Review of velocity models in the Faroe–Shetland Channel

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Abstract: Over the last few decades, a number of wide-angle seismic experiments have been conducted in the Faroe–Shetland Channel area with the objective of mapping the crustal structure. However, the volcanic rocks covering most of the area present a challenge for the imaging of sub-basalt structures. The results of the seismic studies are consistent in describing the Faroe–Shetland Channel as thinned continental crust and in establishing the presence of sub-basalt sediments. However, the various datasets often show differences in depth to crystalline basement and to the Moho. This paper presents a review of the velocity models in the Faroe–Shetland Channel and analyses the differences at line intersections. Down to top basalt the models are fairly consistent, while there are deviations of up to 1 km s−1 in basalt velocities and sub-basalt sediment velocities, 2 km in basalt thickness, 3.2 km in depth to crystalline basement, and 11.7 km in depth to the Moho.

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The Faroe–Shetland Channel (Fig. 1) is characterized by Palaeogene volcanic rocks associated with the North Atlantic Igneous Province and the breakup of the North Atlantic (Larsen et al. 1999). The volcanic rocks cover large areas around the Faroe Islands and make the imaging of deeper sections challenging. Over the last few decades, a number of wide-angle seismic experiments have been conducted in the Faroe–Shetland Channel area with the objective of mapping the crustal velocity structure. The different surveys (Hughes et al. 1998; Richardson et al. 1999; White et al. 1999; Fliedner & White 2003; Raum et al. 2005; Eccles et al. 2007; Makris et al. 2009; Roberts et al. 2009) describe the crust beneath the Faroe–Shetland Channel as thinned continental crust. Further, they all indicate the presence of sub-basalt sediments. However, a comparison of intersecting profiles shows that there are a number of differences between crossing and adjacent lines (Funck et al. 2014). In this paper, we review all velocity models in the Faroe–Shetland Channel that are based on seismic refraction data, and some of them also on gravity data, acquired since 1994. The objective is to quantify the differences at line intersections and to discuss the implications.

The variable seismic properties within the basalt column with a succession of high-impedance contrasts leads to attenuation and scattering of seismic waves during the propagation through the basalts (e.g. Maresh et al. 2006). The adverse effect that basalt has on the imaging of sub-basalt structures is very well illustrated by Neish (2004, p. 142, fig. 15). She showed that there is a large area on the Faroese continental shelf where base basalt and sub-basalt structures are difficult to interpret on seismic reflection data.

One of the main objectives for most refraction experiments around the Faroes is the improvement of the sub-basalt imaging (e.g. Fliedner & White 2003), which is difficult to achieve with seismic reflection data alone. Seismic refraction data can hold information on sub-basalt properties in these areas by providing observations of seismic phases at large offsets.

Comparison of velocity models

Table 1 summarizes the acquisition parameters of the seismic lines reviewed in this study. To ease the comparison of the lines, digital versions of the velocity models were produced. For line AMP-D, a digital model was available, while the remaining models were digitized based on publications and existing reports. The digital models were obtained by converting the colour values according to the colour-scale bar in figures (FLARE and Mobil surveys), by reading velocity contours (iSIMM line) or by converting annotated velocity models (AMG95 and FAST surveys). The location of the models is based on digital navigation (FAST, FLARE and iSIMM surveys) or on digitized location maps.
taken from publications (AMG95 and Mobil surveys). Figure 1 shows the location of all wide-angle seismic lines used in this study.

The modelling of travel times is based on ray theory. All velocity models are developed using a combination of forward and inverse modeling, with the exception of the models regarding the Mobil survey that are based on forward modelling only. In addition, the FAST, FLARE and iSIMM surveys use conventional semblance analysis techniques on reflection seismic data for modelling the post-basalt sediments and the top basalt interface. The FLARE, FAST, AMG95 and AMP-D surveys integrate gravity data in the modelling. The modelling procedures for each survey are summarized below. For details on the modeling, we refer readers to the respective publications.

At line intersections, key model features are compared. This includes the depth to crystalline basement and the Moho, as well as the thickness of the basalt sequence and the underlying sediments. In addition, basalt and sub-basalt velocities are compared.

With the exception of FLARE lines 2–12, all velocity models infer Moho for the full length of the profiles, even though large sections of the...
Moho are not constrained by PmP (reflections from the Moho) and Pn (mantle refractions) arrivals. Where not constrained by seismic data, the Moho is defined by extrapolation, *a priori* information for the area or gravity data. In fact, at no intersection presented here do both profiles have seismic constraints on the depth of the Moho.

*Comparison of lines Mobil-1 and AMG95-2*

Lines Mobil-1 and AMG95-2 (Fig. 2) are offset by 3.8 km and run parallel to each other in a 35 km-wide zone (Fig. 1). The velocity model for line AMG95-2 (Raum *et al*. 2005) was obtained from forward and inverse modelling of travel times. In addition, information from coincident seismic reflection data was incorporated into the model. No PmP or Pn phases were observed that could determine the Moho depth. For this reason, the Moho was inferred from gravity modelling. Subbasalt sediment structures and velocities are based on discontinuous horizons interpreted on seismic reflection data in the area.

The initial velocity model for line Mobil-1 (Hughes *et al*. 1998) is based on forward modelling. Similar to line AMG95-2, the Moho depth is

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**Table 1. Reviewed seismic refraction lines**

| Line name      | Acquisition year | Acquisition parameters                                                                 | Publications used for the digitization of the model |
|----------------|------------------|----------------------------------------------------------------------------------------|------------------------------------------------------|
| AMG95-1 and AMG95-2 | 1995             | **Source:** 79 l airgun array, 150 m shot interval <br>**Receivers:** Ocean-bottom seismographs, 42 stations along AMG95-1 and 40 stations along AMG95-2, 4 km receiver spacing | Raum *et al*. (2005)                                  |
| AMP-D          | 1996             | **Source:** 120 l airgun array, 120 m shot spacing <br>**Receivers:** Ocean-bottom seismographs, 45 stations with 2–4 km spacing | Digital model was available (Klingelhofer *et al*. 2005) |
| FAST           | 1994             | **Source:** 153 l airgun array, 50 m shot interval <br>**Receivers:** Four land stations with vertical component geophones located on Streymoy Faroe Islands and 6 km streamer | Richardson *et al*. (1999)                           |
| FLARE-1        | 1996             | Two-ship acquisition. <br>**Source:** One 85.1 l and one 49.2 l airgun array, 50 m shot interval for each ship. Composite gathers have 100 m shot intervals <br>**Receivers:** One 6 km and one 4.8 km streamer. <br>Offset gap between cables 5.6, 15.2 and 24.8 km. Maximum offset for marine data is 38.4 km. Six additional land seismometers were placed on Suðuroy (Faroe Islands) | White *et al*. (1999)                                |
| FLARE-2 and FLARE-3 | 1996         | Two-ship acquisition. <br>**Source:** One 85.1 l and one 49.2 l airgun array, 50 m shot interval for each ship. Composite gathers have 100 m shot intervals <br>**Receivers:** One 6 km and one 4.8 km streamer. <br>Offset gap between cables 5.6, 15.2 and 24.8 km. Maximum offset is 38 400 m | Latkiewicz & Kirk (1999)                             |
| FLARE-4–FLARE-12 | 1998           | Two-ship acquisition. <br>**Source:** One 58.0 l and one 62.3 l airgun array, 50 m shot interval for each ship. Composite gathers have 100 m shot intervals <br>**Receivers:** Two 6 km streamers. Offset gap between cables 6 km. Maximum offset of 18 km | Latkiewicz & Kirk (1999)                             |
| iSIMM          | 2002             | **Source:** 103 litre airgun array. 100 m shot interval <br>**Receivers:** Ocean-bottom seismographs, 85 stations with 2–6 km spacing | Roberts *et al*. (2009)                              |
| Mobil-1 and Mobil-2 | 1996           | **Source:** 120 litre airgun array. 120 m shot interval <br>**Receivers:** Ocean-bottom seismographs. 24 stations with 3.5 km spacing along Mobil-1 and 42 stations with 3.8 km spacing along Mobil-2 | Makris *et al*. (2009)                              |
constrained by gravity data as there are no clear PmP observations. Only one ocean-bottom seismometer (OBS) recorded a phase that could be a PmP. However, it is unclear whether the reflection is, indeed, from the Moho and not from intruded or underplated magmatic rocks. In the gravity modelling, the Moho depth was set to 30 km beneath the Shetland Platform and to 40–45 km beneath the Faroe Islands. In the Faroe–Shetland Channel, the Moho was then adjusted to maintain isostatic equilibrium. However, the model shown in Figure 2 is based on the later modelling by Makris et al. (2009) without the use of gravity data. They incorporated additional wide-angle seismic data consisting of an OBS array (5 × 8 OBS with a 5 km grid spacing) and a north–south line with 10 OBS crossing this array. This improved the constraints on the Moho along the central part of line Mobil-1 based on PmP reflections. The extent of the line with a seismically constrained Moho in Figure 2 is based on the location of the OBS array, and the uncertainty in Moho depth is estimated from the velocity uncertainties given by Makris et al. (2009). The inferred Moho outside the area with seismic constraint appears to be based on extrapolations only. The sub-basalt velocities appear to be based on the extrapolation of velocities from areas not covered by basalts.

While the basalts have a thickness of 2 km on line AMG95-2, they are only 1 km thick on line Mobil-1. It is not clear how Makris et al. (2009) determined the thickness of the basalts on line Mobil-1: however, the earlier model by Hughes et al. (1998) displays a similar basalt thickness that is constrained by the lateral extent of the refraction in the basalt layer using a velocity gradient obtained from synthetic amplitude modelling. The basalt thickness on line Mobil-1 corresponds

![Figure 2](http://sp.lyellcollection.org/)

**Fig. 2.** Comparison of P-wave velocity models of lines Mobil-1 and AMG95-2. (a) & (b) show different depth scales. The two lines do not intersect but run parallel to each other at a distance of 3.8 km. Annotated velocities are given in km s⁻¹. The map in the lower left-hand corner shows the location of the composite profile. The shaded area shows the basalt cover.
roughly to the upper part of the basalt sequence on line AMG95-2, defined by an intra-basalt low-velocity zone.

A comparison of the key features in the velocity models is given in Table 2. The depth to crystalline basement differs by 3.2 km. Velocities in the sub-basalt sediments are 1.0 km s$^{-1}$ higher on line Mobil-1 than on line AMG95-2. Differences in the sub-basalt velocities can explain some of the misfit in the depth to crystalline basement but are not sufficient to account for the full 3.2 km. The difference in the sub-basalt sediment velocities is difficult to assess, as neither Makris et al. (2009) nor Raum et al. (2005) provide details on how these velocities are constrained. The difference in depth to Moho is 6.3 km, but at the intersection there is no constraint from seismic data.

**Comparison of lines Mobil-2 and iSIMM**

Lines Mobil-2 and iSIMM intersect in the central part of the Faroe–Shetland Channel (Fig. 3). The model for line Mobil-2 is taken from Makris et al. (2009). Similar to line Mobil-1, an earlier model is presented in Hughes et al. (1998). That model shows the Moho to be 6 km deeper, based on gravity modelling. The modelling of line Mobil-2 followed the procedure of line Mobil-1 described above and uses the same OBS array and north–south line dataset to constrain the Moho depth at the centre of the profile. Along the remainder of the profile, the depth to Moho is apparently extrapolated.

The velocity model for line iSIMM (Roberts et al. 2009) is based on combined forward and inverse modelling of travel times. In addition, conventional semblance analysis techniques on reflection seismic data were used for the modelling of sediment velocities. Special attention was given to model the step back indicative of the low-velocity zone (LVZ) below the basalts. The velocity in the LVZ was determined by forward modelling for the thickness of the LVZ at various fixed velocities. The best fit was obtained using a velocity of 4.5 km s$^{-1}$. Crystalline basement was not interpreted. However, the coincident seismic reflection data show a strong reflection across the Fugloy Ridge at about 1.25 s two-way travel time (TWT) below the base of the LVZ, which could represent the crystalline basement (Roberts et al. 2009). The Moho is constrained by PmP phases throughout the profile, and the uncertainty in the Moho depth is given by Roberts et al. (2009).

The velocity model shown in the paper of Roberts et al. (2009) does not specify the sediment velocities above the basalts. However, for a portion of the line, Lau et al. (2010) provide such information using a pre-stack depth-migration workflow. They obtain post-basalt sediment velocities of 1.6–2.6 km s$^{-1}$. This velocity range is similar to the intersecting lines FLARE-11 and Mobil-2.

The comparison of the velocity models of lines Mobil-2 and iSIMM is summarized in Table 3 and reveals a 0.7 km difference in basalt thickness. In fact, the basalt layer on line Mobil-2 peters out at the cross-point with line iSIMM. The velocities of the LVZ deviate by 0.9 km s$^{-1}$ at the top but are similar at the base. The depth to the Moho deviates by 1.9 km. Both lines have constraints on the Moho depth, although not at the actual intersection. The modelling of the lines was carried out without incorporation of gravity data and no a priori information on Moho depth was used.

**Comparison of lines FLARE-1, AMG95-1 and FAST**

The composite transect of lines FLARE-1, AMG95-1 and FAST (Fig. 4) describes a zigzag path running from the southernmost island of the Faroes to the centre of the Faroe–Shetland Channel, back to the Faroe Islands and from there back into the channel. The velocity modelling along line AMG95-1 (Raum et al. 2005) was carried out in a similar way as described above for line AMG95-2. However, the PmP and Pn phases constrain the Moho depth on line AMG95-1. Raum et al. (2005) provided estimates on the depth uncertainty of interfaces.
The shallow velocity structure of line FLARE-1 (Richardson et al. 1999; White et al. 1999) was determined using conventional semblance analysis techniques and the top basalt was derived from the interpretation of the seismic reflection data. Forward and inverse modelling was used for the velocity analysis in the deeper sections. Constraints on basalt velocities were obtained from vertical seismic profiles (VSP) recorded as part of the FIRE experiment (Richardson et al. 1998), the VSP at the Lopra well (Kiørboe & Petersen 1995) and from older seismic refraction data (Palmason 1965). For the lower crust, fixed velocities of 6.4 and 6.8 km s$^{-1}$ at the top and base, respectively, were

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**Fig. 3.** Comparison of P-wave velocity models of lines Mobil-2 and iSIMM. (a) & (b) show the different depth scales. Annotated velocities are given in km s$^{-1}$. The map in the lower left-hand corner shows the location of the composite profile. The shaded area shows the basalt cover. The uncertainty of the Moho depth is set to $\pm 0.5$ km, being representative of the more detailed uncertainties given in Roberts et al. (2009).
used owing to a lack of seismic constraints. These velocities are similar to the ones observed in nearby continental crust in the UK (Richardson et al. 1999). Strong PmP reflections recorded on one land station at the NW end of the profile provided some seismic constraints on the Moho depth that helped in the gravity modelling of the Moho along the remainder of the line. Neither Richardson et al. (1999) nor White et al. (1999) provided estimates on the uncertainty of the Moho depth, which is why a rather large estimate of 2 km is used in Figure 4.

Table 3. Comparison of features of the velocity models at the intersection of lines Mobil-1 and iSIMP

| Feature                        | Mobil-2 | iSIMP  |
|-------------------------------|---------|--------|
| Moho                          | 19.5 km | 17.6 km|
| Crystalline basement          | 7.1 km  |        |
| Basalt thickness              | 0 km    | 0.7 km |
| Basalt velocity               | 4.7 km s\(^{-1}\) | 4.8–5.3 km s\(^{-1}\) |
| Sub-basalt sediment thickness | 3 km    |        |
| Sub-basalt sediment velocities| 3.6–4.5 km s\(^{-1}\) | 4.5 km s\(^{-1}\) |

Fig. 4. Comparison of P-wave velocity models of lines FLARE-1, AMG95-1 and FAST. (a) & (b) show different depth scales. Annotated velocities are given in km s\(^{-1}\). The map in the lower left-hand corner shows the location of the composite profile. The shaded area shows the basalt cover.
Similar to line FLARE-1, the shallow velocities of line FAST (Richardson et al. 1999) were determined using conventional semblance analysis techniques and the top basalt was taken from the interpretation of the stacked profile. The crustal velocity structure was obtained from forward and inverse modelling of travel times from data recorded on the four land seismometers. These seismometers were not deployed along the extension of the shot line but were offset by 27–50 km to the north. High-amplitude wide-angle reflections observed on one of the land stations determined the Moho depth at the NW end. In all other areas, gravity modelling was employed to obtain the depth to the Moho. The uncertainty on the Moho depth was not provided by Richardson et al. (1999), and Figure 4 uses therefore an estimate of 2 km similar to line FLARE-1.

Tables 4 and 5 compare the velocity models at their intersections. At the crossing of lines FLARE-1 and AMG95-1, the deviation in basalt thickness of 1 km is most likely to be related to differences in the interpretation of the data. The sub-basalt velocities are around 3.8 km s\(^{-1}\) on line FLARE-1, but vary between 3.3 and 4.6 km s\(^{-1}\) on line AMG95-1. In addition, the velocity model for line AMG95-1 shows several thick intrusions within the sub-basalt sediments with velocities of 5.15–5.50 km s\(^{-1}\). On lines FLARE-1 and FAST, the LVZ terminates close to the Faroe Islands. This termination is based on observations from the land seismometers, Richardson et al. (1999) suggested that the higher velocities beneath the basalt on the Faroe Islands either relate to intrusions or could represent a crystalline basement high. In contrast, the model of line AMG95-1 shows a continuation of the LVZ beneath the Faroe Islands.

At the intersection of lines AMG95-1 and FAST, the Moho depth is 22.3 and 34 km, respectively. The unreversed ray coverage and the significant offset of the seismic stations relative to the shot line are likely to be the main reasons for the differences. Although the intersection is at an unconstrained location for both lines, this is a quite significant difference, especially when considering that both lines incorporate gravity data in the velocity modelling.

It should be noted that the publications on the FLARE survey use the term ‘basement’ in the meaning of ‘seismic basement’ corresponding to a strong sub-basalt reflection and not crystalline basement (e.g. Fliedner & White 2001; Fruehn et al. 2001). In Fliedner & White (2003, p. 356, fig. 11), the depth to crystalline basement along line FLARE-1 is interpreted at a depth of 10–12 km, whereas the modelled seismic basement is only 5–7 km deep (Fig. 4).

Comparison of lines AMP-D and AMG95-1

Line AMP-D is a strike line in the Faroe–Shetland Channel and is perpendicular to line AMG95-1 that extends to the Faroe Islands (Fig. 1). The velocity model (Fig. 5) of line AMP-D (Klingelhofer et al. 2005) is based on forward and inverse modelling of travel times. In addition, ray-synthetic seismograms were calculated. Large portions of the Moho are constrained by PmP and Pn phases. In addition, gravity modelling was invoked to obtain the Moho depth in the seismically unconstrained segments. The model for line AMP-D has two distinct LVZs beneath basalt layers. Velocities in these LVZs are not constrained, and are set to 3.95–4.15 km s\(^{-1}\) for the upper LVZ and 4.2–4.7 km s\(^{-1}\) for the lower LVZ. The modelling procedures for line AMG95-1 are described earlier in this paper.
A comparison of the model features of the two lines is given in Table 6. The velocity models indicate a less than 0.3 km thin basalt layer at the intersection. Despite this agreement, there are distinct differences in the underlying units. While line AMG95-1 displays several intrusions into the sub-basalt sediments, line AMP-D shows a second continuous basalt layer within these sediments. However, both models use similar velocities for the sub-basalt sediments of 3.95–4.7 km s\(^{-1}\) on line AMP-D and 3.7–4.7 km s\(^{-1}\) on line AMG95-1. There is a 1.5 km misfit in the depth to basement.

Fig. 5. Comparison of P-wave velocity models of lines AMP-D and AMG95-1. (a) & (b) show different depth scales. Annotated velocities are given in km s\(^{-1}\). The map in the lower left-hand corner shows the location of the composite profile. The shaded area shows the basalt cover.

A comparison of the model features of the two lines is given in Table 6. The velocity models indicate a less than 0.3 km thin basalt layer at the intersection. Despite this agreement, there are distinct differences in the underlying units. While line AMG95-1 displays several intrusions into the sub-basalt sediments, line AMP-D shows a second continuous basalt layer within these sediments. However, both models use similar velocities for the sub-basalt sediments of 3.95–4.70 km s\(^{-1}\) on line AMP-D and 3.7–4.7 km s\(^{-1}\) on line AMG95-1. There is a 1.5 km misfit in the depth to basement.

Table 6. Comparison of features of the velocity models at the intersection of lines AMP-D and AMG95-1

|                      | AMP-D     | AMG95-1   |
|----------------------|-----------|-----------|
| Moho                 | 20.8 km   | 16.8 km   |
| Crystalline basement | 7 km      | 8.5 km    |
| Basalt thickness (upper) | 0.3 km | 0.1 km    |
| Basalt velocity      | 4.6–5.3 km s\(^{-1}\) | 5–5.5 km s\(^{-1}\) |
| Sub-basalt sediment thickness | 3.9 km | 5.9 km    |
| Sub-basalt sediment velocities | 3.95–4.70 km s\(^{-1}\) | 3.7–4.7 km s\(^{-1}\)  |

*Not including velocities of sills in the sub-basalt section.
At the Moho level, the deviation between the two lines is 4 km, a misfit that could be reconciled with a Moho uncertainty of 2 km on either line.

**Comparison of lines AMP-D and FLARE-1**

Line AMP-D in the Faroe–Shetland Channel also crosses line FLARE-1, which extends towards Suðuroy (Fig. 1). The modelling procedures for lines AMP-D and FLARE-1 were described earlier.

At the intersection of lines AMD-D and FLARE-1, basalts of line AMP-D are 0.3 km thick, while they are 1 km on line FLARE-1 (Table 7; Fig. 6). The basement of line FLARE-1 is 1.1 km shallower than on line AMP-D. The discrepancy is, again, related to the fact that line FLARE-1 shows the

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**Table 7. Comparison of features of the velocity models at the intersection of lines AMP-D and FLARE-1**

| Feature                        | AMP-D  | FLARE-1 |
|--------------------------------|--------|---------|
| Moho                           | 21 km  | 21 km   |
| Crystalline basement           | 7.1 km | 6.0 km* |
| Basalt thickness               | 0.3 km | 1 km    |
| Basalt velocity                | 4.70 km s^{-1} | 5.25 km s^{-1} |
| Sub-basalt sediment thickness  | 4.0 km | 3.3 km  |
| Sub-basalt sediment velocities | 4.0–4.6 km s^{-1} | 3.75–4.00 km s^{-1} |

*Seismic basement.

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**Fig. 6.** Comparison of P-wave velocity models of lines FOERBAS and AMP-D–FLARE-1. (a) & (b) show different depth scales. Annotated velocities are given in km s^{-1}. The map in the lower left-hand corner shows the location of the composite profile. The shaded area shows the basalt cover.
depth to seismic basement and not to crystalline basement, as is the case for line AMP-D. Seismic basement on line FLARE-1 has approximately the same depth as the base of the lower basalt layer on line AMP-D (Fig. 5b), but it is unclear whether this correlation has some relevance or if it is arbitrary. The sub-basalt sediments of line FLARE-1 are modelled as a single-layer, whilst line AMP-D has two distinct LVZs beneath basalt layers. This can also be seen in relation to line AMG95-1 in the same area, for which several thick intrusions are modelled into the sub-basalt sediments (Fig. 5).

Comparison of lines FLARE-1 to 12

The FLARE survey consists of 12 lines spanning the NW part of the Faroe–Shetland Channel (Fig. 1). From these lines, a composite north–south profile (Fig. 7) was constructed to evaluate the internal consistency of the velocity models.

The velocity modelling for lines FLARE-2–FLARE-12 was performed in the same way as described earlier for line FLARE-1 (Latkiewicz & Kirk 1999; White et al. 1999, 2003; Fliedner & White 2003). The shallow velocity structure was determined using conventional semblance analysis techniques, while stacked seismic records were used to interpret the top of the basalt. Forward and inverse modelling were employed to determine the velocities of deeper structures. The top of the seismic basement interface was mapped by wide-angle reflections, which also provided constraints on the sub-basalt velocities. Basement refractions were rarely observed owing to the limited shot-receiver distance of no more than 38 km. For this reason, basement velocities are generally unconstrained (Latkiewicz & Kirk 1999; White et al. 1999, 2003; Fliedner & White 2003).

The composite line shows that the depth to top basalt and base basalt is consistent at all intersections (Fig. 7). Velocities in the basalt are consistent in most cases, while there are generally larger differences in the sub-basalt velocities – with the largest difference of 1.2 km s\(^{-1}\) occurring at the intersection of lines FLARE-8 and FLARE-1.

Comparison of the FLARE survey with lines AMG95-1 and Mobil-2

As there is a rather dense grid of seismic refraction lines in the Faroe–Shetland Channel, there are a few more line intersections to investigate. Here, the intersections of the FLARE survey with the two lines AMG95-1 (Fig. 8) and Mobil-2 (Fig. 9) are presented. A description of the modelling procedures was given earlier.

The base basalt on line AMG95-1 is up to 1.5 km shallower than on lines FLARE-7 and FLARE-8 (Table 8; Fig. 8). Sub-basalt velocities on line FLARE-7 (3.8 km s\(^{-1}\)) fall within the velocity range observed on line AMG95-1 (3.2–4.7 km s\(^{-1}\)). At the intersection of lines FLARE-8 and AMG95-1, the sub-basalt velocities do not match (Table 9; Fig. 8). The model for line FLARE-8 indicates a rather high velocity of 4.9 km s\(^{-1}\), which contrasts with the velocity range of 3.2–4.5 km s\(^{-1}\) on line AMG95-1. Another striking difference is the presence of sills in the sub-basalt section of line AMG95-1, while no such features are resolved in the models of lines FLARE-1 and FLARE-8.

Lines Mobil-2 and FLARE-11 have similar velocities of 4.3 km s\(^{-1}\) at the top of the basalt sequence (Table 10; Fig. 9). However, further below there are substantial differences in the interpretation. While the basalts on line FLARE-11 are 1.7 km thick, their thickness is only 0.6 km on line Mobil-2. Maximum velocities in the basalts are also higher on line FLARE-11 (5.3 km s\(^{-1}\)) than on line Mobil-2 (4.3 km s\(^{-1}\)). Interestingly, the depth to crystalline basement on line Mobil-2 correlates with the base basalt interpretation on line FLARE-11. Owing to the differences in the velocity distribution, it is safe to say that this match is coincidental as the corresponding reflectors do have different travel times on the seismic record.

Discussion

The comparisons given above show that the velocity models at the intersection of seismic refraction lines match reasonably well down to and into the uppermost basalts. The inconsistency at deeper levels is largely related to difficulties in determining the base of the basalts and the velocities in the sub-basalt sediments that, in most cases, represent a LVZ. While seismic refraction modelling is often presented as an alternative to seismic reflection imaging of sub-basalts (Hughes et al. 1998; Richardson et al. 1999; Fliedner & White 2003; White et al. 2003; Klingelhofer et al. 2005; Raum et al. 2005; Makris et al. 2009), the method clearly has problems of its own regarding this matter. These difficulties relate to the imaging and interpretation of thick basalts, and to the lack of refractions within the sub-basalt sediments due to their character as a LVZ. Lau et al. (2010) stated that the discrimination between the basalt sequence and the underlying geology remains the most critical seismic imaging problem in the Faroe–Shetland Channel.

In some models, the offset range of the refracted basalt phase is used as a measure for the basalt thickness (e.g. line Mobil-1: Hughes et al. 1998). Sometimes a base basalt reflection can be identified...
Fig. 7. The composite FLARE P-wave velocity model consists of sections from all 12 of the profiles, with the location and depth of the Brugdan well annotated. The white marker on the map shows the location of the Brugdan well. Annotated velocities are given in km s\(^{-1}\). The map in the lower left-hand corner shows the location of the composite profile. The shaded area shows the basalt cover.
Fig. 8. Comparison of P-wave velocity models of lines FLARE-7, AMG95-1 and FLARE-8. Annotated velocities are given in km s$^{-1}$. The map in the lower left-hand corner shows the location of the composite profile. The shaded area shows the basalt cover.

Fig. 9. Comparison of P-wave velocity models of lines FLARE-11 and Mobil-2. Annotated velocities are given in km s$^{-1}$. The map in the lower left-hand corner shows the location of the composite profile. The shaded area shows the basalt cover.
interpretations on stacked reflection seismic data are used to infer the basalt thickness (e.g. the FLARE survey: Fliedner & White 2003). However, a strong intra-basalt reflector (cf. Fig. 2) resulting from, for example, an interbedded sedimentary layer poses a problem for all of these methods. First, the intra-basalt reflector can affect the maximum range of the refraction in the basalts. This, in turn, can result in wrong estimates of the total basalt thickness. Second, the reflection from the intra-basalt reflector can be misinterpreted as a reflection from base-basalt. Third, a well-defined reflection from an intra-basalt reflector, in combination with a change in seismic facies, can potentially be misinterpreted as the base of the basalt on stacked seismic reflection data (Petersen 2014).

Such seismic facies changes are observed in a number of settings at volcanic margins. Differences in seismic facies for seawards-dipping reflectors (SDRs), hyaloclastites and flow-foot breccia sequences are shown in Spitzer et al. (2008). Planke et al. (2000) presented an extensive study of seismic volcanostratigraphy, in which they distinguish various facies such as landward flows, lava delta, inner flows, inner SDRs, outer high and outer SDRs. The Lopra-1 well (Christie et al. 2006) is a case where, at the transition from subaerial flows to hyaloclastites, the seismic response changes significantly towards lower amplitudes. Even subaerial basalt formations can display significant differences in seismic facies (Petersen et al. 2006, 2015).

The problem of determining base basalt in the absence of a base basalt reflector was illustrated by Varming et al. (2012), who showed a seismic reflection profile that connects two wells (6005/15-1 and 6005/13-1) displaced about 20 km from each other. While the one well encountered 30 m of basaltic lava flows and 55 m of volcaniclastic sandstone–siltstone, the other well terminated within the volcanic section after encountering a 1475 m-thick series of basaltic lavas and hyaloclastites. However, the seismic profile connecting the two wells did not show a traceable seismic horizon that could represent this significant change in basalt thickness.

One example of where the total basalt thickness could not be determined from seismic data is the Brugdan well in the Faroe–Shetland Channel (Fig. 1). Here base basalt was drilled at 3745 m, while prior to drilling the base of the basalt was predicted at a depth of 2280 m (Øregaard et al. 2007).

| Table 8. Comparison of features of the velocity models at the intersection of lines AMG95-1 and FLARE-7 |
|-------------------------------------------|
| Flare-7 | AMG95-1 |
| Basalt thickness | 1.4 km | 0.3 km |
| Basalt velocity | 4.25–5.20 km s\(^{-1}\) | 5.2 km s\(^{-1}\) |
| Sub-basalt sediment velocities | 3.8 km s\(^{-1}\) | 3.2–4.7 km s\(^{-1}\) |

| Table 9. Comparison of features of the velocity models at the intersection of lines FLARE-8 and AMG95-1 |
|-------------------------------------------|
| AMG95-1 | FLARE-8 |
| Basalt thickness | 1.3 km | 2.8 km |
| Basalt velocity | 4.8–5.5 km s\(^{-1}\) | 5.00–5.25 km s\(^{-1}\) |
| Sub-basalt sediment velocities | 3.2–4.5 km s\(^{-1}\) | 4.9 km s\(^{-1}\) |

| Table 10. Comparison of features of the velocity models at the intersection of lines Mobil-2 and FLARE-11 |
|-------------------------------------------|
| Mobil-2 | FLARE-11 |
| Basalt thickness | 0.6 km | 1.7 km |
| Basalt velocity | 4.3 km s\(^{-1}\) | 4.3–5.3 km s\(^{-1}\) |
| Base basalt–crystalline basement velocity | 3.6–4.4 km s\(^{-1}\) | 4.8 km s\(^{-1}\) |
It is not clear on what this prognosis was based, but it was most likely to have been on the interpretation of seismic reflection data. Line FLARE-6 (Fliedner & White 2003) intersects the Brugdan well (Fig. 7). At this location, the modelled depth of base basalt is about 2800 m, which is 945 m less than what was found in the well. The reason for this mismatch may relate to effects from hyaloclastites. From 2542 m down to the base of the volcanic succession, the lithology in the Brugdan well is dominated by hyaloclastites interbedded with basalt and volcaniclastic sediments (Øregaard et al. 2007).

The comparison of interval velocities from VSP and velocity log shows consistency with the velocity model of line FLARE-6 (Fig. 10), although post-basalt sediment velocities are too high and, subsequently, the top basalt is about 200 m too deep. At 2800 m, line FLARE-6 models base basalt with a velocity inversion that reaches its minimum of 4.25 km s\(^{-1}\) at a depth of 2880 m. If correcting the depth of the modelled velocities according to the discrepancy of the top basalt, the depth of the velocity inversion on line FLARE-6 matches the depth of a velocity inversion actually seen at the top of a 200 m-thick hyaloclastics section in the velocity log at 2686 m. Figure 10 also shows that there is a correlation between the sub-basalt section of the model and the hyaloclastites in the well.

None of the intersecting lines show consistency between different surveys, while intersecting lines within the same survey are fairly consistent, as seen on the FLARE composite profile (Fig. 7). In relation to this, it should be mentioned that the modelling of line iSIMM utilizes the intersecting line FLARE-11 as a constraint (Spitzer & White 2005). This is why the iSIMM profile is consistent with the results of line FLARE-11. All other intersecting lines with regard to different surveys show differences in basalt thickness, depth to crystalline basement, and in velocities and internal structure of the sub-basalt sediments. The Moho, however, is consistent at the intersection of lines Mobil-2 and iSIMM (Fig. 3), as well as at the intersection of lines AMP-D and FLARE-1 (Fig. 6).

The velocity models of the sub-basalt sediments SE of the Faroes display large lateral variations. The models for lines FAST and FLARE-1 show a transition from low sub-basalt velocities (<4.6 km s\(^{-1}\)) to higher sub-basalt velocities (>5.7 km s\(^{-1}\)) when approaching the Faroes (Fig. 4). The change in velocity is interpreted as relating to the landwards termination of the sub-basalt sediments against a basement high or may represent a zone with intrusions (Richardson et al. 1999). In contrast, the sub-basalt sediments on line AMG95-1 continue as a LVZ all the way to the Faroes (Fig. 4).

There also seems to be some correlation between the basalt thickness and whether or not the seismic
line extends beyond the basalt cover in the Faroe–Shetland Channel. In general, the thickness of the basalts tends to be less on lines that reach into the eastern part of the channel with no basalts (lines Mobil-1, Mobil-2 and AMG95-1) than on profiles that are restricted to the basalt-covered area (line AMG95-2 and most of the lines from the FLARE survey).

The largest difference of Moho depth is at the AMG95-1–FAST intersection, with a difference of 11.7 km. Although the intersection is at a location where neither line has constraints from PmP reflections, both lines have a constraint within 20 km of the intersection. Notice, however, that for line FAST the seismic refraction data are from unreversed ray coverage, recorded on land stations with a significant offset to the shot line.

The profile with the best seismic constraints on the Moho depth is the iSIMM line. This is primarily due to the line location across the Fugloy Ridge with significant offsets to either side of the ridge. To the NW, the line extends into oceanic crust, while the thinned continental crust of the Faroe–Shetland Channel is encountered in the SE. This line geometry, together with the use of large airgun sources tuned to produce low-frequency energy, resulted in a good coverage with PmP reflections along the entire length of the profile.

Only for line AMG95-1 are upper-mantle velocities (8.0–8.3 km s⁻¹) constrained by Pn observations. For Mobil-1 and Mobil-2, the upper-mantle velocity (8.0 km s⁻¹) appears to be from Pn observations, although this is not clearly stated, while for lines FLARE-1 and FAST it is assigned at 7.8 km s⁻¹ and for line AMG95-2 at 8.1 km s⁻¹ without constraint from Pn observations.

All models presented here consider uncertainty bounds to some degree. Even though uncertainties are often related to the accuracy of the observed travel times, it is not at all a trivial task to quantify the velocity and depth uncertainties of a multilayer model. Looking at some of the models from the Faroe–Shetland Channel, Raum et al. (2005) and Makris et al. (2009) gave a general estimate on the uncertainties for the entire model, while Richardson et al. (1999) presented uncertainty estimates only down to the base of the LVZ. Similarly, Roberts et al. (2009) concentrated their uncertainty analysis on the LVZ and the depth to the Moho. Klingerhöfer et al. (2005) provided uncertainty estimates for a number of interfaces, including the Moho.

### Conclusion

The inconsistencies of the velocity models in the Faroe–Shetland Channel call for a remodelling of the seismic data guided and constrained by the latest geological models for the area (e.g. Ritchie et al. 2011; Hopper et al. 2014; Funck et al. 2016). Knowledge from available wells that drilled basalts in the Faroe–Shetland Channel should be integrated. In particular, the Brugdan (6104/21-1), William (6005/13-1) and Anne-Marie (6004/8a-1) wells (Fig. 1) are of importance as they were drilled in areas with significant basalt cover. The Brugdan well intersects the FLARE-6 profile and can, as such, be directly fed into the modelling of the seismic refraction data, while the William and Anne-Marie wells are not located on seismic refraction lines. However, the two latter wells can help to improve the understanding of the seismic facies in different types of basalts, and thereby aid the interpretation of basalt sequences on seismic reflection lines in the vicinity of the Faroe Islands. A reinterpretation of the basalts and other regional structures would put significant constraints on a remodelling of all seismic refraction datasets, in addition to the required consistency at all line intersections.

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