-Shetland area, this includes measurements from regional boreholes through the same interval of sediments (Knox *et al.* 1997), and extrapolation laterally from regions further east beyond the feather edge of the basalt flows, where conventional moveout analysis can be used to estimate the seismic velocity in the same interval of sediment.

These approaches indicate that there is a fairly narrow range of velocities between 3.5 and 4.5 km/s for the sub-basalt sediment in the area of our survey on the Faeroes Shelf. This is considerably higher than the average velocity in the younger sediments above the basalt flows, but still lower than the average basalt velocity of about 5 km/s. Although the resolution of the models, based solely on traveltimes, is relatively coarse, it is sufficient to show the top and the base of the basalt flows, with the total basalt thickness varying between zero in the southeast to more than 3 km in the west. The basalts subcrop at the sea-floor near the Faeroe Islands and the top of the basalts increases in depth to more than 2 km below the sea-floor towards the southeast. The thickness of the sediments underlying the basalts and above the top of the high-velocity pre-rift section (here called 'basement') reaches more than 3 km.

PRESTACK DEPTH MIGRATION OF BASE-BASALT AND SUB-BASALT WIDE-ANGLE ARRIVALS

After the 2D velocity model of each line has been derived from the traveltimes of the main arrivals, the raw seismic data can be migrated, using this velocity model, to produce an image of the subsurface. This has the potential to image details of the structure that are poorly resolved in the velocity models, which use only a sparse set of the shot gathers, and

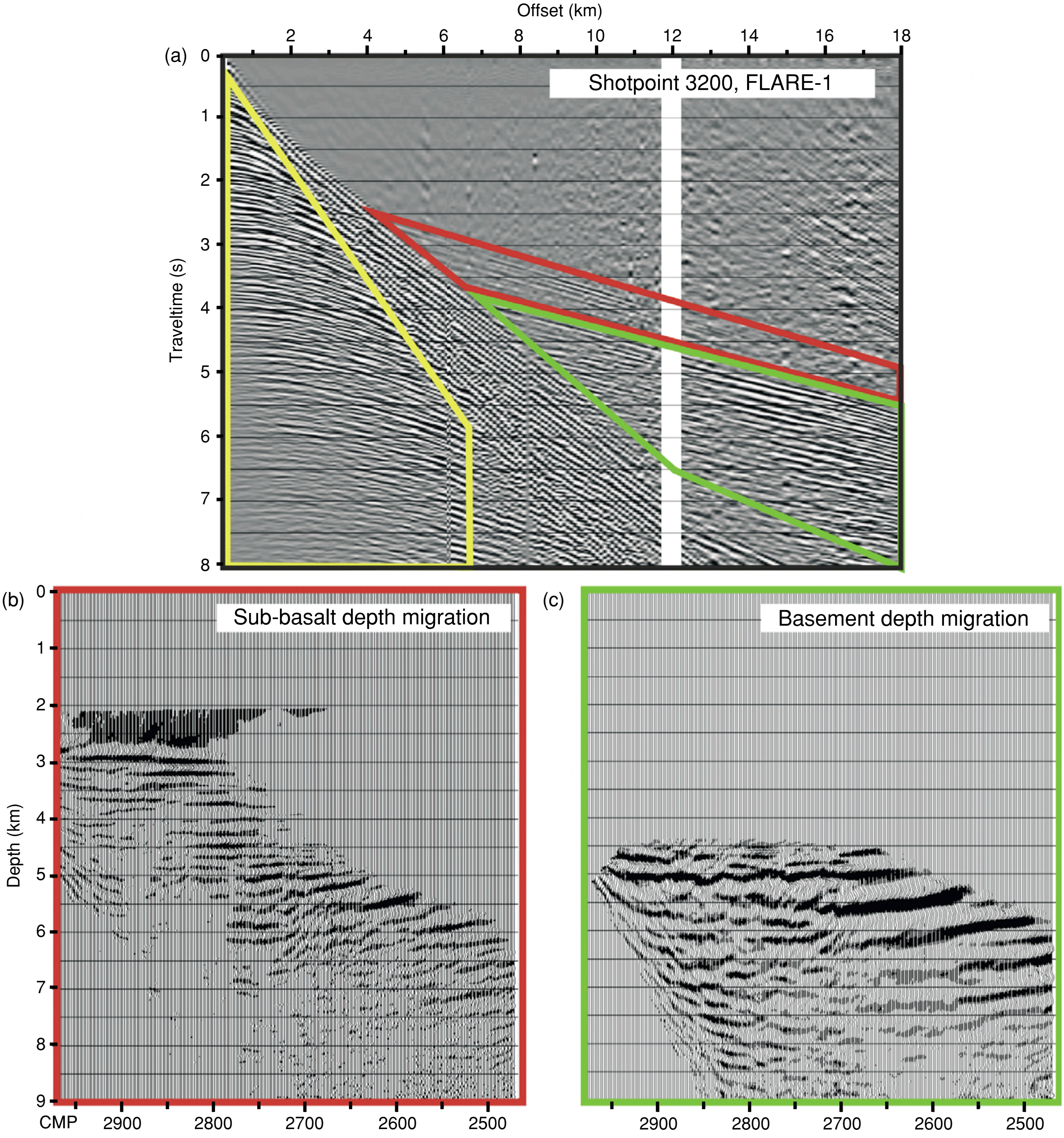


Figure 5 (a) Shot gather 3200 from FLARE-1. Zero offset is at CMP 3200, offsets increase northwestwards. The traveltime–offset regions in which the main compressional wide-angle arrivals lie are outlined by coloured frames. The yellow zone contains hyperbolic reflections used for conventional near-offset seismic imaging. The red zone contains base-basalt and immediately sub-basalt reflections. The green zone contains basement diving waves and reflections off the top of the basement (the colour coding of ray paths in Fig. 3 is identical to that used here). Depth-migrated wide-angle data from: (b) the red zone containing basalt arrivals; (c) the green zone containing basement arrivals.

also to show details of the structure between the main horizons from which traveltimes were picked.

In principle, if the velocity model is sufficiently good, if there is no off-line (i.e. 3D) velocity or structural heterogeneity, and if proper account could be taken in the migration process of the marked phase and amplitude variations that occur as energy is refracted and reflected over different distances and at different angles, then it would be possible to migrate all the seismic energy back to the locations from which it was returned to the surface, and thus to achieve a good representation of the depths and shapes of the subsurface structures. However, not only are most of the caveats mentioned above not satisfied, or only partially satisfied, but the complete seismic dataset is also plagued by energy from scattering, from interbed multiples, and by mode conversion from P- to S-waves and vice versa. All these additional arrivals create energy on the image that will not migrate properly back to its source using a 2D velocity model, and which therefore pollutes the seismic section. More troublesome, because it can lead to misinterpretations, is the problem that much of the energy from multiples and mode conversions remains coherent after migration, and thus may produce apparently real reflections at depths of prime interest, although they are, in fact, not the primary returns that we wish to image. Interbed multiples and converted S-waves are a particular problem because they have moveouts with apparent velocities that are similar to the real velocities of other primary arrivals in the seismic section, and so may migrate well at similar depths to real primary arrivals (Hanssen, Li and Ziolkowski 2000).

One way to reduce some of the problems associated with the mismigration of arrivals, such as those arising from conversions and multiples, is to migrate only those portions of the dataset that come from known arrival phases. We here show the result of migrating just the wide-angle (long-offset) arrivals from the base of the basalt and its immediate underlying region, and from the basement, and then recombining these arrivals with the migrated energy from the conventional image which uses the short-offset data, to achieve a good image of the shallow sediments and the top of the basalts. There is a further advantage to migrating the long-offset data separately, which is that, as we have already noted, the reflections have higher amplitudes at wide angles, so they produce a high-amplitude image with a good signal-to-noise ratio. There is also less interference at large offsets than there is at conventional short offsets with the slower arrivals from the low-velocity sediments overlying the basalts, because at large offsets they arrive later than the basalt reflections.

The shallow sedimentary section and the top of the basalt is imaged best using conventional near-offset data (e.g. Fig. 4). Therefore, to obtain a depth section that extends all the way down from the sea-bed, we merge the migrated wide-angle image built up as shown in Fig. 5 with the conventional prestack depth-migrated image from the near-offset wavefield, to give the composite image shown in Fig. 6. This combines the best features of the conventional near-offset data, including good resolution in the shallow sedimentary section, with the lower resolution but high-amplitude wide-angle image of the base-basalt and immediate underlying region. It is particularly easy to see the basalt layer and its variation in thickness along the profile. Note that on the image in Fig. 6, the amplitudes of the base-basalt reflection are not directly comparable to those of the shallower section, because we have taken advantage of the high amplitudes of

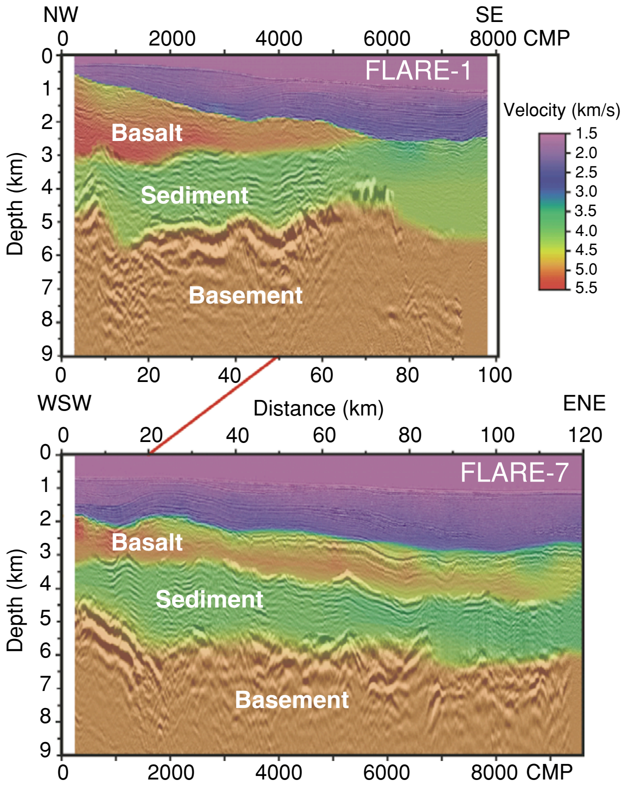


Figure 6 Composite profiles (after Fliedner and White 2001a) along FLARE-1 (downdip) and line 7 (along strike) (see Fig. 1 for location), generated by merging the conventional depth-converted near-offset seismic section above the base of basalt (yellow in Fig. 5) with the prestack depth-migrated base-basalt and sub-basalt arrivals (red in Fig. 5), and the prestack depth-migrated basement arrivals (green in Fig. 5). Colours corresponding to velocities derived from ray-tracing modelling and used for prestack depth migration are superimposed on the seismic profiles.

the wide-angle reflections to produce a strong base-basalt and basement image.

In Fig. 7 we show a crooked-line profile which combines sections of FLARE lines 1, 2 and 7 extending from the region of thick basalts near the Faeroe Islands to the feather edge of the basalts in the southeast (for location see broken red line on Fig. 1). We have migrated the base-basalt wide-angle reflection and merged it with a prestack depth migration of the sediments and top-basalt reflection. It shows good ties at the line intersection points, which gives confidence in the velocity models which were derived independently along each 2D FLARE profile. The image is often poor where the basalts are thin, because the wide-angle seismic data contain only short segments of reflections from the base of the basalt across a limited range of offsets. Furthermore, diving waves through the basalt are also close in traveltime to the wide-angle reflections, so they are not easily separated (see Fig. 3). Fortunately, in areas of thin basalt, conventional short-offset profiles provide adequate penetration in any case, so the prestack depth migration of the long-offset arrivals used in producing our composite image is less important for interpretation where the basalts are thin.

There are also occasional artefacts on the wide-angle prestack depth migrations, such as the inverted-V-shaped 'pull-up' above the base-basalt horizon visible at about 160 km on FLARE-7 (Fig. 7). This locally peaked arrival is probably caused by incorrect migration of the energy in the basalt refraction (diving wave), which arrives earlier than the base-basalt reflection. The true base-basalt reflection is probably the continuous horizon beneath this 'pull-up', which continues without interruption across the section.

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) mean that they have much lower 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. We use the same 2D velocity model for these different migrations. In Fig. 8, we show an example of the use of these two types of section taken from the central portion of FLARE-2.

The upper panel of Fig. 8 shows the prestack depth migration of the entire dataset for a section of FLARE-2. The lower panel of Fig. 8 shows the composite image with the separately migrated and merged base-basalt reflection. The resolution of the base-basalt arrival in the upper panel is better than that of the lower panel. However, since the upper panel also contains many multiples and mode conversions, it is impossible to know from that panel alone which of the many arrivals are from the base of the basalt and which are artefacts from multiples or mode conversions.

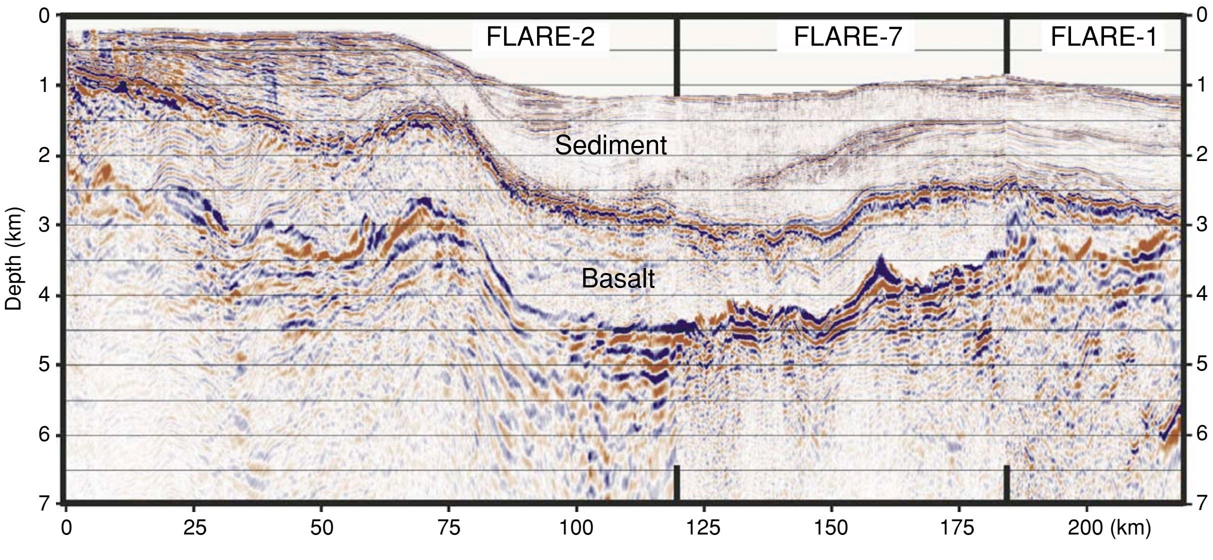
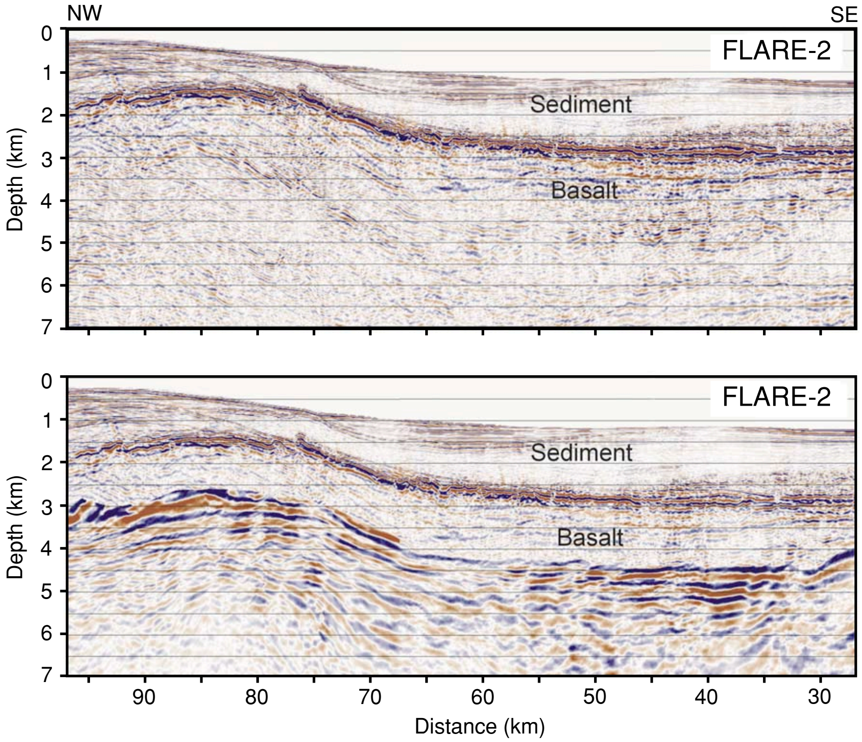


Figure 7 Unfolded seismic section, highlighting the top and base of the basalt flows from lines 1, 2 and 7 along a transect (shown by red dashes on map in Fig. 1), extending from thick basalts near the Faeroe Islands to the feather edge of the subsurface basalt flows beneath the Faeroe-Shetland Trough. Note that the distance scale refers to distance along the unfolded section.

Figure 8 Enlargement of part of line 2, showing prestack depth migration of the entire seismic dataset (upper panel), and the composite image produced by combination of the shallow sediment and top-basalt section with the migrated wide-angle base-basalt arrival (lower panel). Note the better resolution of the upper panel, but the usefulness of the wide-angle data in the lower panel for identifying the base-basalt reflector.



Combination of the location of the base-basalt interface, identified by wide-angle migration in the lower panel, with the prestack depth migration in the upper panel allows us to interpret the structure with confidence on the higher-resolution upper section.

The base of the stack of basalt flows may not be an abrupt transition between sediments and basalts, but it is probably characterized by locally irregular topography, possibly with tuffs, ashfall and baked sediments. Much of this structure is likely to vary on vertical and horizontal scales that are below the resolution of the low-frequency wide-angle arrivals. So although the combined images, such as those shown in Figs 6–8, give an overall picture of the major structure, imaging of finer structure at the base of the basalt will almost certainly require more detailed mapping, such as that produced by 3D seismic surveys, and the ability to make 3D migrations in the processing.

ADDITIONAL CONTROL FROM AMPLITUDES OF ARRIVALS

So far we have discussed the use of only the traveltimes of the seismic data, first for constructing a velocity model and then for migrating the wide-angle data back to a depth section. However, there is a huge amount of additional information in the amplitudes and waveforms of the seismic arrivals, which can provide further constraints on the velocity structure (Fliedner and White 2001b). As an example of this, in Fig. 9 we show the mean (black line) and the range (yellow) of observed peak-to-peak amplitudes from interaction between the basalt diving wave and the base-basalt reflection (broken and solid red arrivals, respectively, in Fig. 3) in a region where the basalts are flat-lying. The main amplitude variations are caused by interference between the diving wave through the basalt and the base-basalt reflection, particularly in the vicinity of the critical distance where both the amplitude and the phase of the reflected wave vary rapidly with offset, to create the amplitude high at about 8 km offset in Fig. 9. The best-fitting velocity model (red lines in Fig. 9), derived from full waveform reflectivity synthetic seismograms (Fuchs and Müller 1971), shows finer details of the velocity structure in the basalt layer than can be derived from the traveltimes alone, and also constrains the sub-basalt sediment velocity.

On the basis of the velocities within the basalt series, it is possible to interpret the stratigraphy of the flows that extend across the Faeroe-Shetland Basin. The Lower Series of flows on the Faeroe Islands are the most massive, averaging 20 m,

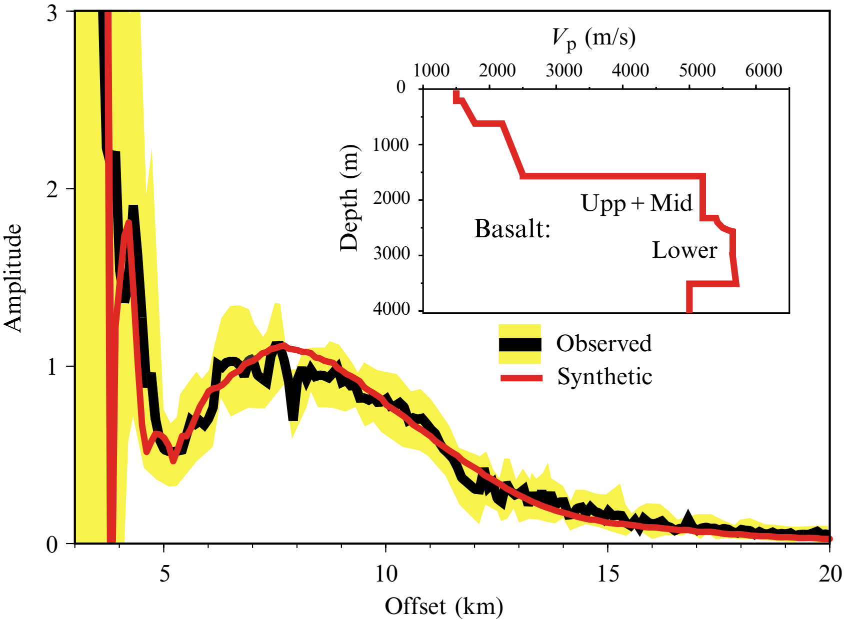


Figure 9 Observed and modelled peak-to-peak amplitudes of a basalt diving wave as a function of offset from the average of 25 adjacent FLARE supergathers in a region of little lateral variation (modified from Fig. 14 of Fliedner and White 2001b). The yellow background shows the range of amplitudes in the individual gathers, with the heavy black line showing the average. The best-fitting P-wave velocity model from synthetic seismogram analysis is shown in red, and uses a P-wave quality factor of 100. Amplitude units are arbitrary, with synthetic and observed amplitudes calibrated on the small-offset sea-floor reflection.

with a range of 5–50 m (Fig. 10). The Middle and Upper Series, in contrast, contain thinner flows, averaging only a little over 2 m in the Middle Series and 13 m in the Upper Series (Fig. 10). The Middle Series was emplaced subaerially, and comprises often vesicular, tholeiitic basalts with basal tuff agglomerate zones. This difference in flow thickness between the Lower and Middle Series is likely to cause a marked difference in average seismic velocities of the two units. The weathered tops, tuffaceous bases and vesicularity of flows have much lower seismic velocities than do the massive interiors of thick flows (Planke and Eldholm 1994), so the sequence of thick flows in the Lower Series exhibits a higher average velocity than does the series of thin flows in the Middle Series, particularly since the Middle Series flows are highly vesicular.

In our example in Fig. 9, the deeper section represents the Lower Series of massive basalts, with their concomitant high average velocity. The shallower section of the basalts, with its reduced velocities, comprises either the Middle or the Upper Series, or more probably contains some of both. The 55–56 Ma age for thin basalts in the Flett Formation, sampled within well 205/9-1 near the feather edge of the basalt flows (for location see Fig. 1 and for stratigraphy see Fig. 2), suggests that the Upper Series extends right across the Faeroes Shelf (Ritchie *et al.* 1999). However, the reduced velocities of the shallow section are also indicative of the presence of a large thickness of the thin-bedded, vesicular Middle Series. In this way, knowledge of the detailed velocity structure may also help in understanding the regional geology.

BASALT AND SUB-BASALT SEDIMENT DISTRIBUTION IN FAEROE-SHETLAND BASIN

We have used the wide-angle FLARE profiles to identify and locate the depth of the base of the basalt and of the acoustic basement across the Faeroe-Shetland Basin, and have then mapped these horizons across the region from the sparse grid of FLARE profiles, using a much denser grid of conventional 2D, and in places 3D, seismic profiles held by Amerada Hess Limited. The results of this mapping are shown in Fig. 11. Each map uses the same colour scale.

The map of the top of the basalt is well constrained by conventional seismic (Fig. 11a), with the added reassurance, from identification of the velocity using the diving wave from within the basalt layer, that we have indeed mapped the top basalt interface and not an equally strong sedimentary reflector such as the Balder tuff. The basalt deepens from outcrop in the Faeroe Islands to 3–4 km below the surface near the feather edge to the southeast. The shallow ridge in the western part of the map extending southeastwards from the southernmost Faeroe Island of Suduroy is the Munkagrunnar Ridge. The map of the base of the basalt (Fig. 11b) shows that once off the shallow shelf immediately adjacent

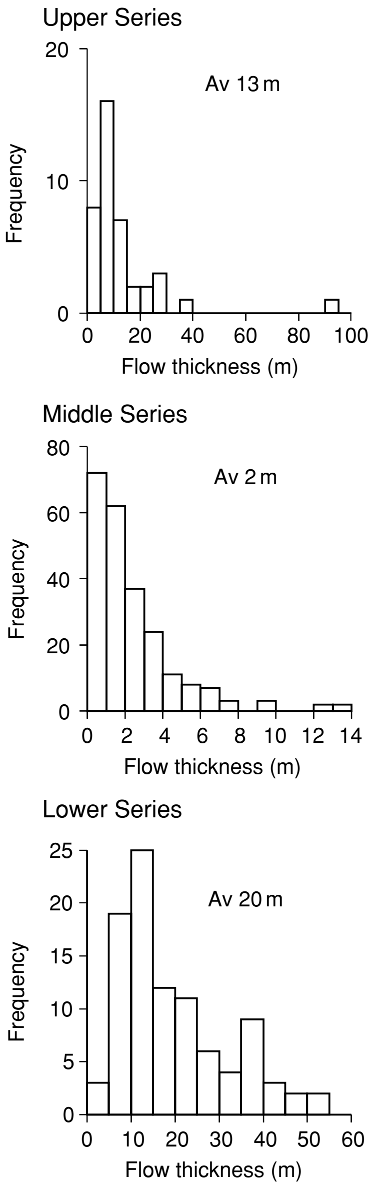


Figure 10 Histograms of basalt flow thicknesses in the Lower, Middle and Upper Series on the Faeroe Islands (Rasmusson and Noe-Nygaard 1970) from outcrop and from sampling in the Vestmanna (Middle Series) and Lopra (Lower Series) drillholes (Hald and Waagstein 1984; Waagstein and Hald 1984).

to the Faeroe Islands, the base of the basalt flows lies mostly at depths of 3–5 km below the surface, although it is clear that it rises towards the feather edge (also seen in cross-section in Fig. 7), and that there is a shallow basalt base beneath the Munkagrunnar Ridge.

When shown as a basalt isopach (Fig. 11c), it becomes apparent that the basalt thickness decreases monotonically from northwest to southeast. The Munkagrunnar Ridge is not as prominent as it is on the top and base-basalt maps, which is consistent with the suggestion that the Munkagrunnar Ridge was formed after extrusion of the basalts by a Tertiary compression and inversion event in the area, which primarily buckled the section, thinning the basalts slightly.

The fourth map (Fig. 11d) shows the isopach from the base of the basalts to the top of the pre-rift basement, using a 250 m contour interval. The pre-rift basement is defined by a prominent horizon that exhibits fault-block topography. Beyond the edge of the basalts this is imaged well, and it is of approximate base Upper Jurassic age. Because the horizon shows prominent fault topography, we take it to be representative of the palaeo-surface, which existed prior to the main episodes of extension and related faulting, and which generated the present Faeroe-Shetland Basin. We do not, of course, know whether it is at exactly the same stratigraphic level beneath the basalts, because there are no drillholes there, but it is reasonable to assume that it is at least approximately the same age, and that the section between this faulted horizon and the base of the basalts corresponds to the sediments that generate the low-velocity zone on the wide-angle profiles.

The thickness of the sediment section between the top pre-rift basement and the base of the basalts is typically 2–4 km, increasing to more than 6 km near the feather edge of the basalts in the southeast (Fig. 11d). Individual fault blocks are not visible on this map, because it has been smoothed prior to contouring. A particularly striking feature is the ridge of thin sub-basalt sediments extending southeastwards from the centre of the Faeroe Islands. This ridge is consistent with the presence of a possible land bridge inferred from palaeoenvironmental studies by Knox *et al.* (1997), and also is in line with the bulge in the edge of the basalts seen in Fig. 11. It is possible that basalts could flow more easily on land than beneath the deeper water to the north, where the palaeo-shelf edge is inferred from foresets in the lava to lie along a basalt escarpment (Kiørboe 1999), thus explaining the presence of the bulge in the basalt flows along this lineament. The Faeroe Islands themselves also lie on this lineation, suggesting that it has been a long-term basement high.

DISCUSSION AND SUMMARY

We have attempted to show that the thickness and distribution of basaltic lava flows and the underlying sediments in

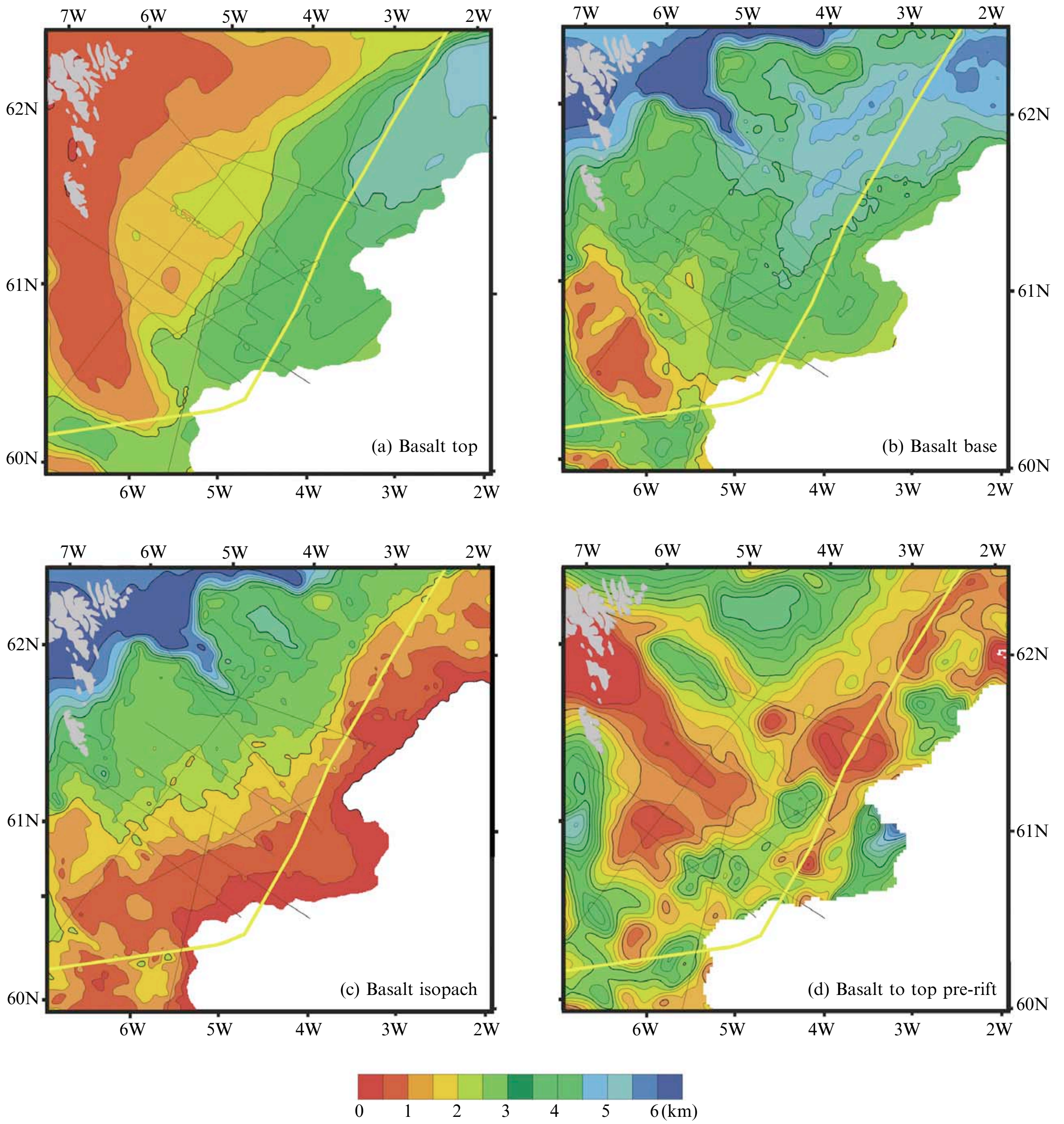


Figure 11 Maps of basalt and sub-basalt sediment thicknesses on the Faeroes Shelf, using as control the results from FLARE profiles (locations shown as light black lines), and a large grid of conventional 6-km streamer 2D and limited 3D seismic profiles in the region held by Amerada Hess Ltd. The white region in the southeast corner marks the feather edge of basalt flows from the Faeroes. (a) Shows depth to the top of the subsurface basalt flows; (b) shows depth to the base of the basalt flows, with the difference between them producing the basalt isopach map shown in (c); (d) shows the sub-basalt late Mesozoic and earliest Tertiary sediment thickness between the base of the basalts and the top of the main pre-rift basement. All the maps are smoothed, with a contour interval of 500 m. The yellow line marks the boundary between UK and Faeroes waters.

the Faeroe-Shetland Basin can be imaged using a combination of long-offset and conventional seismic data, by taking advantage of the refracted and reflected seismic energy outside the water-wave cone, which hitherto has largely been muted in conventional processing. The long-offset data can be used to build a velocity model deep into the crust, which can then be used to migrate, prestack, both the long-offset and the near-offset data. The images of the base of the basalt and of the underlying basement derived by selective migration of just the long-offset portions of the data do not have high resolution (because high frequencies have been absorbed along the long travelpaths at these offsets), and they are susceptible to errors in the migration velocities, either from the velocity modelling itself, or due to vertical to horizontal anisotropy. Nevertheless they provide a good indication of where these major interfaces lie. One of their most significant features is that the first-arriving wide-angle data cannot be either multiple or mode-converted phases. This is of immense importance in interpreting the structure, because sub-basalt imaging is plagued by an abundance of multiple and mode-converted events, many of which migrate with similar velocities and with a similar degree of coherence to the primary arrivals that we wish to identify.

It is clear, however, that conventional single-ship seismic profiles can deliver good images of the internal structure of the basalt, often with returns from the base of the basalt and below, particularly if the source is one rich in low frequencies, and long streamers of 6–12 km length are used. The problem with conventional seismic images remains the difficulty of discriminating between primary energy and mode-converted or peg-leg multiple energy. We suggest that a way round this problem is to use the wide-angle arrivals beyond the water-wave cone to image the base-basalt and deeper horizons, as discussed above, and then to use these to 'tag' the arrivals of interest, such as the base of the basalt. The composite wide-angle migration images can then be used to guide the interpretation of the detailed shape of these deep interfaces from the better resolution prestack depth-migrated profiles, which are processed including the near-offset data. By this means a sparse set of long-offset 2D profiles can be used to guide interpretation of a more detailed 2D or 3D grid.

What about the future? It is always the case that in the presence of lateral variability in structure, 3D surveys are required in order to migrate properly the energy returned from out of the plane of the profile. With current technology it is possible to image well through thin basalt layers, and it will be a natural progression to move to 3D surveys in these settings.

Another potential source of information is S-waves, whether produced directly at the source as is possible in land surveys, or from mode-conversions, as happens frequently and efficiently at the interfaces between basalts and sediments (White and Stephen 1980). The difficulty with identifying converted S-waves on marine profiles is that they have similar moveouts and arrival times to peg-leg sediment multiples. An aid to their interpretation would be to use four-component seismometers on the sea-bed (three orthogonal seismometers plus a hydrophone), either in arrays as in a bottom cable or as stand-alone ocean-bottom seismometers. It may then be possible to identify S-waves directly on sea-bed seismometers from their particle motions, and to use these identifications to identify and to 'tag' the converted arrivals on the denser multiple-fold streamer data acquired across the sea-bed instruments. Finally, good velocity control is essential for prestack depth migration of seismic data, and it becomes increasingly important as longer offsets are used for imaging. Although currently limited in application by their huge demands on computer-processing power, waveform inversion routines are making it possible to derive good velocity control utilizing not just the traveltimes, but also the amplitudes and waveforms of seismic arrivals at large offsets. As larger offsets are included in the migrations, it becomes increasingly important to allow for vertical-to-horizontal anisotropy as well as for lateral variations in the velocity and the velocity gradient.

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