The stratigraphy and structure of the Faroese continental margin

JANA ÓLAVSDÓTTIR[1]*, ÓLUVA R. EIDESGAARD[1] & MARTYN S. STOKER[2]

[1]Jarðfeingi (Faroe Earth and Energy Directorate) Brekkutún 1, Postbox 3059, FO-110 Tórshavn, Faroe Islands

[2]British Geological Survey, The Lyell Centre, Research Avenue South, Edinburgh EH14 4AP, UK

*Correspondence: jana.olavsdottir@jardfeingi.fo

Abstract: This paper presents a summary of the stratigraphy and structure of the Faroese region. As the Faroese area is mostly covered by volcanic material, the nature of the pre-volcanic geology remains largely unproven. Seismic refraction data provide some indications of the distribution of crystalline basement, which probably comprises Archaean rocks, with the overlying cover composed predominantly of Upper Mesozoic (Cretaceous?) and Cenozoic strata. The Cenozoic succession is dominated by the syn-break-up Faroe Islands Basalt Group, which crops out on the Faroe Islands (where it is up to 6.6 km thick) and shelf areas; post-break-up sediments are preserved in the adjacent deep-water basins, including the Faroe–Shetland Basin. Seismic interpretation of the post-volcanic strata shows that almost every sub-basin in the Faroe–Shetland Basin has been affected by structural inversion, particularly during the Miocene. These effects are also observed on the Faroe Platform, the Munkagrunnur Ridge and the Fugloy Ridge, where interpretation of low-gravity anomalies suggests a large-scale fold pattern. The structure of the Iceland–Faroe Ridge, which borders the NW part of the Faroe area, remains ambiguous. The generally thick crust, together with the absence of well-defined seawards-dipping reflectors, may indicate that much of it is underlain by continental material.

The Faroese continental margin is located in the North Atlantic Ocean on the outer part of the NW European continental margin situated approximately in the central part of the North Atlantic Igneous Province (NAIP) (Fig. 1). Rocks associated with the NAIP cover approximately 99% of the Faroese area. This widespread coverage of the volcanic sequence inhibits our understanding of the region owing to what lies below the volcanic sequence. The situation is further complicated by the fact that the upper part of the NAIP is related to the SW–NE seafloor-spreading trend (Saunders *et al.* 1997), while the lower part of the NAIP is related to a NW–SE ridge-trend volcanism. The latter, in particular, complicates our understanding of the opening of the North Atlantic Ocean because the magnetic chrons are not visible across the Greenland–Iceland–Faroe Ridge (GIFR) (Gernigon *et al.* 2012). Moreover, the crust beneath the Iceland–Faroe Ridge (IFR) is in places relatively thick, even though it is assumed to be oceanic (Richardson *et al.* 1998; Smallwood *et al.* 1999).

The interval between approximately 63 and 56 Ma witnessed the contemporaneous eruption of volcanic material along a 2000 km NW–SE disc-shaped ridge area that extended between West Greenland and Great Britain, and Archer *et al.* (2005), Lundin & Doré (2005) and Ziska & Varming 2008 have all suggested that this pre-break-up volcanism was associated with the development of NW–SE-trending fissures that fed shield volcanoes intermittently located along the line of the fissures. By way of contrast, other researchers believe that the pre-break-up plateau basalts are a consequence of hotspot or plume processes (White 1988; Smallwood & White 2002). The oldest volcanic material in this disc-shaped structure is seen in Great Britain and West Greenland, and is dated to approximately 63 Ma (Storey *et al.* 2007; Ganerød *et al.* 2010). Onshore the Faroe Islands, the oldest drilled volcanic material has an age of approximately 62 Ma (Storey *et al.* 2007), but the volcanic sequence has not been fully penetrated by a well.

The Faroese area is juxtaposed with the IFR towards the NW. The former seafloor-spreading ridge – the Aegir Ridge – is located just north of the area. To the east and south of the Faroe Islands, a complex arrangement of Late Palaeozoic–Mesozoic–Early Cenozoic basins comprise the Faroe–Shetland and north Rockall regions (Figs 1 & 2).

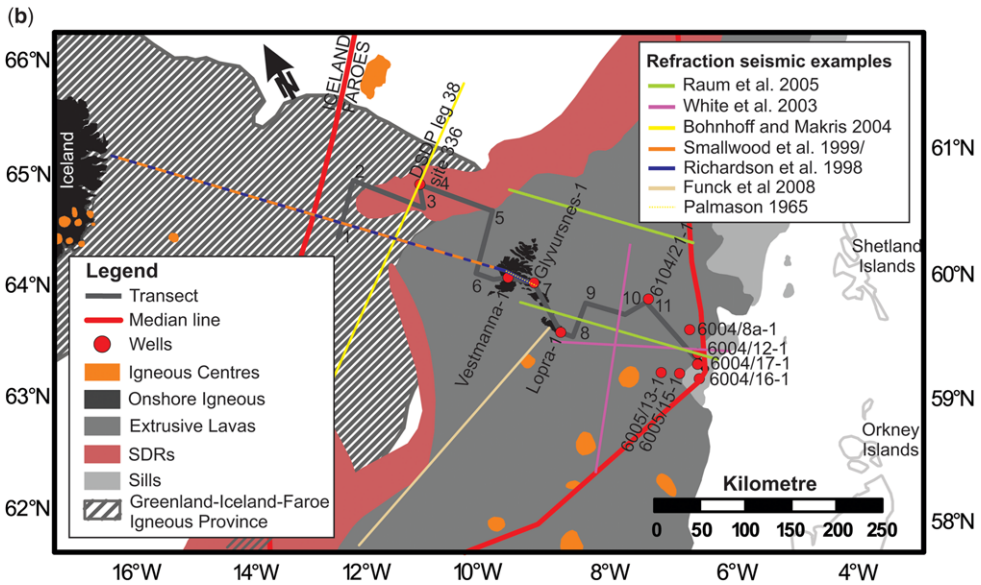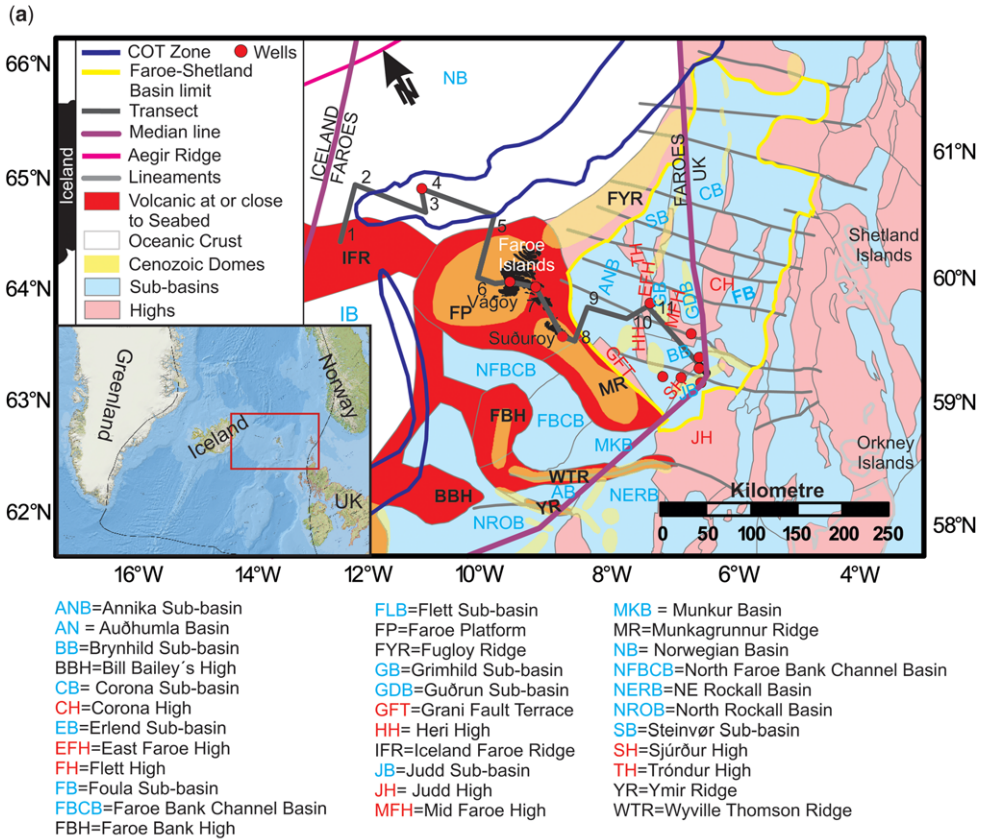**Fig. 1.** Maps showing (**a**) the structural framework and (**b**) the volcanic domains of the Faroese continental margin, modified from Ritchie *et al.* (2011) and Haase & Ebbing (2014). The maps also show the location of the shallow crustal transect shown in Figure 3, the boreholes and wells both onshore and offshore the Faroe Islands, and the various refraction seismic lines referred to in the text.
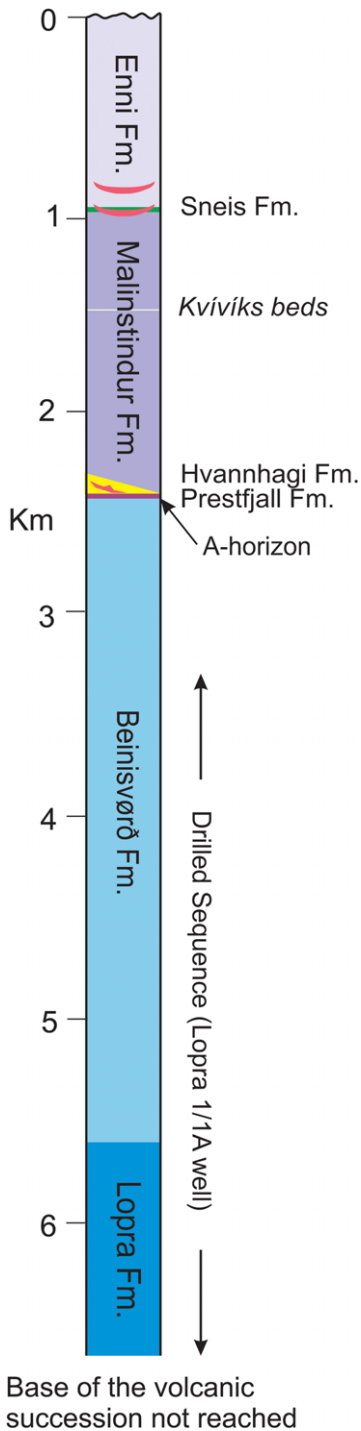
Fig. 2. (**a**) Free-air gravity anomaly map and (**b**) Bouguer gravity anomaly map covering the Faroese continental margin. The maps also retain – for reference – an outline of the main structural elements (detailed in Fig. 1), together with boreholes and wells, and the shallow crustal transect. See Figure 1a for the key to the abbreviations. Both maps are from Haase & Ebbing (2014).

Thus, the geological structure of the Faroese margin is a legacy of a prolonged history of extension and rifting that is related to the fragmentation of Pangaea, which ultimately led to continental break-up to the north and west of the Faroe Islands in the earliest Eocene (Doré *et al.* 1999; Roberts *et al.* 1999; Passey & Hitchen 2011; Ritchie *et al.* 2011; Ólavsdóttir *et al.* 2013; Stoker *et al.*, this volume, in press).

Fig. 3. Stratigraphic subdivision of the onshore Faroe Islands Basalt Group (FIBG), including the drilled sequence from the Lopra 1/1A well. The figure is modified from Passey & Jolley (2009).

A thick succession of Paleocene–Eocene pre- and syn-break-up volcanic rocks – the Faroe Islands Basalt Group (FIBG) (Fig. 3) that is part of the NAIP – covers almost the entire Faroese region: extending eastwards from the continental–ocean transition (COT) into the Faroe–Shetland Basin (Passey & Jolley 2009; Passey & Hitchen 2011) (Figs 1b & 4). As a consequence, very little is known about the pre-Cenozoic geological framework of the continental margin. On seismic reflection profiles, the quality of the data imaged below the top of the volcanic sequence is of poor resolution, which has hindered interpretation of the pre-volcanic strata. Mesozoic and Upper Palaeozoic rocks as old as Devonian in age (Smith & Ziska 2011) have been proved in wells in the UK sector of the Faroe–Shetland Basin. Although a number of sub-basins and highs have been interpreted in the western half (Faroese sector) of the Faroe–Shetland Basin, it is not possible at present – owing to the limited subsurface imaging of the basalt and the lack of well penetrations – to get a clear picture of the underlying pre-volcanic succession. Refraction seismic data have been used to suggest that Mesozoic and Palaeozoic sedimentary rocks might occur between the basement and the volcanic strata (Richardson *et al.* 1998, 1999; Smallwood & White 2002; White *et al.* 2003, 2008; Bohnhoff & Makris 2004; Raum *et al.* 2005), but this remains unsubstantiated as no well in the Faroese sector has penetrated strata older than Paleocene. Thus, the presence of Upper Palaeozoic and Mesozoic rocks in the Faroese sector of the Faroe–Shetland Basin remains largely inferred. Similarly, the structure and fill of the adjacent basins, including the Munkur, Faroe Bank Channel and north Rockall basins, remains unclear (Keser Neish & Ziska 2005; Stoker *et al.*, this volume, in press).

Consequently, the structural framework of the Faroe–Shetland–north Rockall region remains a 'work in progress'. The general pattern of basins and highs shown in Figure 1a has been established by an iterative process of exploration and interpretation over the last few decades, and the present distribution of structural elements combines the most recent compilations (Keser Neish 2004; Ritchie *et al.* 2011; Funck *et al.* 2014). One of the biggest uncertainties concerns the structure of the major present-day bathymetric highs, such as the Fugloy and Munkagrunnur ridges, as well as the Faroe Platform: in particular, whether these are basement-cored structures or inverted basins. In order to address these issues, this paper presents a regional appraisal of the stratigraphy and structure of the Faroese continental margin. The main objective of the study is to establish what is proven fact and what is inference concerning the structure of the continental margin. In turn,
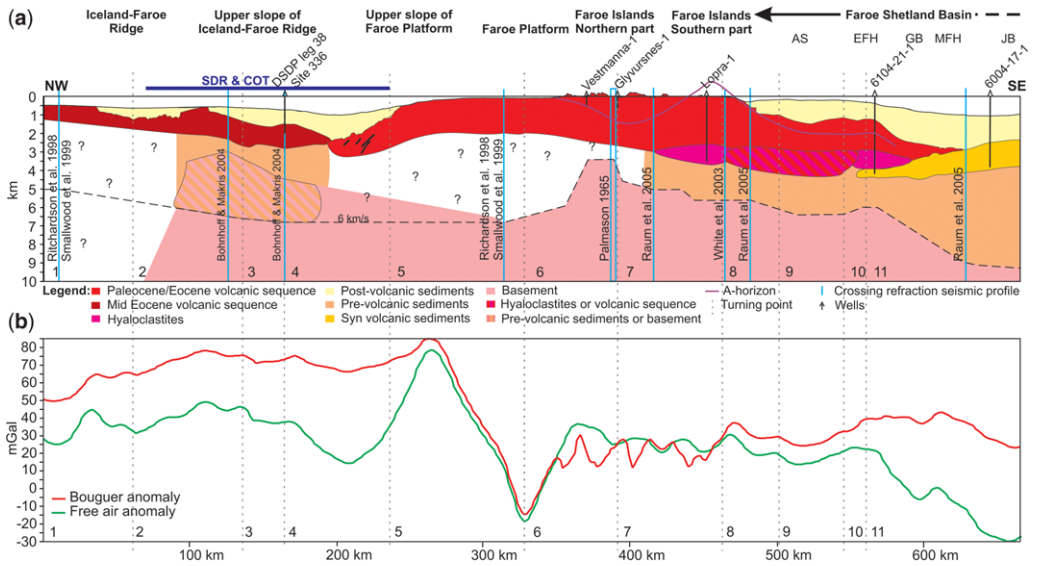
Fig. 4. (**a**) A profile across the Faroese continental margin summarizing the shallow crustal structure as compiled from various refraction seismic studies. The crustal transect is divided into 11 sections that represent specific controlled segments of the profile. The boundaries between the sections are marked with black vertical dashed lines. The vertical purple lines indicate the crossing refraction seismic lines from the various studies utilized in this study. Based on different seismic refraction studies, the top of the crust is marked on the transect at a given location: in addition, the thickness of the volcanic and pre-volcanic sequence can be seen. (**b**) shows the free-air gravity anomaly (green) and Bouguer gravity anomaly (red) values along the transect. Abbreviations: COT, continent–ocean transition; SDRs, seawards-dipping reflectors. See Figure 1a for the key to the abbreviations in the Faroe–Shetland Basin. The location of the profile is shown in Figures 1 and 2.

we hope that this will provide both context and constraints for ongoing discussions of the processes and events that have helped to shape this complex tectonic region.

Geological setting

The Faroe–Shetland Basin dominates the eastern half of the Faroese continental margin (Fig. 1). This NE-trending basin is up to 400 km long and 250 km wide, and consists of a complex amalgam of sub-basins generally separated from one another by north- to NE-trending structural highs (Ritchie *et al.* 2011). The Faroese sector of the Faroe–Shetland Basin comprises the Annika, Brynhild, Grimhild, Guðrun and Steinvør sub-basins, as well as the NW part of the Judd Sub-basin. Whereas their counterparts in the UK sector of the basin, including the Foula, Flett and Judd sub-basins, contain a proven Triassic–Cretaceous fill (Stoker *et al.*, this volume, in press), the known record of sedimentation in the western half of the Faroe–Shetland Basin is, to date, limited to the Cenozoic (Waagstein & Heilmann-Clausen 1995; Andersen *et al.* 2000, 2002; Sørensen 2003; Ólavsdóttir *et al.* 2010, 2013)

(Fig. 5). Many of the intervening structural highs consist of, or are underlain by, Archaean (Lewisian affinity) or Proterozoic basement, which are locally capped by Upper Palaeozoic rocks, including Devono-Carboniferous (Ritchie *et al.* 2011; Smith & Ziska 2011). The continuity of the structural highs is interpreted as being disrupted by NW-trending faults and transfer zones or lineaments (Ritchie *et al.* 2011), although the existence and significance of some of these features is debated (Moy & Imber 2009).

According to Ritchie *et al.* (2011), the Fugloy and Munkagrunnur ridges mark the northern and western boundaries, respectively, of the Faroe–Shetland Basin, with the Fugloy Ridge separating the basin from the COT (Fig. 1). Both of these ridges are interpreted as consisting of crystalline basement blocks capped by Mesozoic and/or early Cenozoic rocks (Smallwood *et al.* 2001; Raum *et al.* 2005; Ritchie *et al.* 2011; Funck *et al.* 2014). The present antiformal geometry of the ridges is inferred to have developed in response to later, post-break-up, contractional deformation and/or the effects of differential thermal subsidence, which affected a large part of the continental margin, including the Wyville Thomson Ridge to the SW, particularly
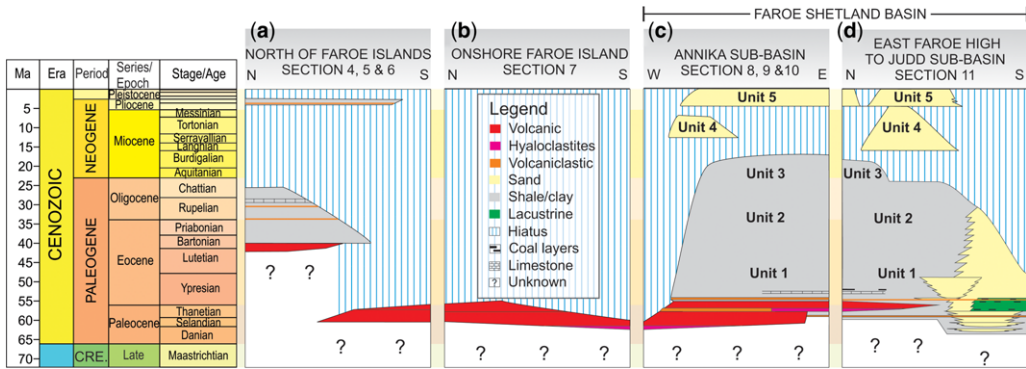
Fig. 5. A regional stratigraphic correlation chart showing the established Cenozoic stratigraphy of the Faroese continental margin. The timescale is based on Gradstein *et al.* (2012).

during the Eocene–Miocene interval (Johnson *et al.* 2005; Ritchie *et al.* 2008). The transition of both the Fugloy Ridge and the Munkagrunnur Ridge with the Faroe Platform is poorly understood.

The post-break-up tectonic movements enhanced the Fugloy and Munkagrunnur ridges as structural highs, and thus helped to create the contemporary bathymetry, whereby the Faroe and West Shetland shelves are separated by the deeper-water Faroe–Shetland Channel, which exceeds a water depth of 1500 m. The latter represents the present-day expression of the Faroe–Shetland Basin, albeit narrower as a consequence of the infilling of the wider Mesozoic basin by episodic shelf-margin progradation of both the East Faroe and West Shetland margins throughout the Cenozoic (Stoker *et al.* 2005, 2013; Ólavsdóttir *et al.* 2010, 2013; Stoker & Varming 2011).

To the NW of the Faroese continental margin, the IFR is a distinct aseismic area of anomalously thick oceanic crust (*c.* 30 km) and shallow ocean floor (á Horni *et al.* 2014) (Fig. 1). This ridge is part of the more extensive GIFR that extends further to the NW beyond Iceland to Greenland, and as such forms a bridge between Greenland and NW Europe. Although it is clear that the GIFR has formed as a result of anomalous melt production, the cause is less certain, and has been variously attributed to the activity of elevated temperatures associated with a mantle plume (White & McKenzie 1989; Smallwood *et al.* 1999) and melting of a fertile upper mantle during plate break-up (Foulger 2002; Lundin & Doré 2005). On the basis of a regional assessment of volcanic seismic facies, á Horni *et al.* (2014) indicated that the boundary between the IFR and the Faroe Platform is marked by a discontinuous cover of volcanic rocks interpreted to be part of the seawards- dipping reflector (SDR) sequence that characterizes the COT (Fig. 1b). However, a key complication along the IFR (and, indeed, the length of the GIFR) is that the

volcanic productivity of the region has remained uniformly high from break-up until present. Thus, vertical layering of basaltic flows from different magnetic polarity chrons prevents simple seafloor-spreading anomalies from developing (Richardson *et al.* 1998; Doré *et al.* 1999, 2008; Ritchie *et al.* 2011; Funck *et al.* 2014). In Figures 1–3, the location of the COT is taken from the seafloor-dipping reflector zone of á Horni *et al.* (2014).

Data and methods

In this study, we have summarized all available information from the Faroe continental margin: this includes reflection and refraction seismic data, gravity data, released well data, field observations, and published material. To date, no well has drilled into the rocks that lie below the volcanic sequence, except for some thin siliciclastic layers at the bottom of the Anne Marie well (6004/8a-1: Fig. 1b): thus, there is no physical proof of the composition of the sub-volcanic succession. However, seismic refraction data provide some indications of the nature and character of the sub-volcanic succession, and information has also been compiled from various studies (e.g. Pálmason 1965; Richardson *et al.* 1998; Smallwood & White 2002; White *et al.* 2003; Bohnhoff & Makris 2004; Raum *et al.* 2005) that intersect the chosen transect of this study (Figs 1–3) where important information such as e.g. the top of the crust has been plotted. The transect runs from the SE part of the IFR, across the Faroe Platform and ends in the Faroe–Shetland Basin (the Judd Sub-basin) (Fig. 1). The transect was chosen in an attempt to illustrate a zone that links the better known Faroe–Shetland Basin with the less known Faroe Platform and Iceland–Faroe Ridge areas with respect to the adjacent areas, such as Munkagrunnur and Fugloy ridges. The line of transect was positioned in order to utilize available

seismic profiles, where the location of the seismic lines were chosen so that they cut through the wells. Onshore of the Faroe Islands, no reflection seismic data were available and therefore the profile from Waagstein (1988) was used. The section was divided into 11 segments, as shown in Figures 1 and 2, where section 1 is the northernmost part of the transect and section 11 is located in the central Faroe–Shetland Basin.

It is commonly assumed that gravity data cannot be used for distinguishing between crystalline basement rocks in volcanic terrains due to their comparable relatively high density. For example, the density of the Scottish Lewisian Gneiss, which also is expected to underlie the Faroe area, is $2.76-2.84$ g cm^{-3} (Watts 1971), whereas investigations into the density of basalt onshore the Faroe Islands give an average density of 2.86 g cm^{-3} (Saxov & Abrahamsen 1964). By way of contrast, the density of volcaniclastic sediments and tuffs is 2.66 g cm^{-3} (Ólavsdóttir *et al.* 2015) and 2.17 g cm^{-3} (Saxov & Abrahamsen 1964), respectively.

We have chosen to calculate the density of the volcanic interval in some of the Faroese wells. The common thought is that the Faroses volcanics contain mostly basalt and should, therefore, have a high density. However, the volcanic interval does not only consist of basalt but also of different volcanic material, such as, for example, hyaloclastites, volcanic sediments, tuffs, vesicular basalt, dolorite, in addition to basalt, which gives the volcanic interval a varying density, as pointed out above. To show this, the average compensated bulk density in three volcanic-rich wells in the Faroese area was found. The mean density of the volcanic interval from 0 to 3137 m in the Lopra-1 well was found to be 2.8 g cm^{-3}, while the density of the volcanic interval from 3100 to 3860 m in the Brugdan-1 well (6104/21-1) was 2.47 g cm^{-3}, and, in a larger interval from 2200 to 4050 m in the Brugdan-II well, the density was found to be 2.67 g cm^{-3} (Fig. 1b). If the volcanic sequence had only consisted of basalt, then the density of the intervals would most likely have been higher, but as it does not, the density is lower than expected. If the volcanic interval had had a higher density than the expected basement at the given position, it would most likely have affected the gravity data, so that areas with thick volcanic intervals – such as sub-basins filled with volcanic material – would act as high gravity anomaly areas.

We note that gravity data are used together with other types of geophysical data to help to resolve the sub-basalt geology in volcanic basins in other parts of the world, such as the Deccan Volcanic Province in India, the Sicily Channel in Italy and the Jungar Basin in China (Diljith *et al.* 2008; Yang *et al.* 2009; Ray *et al.* 2010; Rao *et al.* 2013) where subbasins have low gravity anomaly values. Thus, we have utilized gravity data in our study as an aid to structural interpretation.

For ease of description, we have presented the results of our study in terms of three main structural domains: the Iceland–Faroe Ridge (IFR); the Faroe Platform (including the Fugloy and Munkagrunnur ridges); and the Faroe–Shetland Basin. We describe each of these domains in terms of what is known about their stratigraphical and structural character, with the latter incorporating seismic and gravity data where available. For the shallow crustal transect, the IFR includes transect sections 1–4; the Faroe Platform includes transect sections 5–7; and the Faroe–Shetland Basin includes transect sections 8–11 (Fig. 4).

Iceland–Faroe Ridge

Stratigraphy

Post-volcanic. On the SE part of the IFR, the post-volcanic sediment cover is thickest adjacent to the Faroe Platform where up to 1 s TWTT (two-way travel time) of Eocene and younger rocks are preserved (Fig. 4). The age of this sediment cover has been proved by DSDP site 336, which was drilled in a water depth of 811 m and had a total penetration below seabed of 515 m. The borehole drilled 168.5 m of Pliocene–Pleistocene marine and glacimarine mud and sporadic sand that unconformably overlies a 295 m-thick sequence of Middle–Upper Eocene–Oligocene marine mudstone, which, in turn, overlies a Middle Eocene volcanic section (see below) in which the borehole terminates (Talwani *et al.* 1976; Stoker & Varming 2011) (Fig. 5a). This sequence forms the eroded featheredge of a much thicker succession (up to 2 km) of post-volcanic sedimentary rocks that are preserved on the upper to mid-slope of the IFR as part of a shelf-margin succession that thickens and prograde northwards into the oceanic Norwegian Basin (Nielsen & van Weering 1998). This succession is also preserved on the northern slope of the Faroe Platform, as well as on the adjacent Fugloy Ridge. At its thickest development, the Eocene–Oligocene succession is up to 1 km thick. Although the Miocene succession is absent in DSDP site 336, a distinctive shelf-margin wedge, up to 550–600 m thick, of probable Miocene–earliest Pliocene age is preserved on the mid-slope region of the IFR. The Pliocene–Pleistocene sequence reaches a maximum thickness of about 200 m in this area of the slope (Nielsen & van Weering 1998).

Volcanic. DSDP site 336 cored 30.5 m of Middle Eocene basalts that have been radiometrically dated by K–Ar to be 41.5 ± 2.5 Ma (Talwani *et al.* 1976; Ganerød *et al.* 2014; Wilkinson *et al.*, this volume, in review), and which form the upper part of the

IFR volcanic section (Figs 1a, 4 & 5a). The basalt is overlain by an 8 m-thick unit of volcanic conglomerate (basaltic rubble), which is overlain by a 13 m-thick unit of red claystone, interpreted as a ferruginous lateritic palaeosol formed by *in situ* weathering of the basaltic ridge (Nilsen 1978; Nilsen & Kerr 1978).

Pre-volcanic. In terms of the pre-volcanic stratigraphy, some information is derived from a NE–SW refraction seismic line orientated approximately perpendicular to the trend of the IFR (Fig. 1b), and which crosses the shallow crustal transect in the southern part of section 2 and at the boundary between sections 3 and 4, where DSDP site 336 is located (Bohnhoff & Makris 2004). At these two intersecting points, a low-velocity layer beneath the volcanic sequence has been proposed, which has been suggested to represent Mesozoic sedimentary rocks, with a thickness of 0.5 and 1.5 km, respectively (Figs 1b & 4).

A pre-volcanic low-velocity layer up to 1 km thick has also been modelled from a refraction seismic line located approximately 30 km in a easterly direction from the junction of transect sections 4 and 5 (Raum *et al.* 2005; Roberts *et al.* 2009) (Fig. 1b). By way of contrast, a refraction seismic line – the FIRE line – orientated along the axis of the IFR did not reveal a low-velocity layer anywhere along the line (Richardson *et al.* 1998; Smallwood *et al.* 1999; Smallwood & White 2002) (Fig. 1b).

Structure. The nature of the crustal structure of the IFR remains ambiguous. Whereas in much of the NE Atlantic region it is relatively easy to define the COT on the basis of magnetic chrons and the SDRs from seismic reflection data, this is not the case for the IFR where neither of these identifiers is definitive. The trend of the SDRs east (Norwegian Basin) and west (Iceland Basin) of the IFR changes direction, so the COT trends – at least in part – along the ridge instead of crossing it (Fig. 1), whereas the magnetic chrons stop when they reach the ridge. In transect section 1, on the SE part of the IFR, Bohnhoff & Makris (2004) interpreted the crust to be about 15 km thick and of a stretched continental character, with the top at a depth of 3 km (Fig. 4). Transect sections 2–4 are located on the COT (Fig. 1) where SDRs are clearly observed.

In terms of the deeper crustal structure, it is interesting to note that the refraction seismic line of Bohnhoff & Makris (2004) is crossed by the FIRE line reported by both Richardson *et al.* (1998) and Smallwood *et al.* (1999) 42 km west of the southern part of transect section 2 (Fig. 1b). Where these two lines intersect, the authors interpret the Moho to be at different depths: Bohnhoff & Makris (2004)

suggested a depth of 23 km, whereas Richardson *et al.* (1998) and Smallwood *et al.* (1999) inferred 40 and 35 km, respectively. This represents a variation in the interpreted depth to the Moho of 17 km at the same position, which raises some doubt as to the reliability of the data.

A high free-air anomaly triple junction structure is seen north of the Faroe Islands. One leg crosses eastwards along the western part of the Fugloy Ridge, the second leg is crosses the northern Faroe Platform area and the third leg runs along the SE edge of the IFR (Fig. 2a). The values of the high free-air anomaly triple junction area range from 60 to 70 mGal (Fig. 2a). On the central IFR, just west of the third leg of the triple junction structure, a NW–SE-trending low free-air anomaly area with values down to 10 mGal can be seen.

The triple junction structure is not as clear on the Bouguer anomaly map (Fig. 2b), most probably due to the high values of the Norwegian Basin (up to 90 mGal), but the NW–SE-trending low gravity anomaly values on the central southern IFR can be seen, with values down to 40 mGal (Fig. 2).

Faroe Platform (including the Fugloy and Munkagrunnur ridges)

On the Faroe Platform, volcanic material crops out onshore of the Faroe Islands, as well as at the seabed on the adjacent continental shelf, including the Fugloy and Munkagrunnur ridges. Offshore, there is a general lack of seismic reflection data, and what is available is of poor quality (a consequence of the low signal-to-noise ratio caused by the volcanic sequence): thus, a detailed interpretation of the sub-volcanic geology is not possible. By way of contrast, there exists a detailed description of the onshore volcanic succession, which is up to 6.6 km thick, and has been described from a combination of outcrop and well data (e.g. Lopra-1, Glyvursnes-1 and Vestmanna-1) (Figs 1–4).

Stratigraphy

Post-volcanic. On the Faroe Platform, the post-volcanic stratigraphy wholly comprises Quaternary glacial and post-glacial deposits (Jørgensen & Rasmussen 1986).

Volcanic. The onshore volcanic sequence is assigned to the Faroe Islands Basalt Group (FIBG), which is divided into seven formations, comprising (in ascending order): the Lopra, Beinisvørð, Prestfjall, Hvannhagi, Malinstindur, Sneis and Enni formations (Fig. 3) (Passey & Jolley 2009). The Lopra Formation is dominated by volcaniclastic and hyaloclastic rocks containing microfossils indicative of a marine environment, whereas the Beinisvørð, Malinstindur and Enni formations are

dominated by basaltic lava flows indicative of an overall terrestrial environment (Rasmussen & Noe-Nygaard 1969, 1970; Berthelsen *et al.* 1984; Passey & Bell 2007; Passey 2009). The basaltic formations are separated by three sedimentary units: the Prestfjall and Hvannhagi formations, which lie between the Beinisvørð Formation and the Malinstindur Formation, and the Sneis Formation, which separates the Malinstindur and Enni formations. These sedimentary units were deposited during significant breaks in the eruption of the lava flows (Passey & Bell 2007). The Prestfjall Formation is a coal-bearing sedimentary sequence (Ellis *et al.* 2002; Passey & Bell 2007); the Hvannhagi Formation comprises interbedded basaltic tuffs and volcaniclastic sedimentary lithologies (Passey & Bell 2007); and the Sneis Formation consists of epivolcaniclastic mass-flow deposits (Passey 2009). On the basis of radiometric dating and biostratigraphical data, the FIBG is of Paleocene–earliest Eocene age (*c.* 61.0–54.5 Ma) (Waagstein 1988; Waagstein *et al.* 2002; Storey *et al.* 2007; Passey & Jolley 2009; Passey & Hitchen 2011; Mudge 2015) (Figs 3 & 5).

Pre-volcanic. The refraction seismic lines of White *et al.* (2003) and Raum *et al.* (2005) cross the crustal transect in the Faroe Platform area in the central part of transect section 7 and in the northern part of transect section 8, and a pre-volcanic sedimentary layer, up to 2 km thick, has been inferred. In contrast, in the southern part of transect section 6, Richardson *et al.* (1998) and Pálmason (1965) – who shot onshore refraction lines – did not interpret a pre-volcanic sedimentary layer, though their studies were more focused on defining the top of the basement.

Structure. Aspects of the structure of the Faroe Platform can be discerned at several levels: (1) a broad pattern of folding is evident from the gravity data, together with the structural disposition of some of the volcanic formations in the FIBG; (2) fault analysis on the Faroe Islands provides an insight into extensional stresses that have affected the platform; and (3) seismic refraction data provide information on the depths to basement and the Moho.

The gravity anomalies in the area show variations in the free-air and Bouguer anomalies across the Faroe Platform that could suggest a pattern of domes and troughs (Figs 2 & 4). Both free-air and Bouguer anomaly gravity data show low values in the NW and southern part of the islands (Saxov & Abrahamsen 1964; Saxov 1966). The free-air and the Bouguer gravity values in the NW part of the Faroe Islands are −20 and −15 mGal, respectively, while the values in the southern part of the islands are 10 and 20 mGal, respectively. The gravity

values in the area between these two low gravity areas (in the central part of the Faroe Islands) range up to 30 mGal for both free-air and Bouguer (Figs 2 & 4). From the onshore stratigraphy, the doming structure in the southern part of the Faroe Islands (Waagstein 1988; Andersen *et al.* 2002; Ólavsdóttir *et al.* 2013) can be observed from the structural disposition of the A-horizon (the unconformable boundary between the Prestfjall and Beinisvørð formations: Figs 3 & 4a) where section 7 and 8 intersect, whereas part of the doming structure in the NW part of the Faroe Islands can be seen in section 6 (Fig. 4a). These domal structures are coincident with the low gravity areas.

In terms of shallow brittle deformation of the Faroe Platform, a preferred orientation and evolution of faults, fractures and dykes onshore the Faroe Islands has been noted by various authors (e.g. Rasmussen & Noe-Nygaard 1969; Geoffroy *et al.* 1994; Walker *et al.* 2011; Ziska 2012). In summary, the fracture pattern reveals a progressive anti-clockwise rotation of extension vectors from NE–SW/east–west to NW–SE immediately prior to and following early Palaeogene continental break-up in this area. The significance of this evolutionary trend is that immediately prior to break-up there was a distinct period of margin-parallel extension, which might have implications for NW–SE-trending sub-volcanic basins/rifts on the platform (see the Discussion later in this paper).

In terms of the deeper structure, a number of refraction seismic lines cross section 5 and the offshore part of section 7 (Richardson *et al.* 1998; Smallwood & White 2002; White *et al.* 2002; Raum *et al.* 2005) (Figs 1b & 4). Of particular note is the interpretation of the FIRE line (Richardson *et al.* 1998; Smallwood & White 2002), which crosses the western part of section 5 of the transect. At this position, the depth to crust is interpreted to be 6 km, while the depth to Moho is interpreted to be 43 km in both of these studies cases. Onshore seismic refraction data suggests that depth to basement is between 3 and 6 km (Pálmason 1965) (Figs 1b & 4).

The extension of the Faroe Platform area to the east and south incorporates two major antiformal structures: the Fugloy Ridge and the Munkagrunnur Ridge. On both of these ridges, the volcanic sequence crops out at the seabed, which results in poor seismic resolution. On the southern part of the Munkagrunnur Ridge, the free-air and the Bouguer gravity data show values up to 60 and 70 mGal, respectively, while the northern part of the ridge has lower values of 20 and 30 mGal, respectively (Fig. 2). This low gravity area is an extension of the low gravity area in the southern part of Faroe Platform, where the island of Suðuroy is situated, and has an overall NW–SE trend. Seismic

refraction lines across the Munkagrunnur Ridge indicate a pre-volcanic sediment thickness of up to 4.5 km beneath the western part of the ridge, whereas the volcanic sequence has a thickness of approximately 500–2000 m (White *et al.* 2003). Funck *et al.* (2014) have suggested that the remnants of two pre-break-up volcanoes are preserved on both the eastern and western flanks of the central part of Munkagrunnur Ridge. This interpretation is supported by the high free-air and Bouguer gravity anomalies (Hitchen & Ritchie 1987) of the southern part of the ridge, which range from 50 to 70 mGal (Hitchen & Ritchie 1987).

On the Fugloy Ridge, the western part of the ridge has free-air values of up to 50 mGal, whereas the eastern end displays lower values down to 10 mGal (Fig. 2). On the basis of refraction seismic lines crossing the Fugloy Ridge close to its junction with the Faroe Platform, it has been suggested that Cretaceous and pre-Cretaceous sediments are present below the outcropping volcanic sequence (Raum *et al.* 2005). According to various authors, the Fugloy Ridge has been shaped, at least in part, by contractional deformation, especially during the Miocene (Boldreel & Andersen 1993, 1998; Ólavsdóttir *et al.* 2013), and particularly along the eastern part of the ridge where low gravity values are indicated. However, its deeper interpretation remains ambiguous. The possibility that the ridge is entirely basement-cored has been proposed by Keser Neish (2004) and Ritchie *et al.* (2011).

Faroe–Shetland Basin

Stratigraphy

Post-volcanic. Reactivation of older, Palaeozoic and Mesozoic, structural elements such as the lineaments seem to control the sediment pathways and restrict the depositional areas because the basement highs act as obstacles (Ólavsdóttir *et al.* 2013).

The post-volcanic deposits in the Faroese sector of the Faroe–Shetland Basin have been divided into the following five regional formations/units (1–5) (Ólavsdóttir *et al.* 2013): (1) Lower–Middle Eocene; (2) Upper Eocene–Oligocene; (3) Early Miocene; (4) Middle Miocene–Lower Pliocene; and (5) Lower Pliocene–Holocene (Fig. 5c, d). It is clear that the sediment thickness is significant in the sub-basins, such as Annika, Corona, Guðrun and Steinvør, where the thickness ranges up to 1500, 3500, 2000 and 2000 m, respectively, while the post-volcanic sediments thin out against the ridges (e.g. the East Faroe, Heri, Sjúrður and Tróndur highs), where the thickness ranges up to approximately 1000 m.

Unit 1 is found across the entire Faroe Shetland area, but is thicker in the central part of the Faroe–Shetland Basin east of East Faroe High (Fig. 5c & d). The maximum thickness of Unit 1 is in the Corona Sub-basin, where it has a thickness of approximately 2000 m. Unit 2 appears across almost the entire area, except in the Judd Sub-basin. The maximum thickness of Unit 2 is in the Guðrun Sub-basin, where it has a thickness of 1200 m (Ólavsdóttir *et al.* 2013) (Fig. 5c, d).

Unit 3 is mostly concentrated in the NE part of the Faroese section of the Faroe–Shetland Basin (Fig. 5c, d), with a maximum thickness of 800 m in the Steinvør Sub-basin (Ólavsdóttir *et al.* 2013). Unit 4 has been encountered more sporadically across the Faroe–Shetland Basin (Fig. 5c, d) (Ólavsdóttir *et al.* 2013). The lack of preservation may be controlled by the sub-basin inversion affecting the areas during Miocene time (e.g. Annika, Brinhild, Grimhild and Guðrun sub-basins).

Unit 5 is highly concentrated in the Annika Sub-basin (Fig. 5c, d), with a thickness of 500 m, and forms part of a regional sediment wedge that progrades eastwards from the Faroe Platform, and downlaps and thins into the central part of Faroe–Shetland Basin (Ólavsdóttir *et al.* 2013).

Volcanic. Volcanic rocks underlie most of the Faroe–Shetland Basin, with the exception of the Judd Sub-basin, although, even in this region, the rocks are heavily intruded by sills. There are no wells in the Annika Sub-basin, therefore it is not possible to say much about the composition or thickness of the volcanic sequence in this area. However, Raum *et al.* (2005) have suggested a thickness of up to 3000 m on the basis of refraction seismic data (Fig. 4a). On the East Faroe High, well 6104/21-1 drilled approximately 3000 m of volcanic rocks without reaching the base of the succession (Fig. 4a). On the Mid Faroe High, well 6004/8a-1 drilled a thick pile of volcanic material with a thickness of 1300 m. Information from these two wells further indicates that only approximately 20–25% of the volcanic material is sub-areal basalt: most of the material is volcaniclastic, of which hyaloclastite deposits form an important component, and is especially concentrated towards the base of the succession. A significant volcaniclastic component is also characteristic of the volcanic stratigraphy proved in the Lopra-1 well (Fig. 1), where the lowermost 1000 m of the drilled succession consists of hyaloclastites.

Pre-volcanic. Refraction seismic data from the Faroese part of the Faroe–Shetland Basin suggest that there is a low-velocity layer under the volcanic sequence (White *et al.* 2003; Raum *et al.* 2005). This sequence is further interpreted to be heavily intruded by sills, with an approximate thickness of 2000 m in the Annika Sub-basin, but possibly with an thickness of between 6000 and 7000 m further

towards the SE (Raum *et al.* 2005) (Fig. 4a). However, it should be noted that none of the wells so far drilled in the Faroese part of the Faroe–Shetland Basin have penetrated deeper than early Paleocene strata.

Structure. The arrangement of sub-basins and highs that form part of the Faroe–Shetland Basin (Fig. 1) was established by Keser Neish (2004) and Ritchie *et al.* (2011). However, this structural pattern remains to be improved, as the seismic data available for the current interpretation were of poor quality. Potential field data have provided some additional insights into the structural configuration. The gravity anomaly pattern in the Faroe–Shetland Basin is similar to the domes and troughs described from the Faroe Platform. In the Faroe–Shetland Basin, the existence of such a fold pattern is confirmed by seismic data throughout the basin (including the UK sector) where numerous antiforms and synforms have been reported (Sørensen 2003; Johnson *et al.* 2005; Ólavsdóttir *et al.* 2013). In the Faroe–Shetland Basin, some of these antiforms are situated in low gravity areas displaying a NE–SW trend, such as in the Annika, Brinhild, Corona, Grimhild, Guðrun, Judd and Steinvør sub-basins (Figs 1, 2 & 3b), and the age of these dome structures ranges from the Eocene to the Miocene. Other dome structures are situated on high gravity areas such as the Corona, East Faroe, Mid Faroe and Tróndur highs (Figs 1, 2 & 3b). Ritchie *et al.* (2011) interpreted these areas as basement structural high areas. These basement structural high areas are displaying an overall NE–SW trend.

In terms of the deeper structure, Raum *et al.* (2005) suggested that depth to crystalline basement in the northern part of the Annika Sub-basin is 8 km (Figs 1b & 4a): in the central part of the sub-basin, however, another refraction seismic line from the same authors suggests a depth to basement of approximately 5.5 km. In the Judd Sub-basin, the depth to top basement has been estimated at approximately 9 km (Fig. 4a) (Raum *et al.* 2005). To date, no well in the Faroese sector of the Faroe–Shetland Basin has drilled into crystalline basement.

Discussion

Whereas the syn- to post-break-up development of the Faroese continental margin, NE Atlantic Ocean, is fairly well documented, the widespread and commonly thick cover of the Paleocene–Early Eocene FIBG hinders our understanding of its pre-break-up structural and geological framework. In terms of the pre-break-up setting, the following discussion focuses on the key observations and interpretations regarding the nature and character of the sub-basalt (FIBG) crustal structure and stratigraphical framework; we will also address the issue of the ambiguity of the definition of the COT on the IFR.

Sub-basalt (FIBG) crustal structure and stratigraphical framework

The compilation – based on seismic refraction data – of the shallow crustal structure underlying the Faroese continental margin presented in Figure 3 provides a variable interpretation of the sub-basalt geology (Richardson *et al.* 1998, 1999; Smallwood & White 2002; White *et al.* 2003; Bohnhoff & Makris 2004; Raum *et al.* 2005; Funck *et al.* 2008). The compilation has focused on the boundary between the 'basement' and an overlying low-velocity layer, which immediately underlies the FIBG and its lateral correlatives in the Faroe–Shetland Basin and on the IFR. This interpretation is most robust in the area between the central Faroe Platform (including the Faroe Islands) and the Faroe–Shetland Basin. This is consistent with the basement depth model shown in Funck *et al.* (2014) based on several refraction seismic lines in the Faroe–Shetland Basin: however, their model is based on no data coverage in the Faroe Platform area. In contrast, the presence of a low-velocity layer below the NW part of the Faroe Platform and, indeed, the very nature of the shallow crustal layer below the SE part of the IFR remain equivocal. Indeed, this ambiguity even extends to the deeper crustal levels beneath the IFR, where a difference of up to 17 km has been reported for the depth to the Moho (Richardson *et al.* 1998; Smallwood *et al.* 1999; Bohnhoff & Makris 2004). This highlights a variable degree of reliability attached to the interpretation of refraction seismic data, whereby contrasting and conflicting interpretations of the different surveys (and even between interpretations of the same dataset obtained by various researchers) are common. The 370 km-long ISFA profile illustrated by Bohnhoff & Makris (2004) has 43 ocean-bottom seismometer (OBS) stations located perpendicular to the Iceland–Faroe Ridge over a 370 km-long distance where they shoot a 60 l sleeve gun every 250 m along the profile. The FIRE profile illustrated in the work of Richardson *et al.* (1998) and Smallwood *et al.* (1999) has seven OBH stations placed along the Iceland–Faroe Ridge, along which they shot a 9324 in[3] airgun every 75 m. The depth to the Moho in the two studies of the FIRE line are more equal (5 km difference) than with the ISFA profile, where the difference is 12 and 17 km, respectively. The variation in the depth to the Moho in these two profiles could be caused by the difference in line orientation, the variation in the number of OBH/OBS and/or the difference in the size of the airguns/sleeve guns that were used. In addition, the perceived starting model for

each study might be different, which might impact on the way in which the study concludes. Such a variation in the results of these refraction data highlights the continuing ambiguity of these types of study.

The basement shown in Figure 3 is generally defined as 'crystalline basement' (Raum *et al.* 2005). The probable composition of this upper-crustal layer is informed by well and outcrop data from the adjacent UK West Shetland area and the East Greenland Kangerlussuaq area, between which the Faroe Islands is commonly placed in pre-break-up reconstructions (e.g. Larsen & Whitham 2005). In the UK sector of the Faroe–Shetland Basin, crystalline basement has been proven in a number of wells to the west and north of Shetland. West of Shetland, the crystalline basement consists predominantly of Archaean rocks (Lewisian Gneiss), which have been assigned the term 'Faroe–Shetland Block' as an indicator of the crustal domain (Skogseid *et al.* 2000). In eastern Greenland, exposed gneissic basement of Archean age is also described from the Kangerlussuaq region (Larsen *et al.* 2006). This forms part of the Archaean–Proterozoic Central Greenland Craton, and has been suggested as a correlative of the Faroe–Shetland Block (Skogseid *et al.* 2000). A separate crustal domain to the north of Shetland, termed the Erlend–East Shetland Block, comprises a mixed Late Archaean–Proterozoic assemblage, with a predominance of Proterozoic ages. The wider correlation of this crustal block is more enigmatic, and could suggest a correlation with the Central Greenland Craton or, possibly, the East Greenland Terrane, located to the north (Doré *et al.* 1999; Skogseid *et al.* 2000).

As noted earlier, the low-velocity layer beneath the volcanic sequence and the top of basement is interpreted fairly consistently between the central part of the Faroe Platform and the Faroe–Shetland Basin (Fig. 4). Raum *et al.* (2005) estimated that this layer ranges from being 2 km thick below the Faroe Platform to a maximum of 8 km in thickness in the Faroe–Shetland Basin. In comparison with the UK sector of the Faroe–Shetland Basin, the composition of the low-velocity layer has been attributed to the occurrence of Upper Palaeozoic–Mesozoic sedimentary rocks. Cretaceous rocks up to 5 km thick have been proved in the UK sector, together with varying thicknesses of Jurassic, Permo-Triassic and Devono-Carboniferous rocks (Ritchie *et al.* 2011; Ellis & Stoker 2014). The continuation of the low-velocity layer beneath the NW part of the Faroese continental margin (and, possibly, on to the SE part of the IFR?) remains uncertain, although the occurrence of Mesozoic basins on the outermost part of the Rockall–Hatton margin, to the SW of the study area (Ellis & Stoker 2014), indicates that there is no reason why a similar

arrangement of basins might not exist beneath the NW Faroe Platform, or even the Fugloy Ridge (cf. Raum *et al.* 2005). One important implication of this scenario is the definition of the western margin of the Faroe–Shetland Basin. The current structural framework (i.e. Ritchie *et al.* 2011) locates the boundary of the basin along the margins of the Fugloy and Munkagrunnur ridges (Figs 1 & 2). However, as described previously, these are late-stage (post-break-up) antiformal structures (Johnson *et al.* 2005; Ritchie *et al.* 2008). If basins do exist to the west of the currently accepted boundary, this might warrant a reappraisal of the definition of the Faroe–Shetland Basin.

Support for sub-volcanic basins beneath the Faroe Platform, the Munkagrunnur Ridge and the IFR is provided by the regional gravity maps, which show that there are indications of two NW–SE-trending low gravity areas that could be indicative of sub-basins. Inspection of Figure 2b shows one of these NW–SE-trending gravity lows extending between the area NW of Mykines towards Suðuroy in the SE to the central Munkagrunnur Ridge area; and a second gravity low running between the Annika Sub-basin across the Heri High, the Brynhild Sub-basin and the Sjúrður High into the Judd Sub-basin. These two low gravity areas are sub-parallel and separated by a higher gravity area situated east of the Faroe Islands. A third trending gravity low area can be seen on the SE area of the IFR. One could speculate that the trend of these gravity lows – if they represent sub-volcanic basins – reflects the pre-break-up phase of margin-parallel extension proposed by Geoffroy *et al.* (1994), Lundin & Doré (2005), Walker *et al.* (2011) and Ziska (2012).

Evidence in favour of the southern part of the Faroe Islands/Platform being a former sub-basin can be found in the bottom of the Lopra-1 well, which penetrated through 1000 m of marine hyaloclastic deposits (Ellis *et al.* 2002). Overlying the hyaloclastites is subareal volcanic material dated to an age of approximately 61 Ma (Storey *et al.* 2007). This suggests that such a basin could have acted as a depocentre for pre- and syn-break-up material (Cretaceous–early Paleocene) prior to burial beneath the widespread subareal volcanic rocks. It is interesting to note that traces of hydrocarbons were recorded in samples from the Beinisvørð Formation in Vágoy and Suðuroy (White 1989; Smallwood *et al.* 1999). Smallwood *et al.* (1999) suggested that these hydrocarbons were probably generated from a marine shale source rock, perhaps with a slight marly character, at early to peak oil-window maturity where the age of the source rock is suggested to be Jurassic or younger.

Seismic reflection interpretation throughout the Faroe–Shetland Basin indicates that all of the

sub-basins – whether pre- or post-volcanic – in the Faroese part of the Faroe–Shetland Basin were inverted during the Eocene–Holocene (Ólavsdóttir *et al.* 2013). In terms of the possible NW-trending pre-volcanic basins described previously, the area west of the island of Mykines, and in the area where Suðuroy is situated, have been up-lifted more than the surrounding areas of the Faroe Platform (Fig. 4) during Miocene–Pliocene time, and have since been affected by erosion of approximately 2000 and 700 m, respectively (Jørgensen 1984, 2006; Andersen *et al.* 2002). Further east, the Annika and Brynhild sub-basins were inverted during the Miocene, and the Heri High was formed at this time. This raises the possibility that this 'structural high', as depicted by Ritchie *et al.* (2011), might be more accurately described as a domal structure formed during the inversion process.

Continent–ocean transition on the Iceland–Faroe Ridge

As described earlier, the vertical layering of basal-tic flows from different magnetic polarity chrons has prevented the delineation of a simple pattern of seafloor-spreading anomalies on the IFR: thus, the definition of the COT on the NW margin of the Faroe Islands remains equivocal. The refraction seismic models of Smallwood & White (2002) and Bohnhoff & Makris (2004) suggest crustal thicknesses in excess of 20–30 km in the area north of the currently interpreted COT. On the basis of this modelling, it could be speculated that continental crust extends almost to transect section 1 (Fig. 4). The implication of this is that the southern part of the IFR is an extension of continental crust rather than oceanic crust (Bohnhoff & Makris 2004). In the area SE of Iceland, Torsvik *et al.* (2015) suggested that this part of the IFR is old continental crust with a thickness in excess of 30 km, although the central part of the IFR might be thinner (20 km) (Smallwood *et al.* 1999; Smallwood & White 2002).

The potential admixture or juxtaposition of continental and oceanic (e.g. the SDR sequences) crustal elements on the IFR invites speculation on the general origin of the GIFR. The GIFR is commonly referred to as a Paleocene–Holocene plume track of the Iceland 'hotspot' (e.g. (White 1989; Skogseid *et al.* 2000), despite the fact that it is not time-transgressive in one direction as the Iceland 'hotspot' has never been positioned below the IFR side of the GIFR (Lundin & Doré 2002, 2005; Foulger 2010), except if the hotspot is situated around the spreading ridge all the time, which is probably untenable. As an alternative, Ellis & Stoker (2014) have suggested that the GIFR was formed by purely plate tectonic mechanisms, with

lithospheric thinning and variable decompressive upper-mantle melting being facilitated by trans-tension along a NW-trending rift that extended between Kangerlussuaq (East Greenland) and the Faroe region. The inclusion of continental fragments within this zone of transtension might have been linked to the complex break-up between East Greenland, Jan Mayen and NW Europe.

Conclusions

Key conclusions from this appraisal of regional geological and geophysical data from the Faroes continental margin include the following:

- Seismic refraction studies suggest that the pre-break-up structure of the Faroese continental margin comprises a low-velocity layer overlying 'basement'. The latter most probably consists of Archaean crystalline rocks, as in pre-break-up reconstructions the Faroe region would have been part of the Central Greenland Craton–Faroe–Shetland Block. The low-velocity layer is inferred to comprise Upper Palaeozoic–Mesozoic strata, although, in common with the adjacent UK sector, this succession is probably dominated by Cretaceous rocks.

- The regional gravity maps indicate NW–SE-trending gravity low areas on and adjacent to the Faroe Platform, as well as the IFR, which might represent pre-break-up sub-volcanic basins. These basins might have acted as depocentres for pre- and syn-break-up Cretaceous–Early Paleocene material, including hyaloclastite deposition that preceded the widespread extrusion of subareal basalts.

- The Faroe Islands Basalt Group (FIBG) represents the syn-break-up phase that led to seafloor spreading to the NW of the Faroe Islands at about 54.5 Ma. The combination of radiometric and biostratigraphic data suggests that this occurred in the interval between approximately 61 and 54.5 Ma (i.e. Mid-Paleocene–earliest Eocene).

- The post-break-up development of the Faroese continental margin has been dominated by contractional deformation, which has contributed to the creation of the present-day large-scale bathymetry of the Faroe–Shetland region, including the Fugloy and Munkagrunnur ridges. The preserved pattern of sedimentation is a response to these vertical movements. The combination of gravity and refraction seismic data suggests that present-day highs, such as the Fugloy and Heri highs, might represent inverted basins.

- The identification of the continent–ocean transition (COT) on the IFR remains equivocal. The generally thick crust below the IFR, together

with the absence of well-defined SDRs, might be an indication that much of the IFR is underlain by continental material.

Reference

Á HORNI, J., GEISSLER, W.H. *ET AL.* 2014. Offshore volcanic facies. *In*: HOPPER, J.R., FUNCK, T., STOKER, M.S., ÁRTING, U., PERON-PINVIDIC, G., DOORNENBAL, H. & GAINA, C. (eds) *Tectonostratigraphic Atlas of the North-East Atlantic Region*. Geological Survey of Denmark and Greenland (GEUS), Copenhagen, 235–253.

ANDERSEN, M.S., NIELSEN, T., SØRENSEN, A.B., BOLDREEL, L.O. & KUIJPERS, A. 2000. Cenozoic sediment distribution and tectonic movements in the Faroe region. *Global and Planetary Change*, **24**, 239–259, https://doi.org/10.1016/s0921-8181(00)00011-4

ANDERSEN, M.S., SØRENSEN, A.B., BOLDREEL, L.O. & NIELSEN, T. 2002. Cenozoic evolution of the Faroe Platform: comparing denudation and deposition. *In*: DORÉ, A.G., CARTWRIGHT, J.A., STOKER, M.S., TURNER, J.P. & WHITE, N. (eds) *Exhumation of the North Atlantic Margin: Timing, Mechanisms and Implications for Petroleum Exploration*. Geological Society, London, Special Publications, **196**, 291–311, https://doi.org/10.1144/GSL.SP.2002.196.01.16

ARCHER, S.G., BERGMAN, S.C., ILIFFE, J., MURPHY, C.M. & THORNTON, M. 2005. Palaeogene igneous rocks reveal new insights into the geodynamic evolution and petroleum potential of the Rockall Trough, NE Atlantic Margin. *Basin Research*, **17**, 171–201, https://doi.org/10.1111/j.1365-2117.2005.00260.x

BERTHELSEN, O., NOE-NYGAARD, A. & RASMUSSEN, J. 1984. The Deep Drilling Project 1980–1981 in the Faeroe Islands. *Annales Societatis Scientiarum Færoensis, Supplementum*, **9**.

BOHNHOFF, M. & MAKRIS, J. 2004. Crustal structure of the southeastern Iceland-Faeroe Ridge (IFR) from wide aperture seismic data. *Journal of Geodynamics*, **37**, 233–252.

BOLDREEL, L.O. & ANDERSEN, M.S. 1993. Late Paleocene to Miocene compression in the Faeroe–Rockall area. *In*: PARKER, J.R. (ed.) *Petroleum Geology of Northwest Europe: Proceedings of the 4th Conference*. Geological Society, London, 1025–1034.

BOLDREEL, L.O. & ANDERSEN, M.S. 1998. Tertiary compressional structures on the Faroe–Rockall Plateau in relation to northeast Atlantic ridge-push and Alpine foreland stresses. *Tectonophysics*, **300**, 13–28, https://doi.org/10.1016/s0040-1951(98)00231-5

DILJITH, D.T., KUMAR, N. & SINGH, B. 2008. Imaging of sub-basalt geology in the Deccan Volcanic Province of cental India from gravity studies. *In*: *Proc. SPG 7th International Conference & Symposium on Petroleum, Geophysics*, 14–16 January 2008, Hyderabad, India, 346–351.

DORÉ, A.G., LUNDIN, E.R., JENSEN, L.N., BIRKELAND, Ø., ELIASSEN, P.E. & FICHLER, C. 1999. Principal tectonic events in the evolution of the northwest European Atlantic margin. *In*: FLEET, A.J. & BOLDY, S.A.R. (eds) *Petroleum Geology of Northwest Europe – Proceedings of the 5th Conference*. Geological Society, London, 41–61.

DORÉ, A.G., LUNDIN, E., KUSZNIR, N.J. & PASCAL, C. 2008. Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: pros, cons and some new ideas. *In*: JOHNSON, H., DORÉ, A.G., GATLIFF, R.W., HOLDSWORTH, R., LUNDIN, E. & RITCHIE, J.D. (eds) *The Nature and Origin of Compression in Passive Margins*. Geological Society, London, Special Publications, **306**, 1–26, https://doi.org/10.1144/SP306.1

ELLIS, D. & STOKER, M.S. 2014. The Faroe–Shetland Basin: a regional perspective from the Paleocene to the present day and its relationship to the opening of the North Atlantic Ocean. *In*: CANNON, S.J.C. & ELLIS, D. (eds) *Hydrocarbon Exploration to Exploitation West of Shetlands*. Geological Society, London, Special Publications, **397**, 11–31, https://doi.org/10.1144/SP397.1

ELLIS, D., BELL, B.R., JOLLEY, D.W. & O'CALLAGHAN, M. 2002. The stratigraphy, environment of eruption and age of the Faroes Lava Group, NE Atlantic Ocean. *In*: JOLLEY, D.W. & BELL, B.R. (eds) *The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes*. Geological Society, London, Special Publications, **197**, 253–269, https://doi.org/10.1144/GSL.SP.2002.197.01.10

FOULGER, G. 2002. Plumes, or plate tectonic processes? *Astronomy and Geophysics*, **43**, 19–23.

FOULGER, G. 2010. *Plates vs Plumes: A Geological Controversy*. Wiley-Blackwell, Oxford.

FUNCK, T., ANDERSEN, M.S., NEISH, J.C.K. & DAHL-JENSEN, T. 2008. A refraction seismic transect from the Faroe Islands to the Hatton–Rockall Basin. *Journal of Geophysical Research*, **113**, B12405, https://doi.org/10.1029/2008JB005675

FUNCK, T., HOPPER, J.R. *ET AL.* 2014. Crustal structure. *In*: HOPPER, J.R., FUNCK, T., STOKER, M.S., ÁRTING, U., PERON-PINVIDIC, G., DOORNENBAL, H. & GAINA, C. (eds) *Tectonostratigraphic Atlas of the North-East Atlantic Region*. Geological Survey of Denmark and Greenland (GEUS), Copenhagen, 69–126.

GANERØD, M., SMETHURST, M.A. *ET AL.* 2010. The North Atlantic Igneous Province reconstructed and its relation to the Plume Generation Zone: the Antrim Lava Group revisited. *Geophysical Journal International*, **182**, 183–202, https://doi.org/10.1111/j.1365-246X.2010.04620.x

GANERØD, M., WILKINSON, C.M. & HENDRIKS, H. 2014. Geochronology. *In*: HOPPER, J., FUNCK, T., STOKER, M.S., ÁRTING, U., PÉRON-PINVIDIC, G., DOORNENBAL, H. & GAINA, C. (eds) *NAG-TEC Atlas: Tectonostratigraphic Atlas of the North-East Atlantic Region*. Geological Survey of Denmark and Greenland (GEUS), Copenhagen, 253–261.

GEOFFROY, L., BERGERAT, F. & ANGELIER, J. 1994. Tectonic evolution of the greenland-Scotland ridge during the Paleogene: new constraints. *Geology*, **22**, 653–656.

GERNIGON, L., GAINA, C., OLESON, O., BALL, P.J., PÉRON-PINVIDIC, G. & YAMASAKI, T. 2012. The Norway Basin revisited: from continental breakup to spreading ridge extinction. *Marine and Petroleum Geology*, **35**, 1–19, https://doi.org/10.1016/j.marpetgeo.2012.02.015

GRADSTEIN, F.M., OGG, J.G., SCHMITZ, M.D. & OGG, G.M. 2012. *The Geologic Time Scale*. Elsevier, Amsterdam.

HAASE, C. & EBBING, J. 2014. Gravity data. *In*: HOPPER, J.R., FUNCK, T., STOKER, M.S., ÁRTING, U., PÉRON-PINVIDIC, G., DOORNENBAL, H. & GAINA, C. (eds) *NAG-TEC Atlas: Tectonostratigraphic Atlas of the North-East Atlantic Region*. Geological Survey of Denmark and Greenland (GEUS), Copenhagen, 29–39.

HITCHEN, K. & RITCHIE, J.D. 1987. Geological review of the West Shetland area. *In*: BROOKS, J. & GLENNIE, K.W. (eds) *Petrouleum Geology of Northwest Europe, Proceedings of the 3rd Conference*. Graham & Trotman, London, 737–749.

JOHNSON, H., RITCHIE, J.D., HITCHEN, K., MCINROY, D.B. & KIMBELL, G.S. 2005. Aspects of the Cenozoic deformational history of the Northeast Faroe–Shetland Basin, Wyville–Thomson Ridge and Hatton Bank areas. *In*: DORÉ, A.G. & VINING, B.A. (eds) *Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference*. Geological Survey, London, 993–1007.

JØRGENSEN, G. & RASMUSSEN, J. 1986. Glacial striae, roches moutonnées and ice movements in the Faroe Islands. *Danmarks Geologiske Undersøgelse*, DGU Series C, No. 7.

JØRGENSEN, O. 1984. Zeolite zones in the basaltic lavas of the Faeroe Islands. *In*: BERTHELSEN, O., NOE-NYGAARD, A. & RASMUSSEN, J. (eds) *The Deep Drilling Project 1980–1981 in the Faeroe Islands*. Føroya Fróðskaparfelag (Faroese Scientific Society), Tórshavn, Faroe Islands, 71–91.

JØRGENSEN, O. 2006. The regional distribution of zeolites in the basalts of the Faroe Islands and the significance of zeolites as palaeotemperature indicators. *In*: CHALMERS, J.A. & WAAGSTEIN, R. (eds) *Scientific Results from the Deepened Lopra-1 Borehole, Faroe Islands*. Geological Survey of Denmark and Greenland (GEUS), Copenhagen, 123–156.

KESER NEISH, J. 2004. *A Standard Structural Nomenclature System*. Faroese Geological Survey, Tórshavn.

KESER NEISH, J. & ZISKA, H. 2005. Structure of the Faroe Bank Channel Basin, offshore Faroe Islands. *In*: DORÉ, A.G. & VINING, B.A. (eds) *Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference*. Geological Society, London, 873–885.

LARSEN, M. & WHITHAM, A. 2005. Evidence for a major sediment input point into the Faroe–Shetland Basin from Kangerlussuaq region of southern East Greenland. *In*: DORÉ, A.G. & VINING, B.A. (eds) *Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference*. Geological Society, London, 913–922.

LARSEN, M., KNUDSEN, C., FREI, D., FREI, M., RASMUSSEN, T. & WITHHAM, A.G. 2006. East Greenland and Faroe–Shetland sediment provenance and Palaeogene sand dispersal systems. *Geological Survey of Denmark and Greenland Bulletin*, **10**, 29–32.

LUNDIN, E. & DORÉ, A.G. 2002. Mid-Cenozoic postbreakup deformation in the 'passive' margins bordering the Norwegian–Greenland Sea. *Marine and Petroleum Geology*, **19**, 79–93, https://doi.org/10.1016/s0264-8172(01)00046-0

LUNDIN, E.R. & DORÉ, A.G. 2005. NE Atlantic break-up: a re-examination of the Iceland mantle plume model and the Atlantic–Arctic linkage. *In*: DORÉ, A.G. & VINING, B.A. (eds) *Petroleum Geology: North-West Europe and Global Perspectives – Proceedings of the 6th Petroleum Geology Conference*. Geological Society, London, 739–754.

MOY, D.J. & IMBER, J. 2009. A critical analysis of the structure and tectonic significance of rift-oblique lineaments ('transfer zones') in the Mesozoic–Cenozoic succession of the Faroe-Shetland Basin, NE Atlantic margin. *Journal of the Geological Society, London*, **166**, 831–844, https://doi.org/10.1144/0016-76492009-010

MUDGE, D.C. 2015. Regional controls on Lower Tertiary sandstone distribution in the North Sea and NE Atlantic margin basins. *In*: MCKIE, T., ROSE, P.T.S., HARTLEY, A.J., JONES, D.W. & ARMSTRONG, T.L. (eds) *Tertiary Deep-Marine Reservoirs of the North Sea Region*. Geological Society, London, Special Publications, **403**, 17–42, https://doi.org/10.1144/SP403.5

NIELSEN, T. & VAN WEERING, T.C.E. 1998. Seismic stratigraphy and sedimentary processes at the norwegian Sea margin northeast of the Faeroe Islands. *Marine Geology*, **152**, 141–157.

NILSEN, T.H. 1978. Lower Tertiary laterite on the Iceland-Faeroe Ridge and the Thulean land bridge. *Nature*, **274**, 786–788.

NILSEN, T.H. & KERR, D.R. 1978. Turbidites, redbeds, sedimentary structures and trace fossils observed in DSDP leg 38 cores and the sedimentary history of the Norwegian-Greenland Sea. *In*: *Deep Sea Drilling Project: Supplement to Volumes XXXVIII, XXXIX, XL and XLI*. Government Printing Office, Washington, DC, 259–288.

ÓLAVSDÓTTIR, J., BOLDREEL, L.O. & ANDERSEN, M.S. 2010. Development of a shelf margin delta due to uplift of Munkagrunnur Ridge at the margin of Faroe-Shetland Basin: a seismic sequence stratigraphic study. *Petroleum Geoscience*, **16**, 91–103, https://doi.org/10.1144/1354-079309-014

ÓLAVSDÓTTIR, J., ANDERSEN, M.S. & BOLDREEL, L.O. 2013. Seismic stratigraphic analysis of the Cenozoic sediments in the NW Faroe Shetland Basin – Implications for inherited structural control of

sediment distribution. *Marine and Petroleum Geology*, **46**, 19–35, https://doi.org/10.1016/j.marpetgeo.2013.05.012

ÓLAVSDÓTTIR, J., ANDERSEN, M.S. & BOLDREEL, L.O. 2015. Reservoir quality of intra-basalt volcaniclastic units onshore Faroe Islands, North Atlantic Igneous Province, NE Atlantic. *American Association of Petroleum Geologists Bulletin*, **99**, 467–497, https://doi.org/10.1306/08061412084

PÁLMASON, G. 1965. Seismic refraction measurements of the basalt lavas of the Faeroe Islands. *Tectonophysics*, **2**, 475–482.

PASSEY, S.R. 2009. *Recognition of a Faulted Basalt Lava Flow Sequence Through the Correlation of Stratigraphic Marker Units, Skopunarfjørður, Faroe Islands*. Annales Societatis Scientiarum Færoensis, Tórshavn.

PASSEY, S.R. & BELL, B.R. 2007. Morphologies and emplacement mechanisms of the lava flows of the faroe islands basalt group, faroe islands, NE atlantic ocean. *Bulletin of Volcanology*, **70**, 139–156, https://doi.org/10.1007/s00445-007-0125-6

PASSEY, S.R. & HITCHEN, K. 2011. Cenozoic (igneous). *In*: RITCHIE, J.D., ZISKA, H., JOHNSON, H. & EVANS, D. (eds) *Geology of the Faroe–Shetland Basin and Adjacent Areas. BGS Research Report, RR/11/01*. British Geological Survey, Keyworth, Nottingham, 209–228.

PASSEY, S.R. & JOLLEY, D.W. 2009. A revised lithostratigraphic nomenclature for the palaeogene Faroe Islands basalt Group, North Atlantic. *Earth and Environmental Science Transaction of the Royal Society of Edinburgh*, **99**, 127–158.

RAO, B.N., SINGH, B., SINGH, A.P. & TIWARI, V.M. 2013. Resolving sub-basalt Geology from Joint Analysis of Gravity and Magnetic Data over the Deccan Trap of Central India. *Geohorizons*, **18**, 57–63.

RASMUSSEN, J. & NOE-NYGAARD, A. 1969. *Beskrivelse til Geologisk Kort over Færøerne i målestok 1:50.000*. C. A. Reitzels Forlag (Jørgen Sandal), Copenhagen.

RASMUSSEN, J. & NOE-NYGAARD, A. 1970. *Geology of the Faroe Islands (Pre-Quaternary)*. (HENDERSON, G., trans.) Geological Survey of Denmark Series 1, **25**.

RAUM, T., MJELDE, R. *ET AL.* 2005. Sub-basalt structures east of the Faroe Islands revealed from wide-angle seismic and gravity data. *Petroleum Geoscience*, **11**, 291–308, https://doi.org/10.1144/1354-079304-627

RAY, A., WITTE, S. & MCALLISTER, E. 2010. Sicily Channel – integrated interpretation of gravity and magnetic data. *Paper presented at the EGM 2010 International Workshop*, 11–14 April 2010, Capri, Italy.

RICHARDSON, K.R., SMALLWOOD, J.R., WHITE, R.S., SNYDER, D.B. & MAGUIRE, P.K.H. 1998. Crustal structure beneath the Faroe Islands and the Faroe–Iceland Ridge. *Tectonophysics*, **300**, 159–180, https://doi.org/10.1016/s0040-1951(98)00239-x

RICHARDSON, K.R., WHITE, R.S., ENGLAND, R.W. & FRUEHN, J. 1999. Crustal structure east of the Faroe Islands: mapping sub-basalt sediments using wide-angle seismic data. *Petroleum Geoscience*, **5**, 161–172, https://doi.org/10.1144/petgeo.5.2.161

RITCHIE, J.D., JOHNSON, H., QUINN, M.F. & GATLIFF, R.W. 2008. Cenozoic compressional deformation within the Faroe–Shetland Basin and adjacent areas. *In*: JOHNSON, H., DORÉ, A.G., HOLDSWORTH, R.E., GATLIFF, R.W., LUNDIN, E.R. & RITCHIE, J.D. (eds) *The Nature and Origin of Compression in Passive Margins*. Geological Society, London, Special Publications, **306**, 121–136, https://doi.org/10.1144/SP306.5

RITCHIE, J.D., ZISKA, H., KIMBELL, G., QUINN, M. & CHADWICK, A. 2011. Structure. *In*: RITCHIE, J.D., ZISKA, H., JOHNSON, H. & EVANS, D. (eds) *Geology of the Faroe–Shetland Basin and Adjacent Areas. BGS Research Report, RR/11/01*. British Geological Survey, Keyworth, Nottingham, 9–70.

ROBERTS, A.W., WHITE, R.S. & CHRISTIE, P.A.F. 2009. Imaging igneous rocks on the North Atlantic rifted continental margin. *Geophysical Journal International*, **179**, 1024–1038, https://doi.org/10.1111/j.1365-246X.2009.04306.x

ROBERTS, D.G., THOMPSON, M., MITCHENER, B., HOSSACK, J., CARMICHAEL, S. & BJØRNSETH, H.-M. 1999. Palaeozoic to Tertiary Rift and Basin Dynamics: mid-Norway to the Bay of Biscay – a new context for hydrocarbon prospectivity in the deep water frontier. *In*: FLEET, A.J. & BOLDY, S.A.R. (eds) *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. Geological Society, London, 7–40.

SAUNDERS, A.D., FITTON, J.G., KERR, A.C., NORRY, M.J. & KENT, R.W. 1997. The North Atlantic Igneous Province. *In*: MAHONEY, J.J. & COFFIN, M.L. (eds) *Large Igneous Provinnce, Continental Oceanic, and Planetary Flood Volcanism*. American Geophysical Union, Geophysical Monographs, **100**, 45–93.

SAXOV, S. & ABRAHAMSEN, N. 1964. A Note on some gravity and density measurings in the Faroe Islands. *Bollettino di Geofisica Teorica ed Applicata*, **VI**, 249–262.

SAXOV, S. & ABRAHAMSEN, N. 1966. Some geophysical investigations in the Faroe Islands. A preliminary report. *Zeitschrift fur Geophysik*, **32**, 455–471.

SKOGSEID, J., PLAMKE, S., FALEIDE, J.I., PEDERSEN, T., ELDHOLM, O. & NEVERDAL, F. 2000. NE Atlantic continental rifting and volcanic margin formation. *In*: NØTTVEDT, A. (ed.) *Dynamics of the Norwegian Margin*. Geological Society, London, Special Publications, **167**, 295–326, https://doi.org/10.1144/GSL.SP.2000.167.01.12

SMALLWOOD, J.R. & WHITE, R.S. 2002. Ridge-plume interaction in the North Atlantic and its influence on continental breakup and seafloor spreading. *In*: JOLLEY, D.W. & BELL, B.R. (eds) *The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes*. Geological Society, London, Special Publications, **197**, 15–37, https://doi.org/10.1144/GSL.SP.2002.197.01.02

SMALLWOOD, J.R., STAPLES, R.K., RICHARDSON, K.R. & WHITE, R.S. 1999. Crust generated above the Iceland mantle plume: from continental rift to oceanic spreading center. *Journal of Geophysical Research*, **104**, 22,885–822,902.

SMALLWOOD, J.R., TOWNS, M.J. & WHITE, R.S. 2001. The structure of the Faeroe-Shetland Trough from integrated deep seismic and potential field modelling. *Journal of the Geological Society, London*, **158**, 409–412, https://doi.org/10.1144/jgs.158.3.409

SMITH, K. & ZISKA, H. 2011. Devonian and carboniferous. *In*: RITCHIE, J.D., ZISKA, H., JOHNSON, H. & EVANS, D. (eds) *Geology of the Faroe–Shetland Basin and*

Adjacent Areas. BGS Research Report, RR/11/01. British Geological Survey, Keyworth, Nottingham, 79–91.

SØRENSEN, A.B. 2003. Cenozoic basin development and stratigraphy of the Faroes area. *Petroleum Geoscience*, **9**, 189–207, https://doi.org/10.1144/1354-079302-508

STOKER, M.S. & VARMING, T. 2011. Cenozoic (sedimentary). *In*: RITCHIE, J.D., ZISKA, H., JOHNSON, H. & EVANS, D. (eds) *Geology of the Faroe-Shetland Basin and Adjacent Areas. BGS Research Report, RR/11/01*. British Geological Survey, Keyworth, Nottingham, 151–208.

STOKER, M.S., HOULT, R.J. ET AL. 2005. Sedimentary and oceanographic responses to early Neogene compression on the NW European margin. *Marine and Petroleum Geology*, **22**, 1031–1044, https://doi.org/10.1016/j.marpetgeo.2005.01.009

STOKER, M.S., LESLIE, A.B. & SMITH, K. 2013. A record of Eocene (Stronsay Group) sedimentation in 1 BGS borehole 99/3, offshore NW Britain: implications for early post-breakup development of the Faroe-Shetland Basin. *Scottish Journal of Geology*, **49**, 1–17, https://doi.org/10.1144/sjg2013-001

STOKER, M.S., STEWART, M.A. ET AL. In press. An overview of the Upper Palaeozoic–Mesozoic stratigraphy of the NE Atlantic region. *In*: PÉRON-PINVIDIC, G., HOPPER, J., GAINA, C., STOKER, M.S., DOORNENBAL, H., FUNCK, T. & ÁRTING, U. (eds) *The NE Atlantic Region: A Reappraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution*. Geological Society, London, Special Publications, **447**, https://doi.org/10.1144/SP447.2

STOREY, M., DUNCAN, R.A. & TEGNER, C. 2007. Timing and duration of volcanism in the North Atlantic Igneous Province: implications for geodynamics and links to the Iceland hotspot. *Chemical Geology*, **241**, 264–281.

TALWANI, M., UDINTSEV, G. ET AL. 1976. Sites 336 and 352. *In*: TALWANI, M., UDINTSEV, G. ET AL. (eds) *Initial Reports of the Deep Sea Drilling Project*. Government Printing Office, Washington, DC, 23–116.

TORSVIK, T.H., AMUNDSEN, H.E.F. ET AL. 2015. Continental crust beneath southeast Iceland. *Proceedings of the National Academy of Sciences*, **112**, E1818–E1827, https://doi.org/10.1073/pnas.1423099112

WAAGSTEIN, R. 1988. Structure, composition and age of the Faeroe basalt plateau. *In*: MORTON, A.C. & PARSON, L.M. (eds) *Early Tertiary Volcanism and the Opening of the NE Atlantic*. Geological Society, London, Special Publications, **39**, 225–238, https://doi.org/10.1144/GSL.SP.1988.039.01.21

WAAGSTEIN, R. & HEILMANN-CLAUSEN, C. 1995. Petrography and biostratigraphy of Palaeogene volcanclastic sediments dredged from the Faeroes shelf. *In*: SCRUTTON, R.A., STOKER, M.S., SHIMMIELD, G.B. & TUDHOPE, A.W. (eds) *The Tectonics, Sedimentation and Palaeoceanography of the North Atlantic Region*. Geological Society, London, Special Publications, **90**, 179–197, https://doi.org/10.1144/GSL.SP.1995.090.01.11

WAAGSTEIN, R., GUISE, P. & REX, D. 2002. K/Ar and $^{39}Ar/^{40}Ar$ whole-rock dating of zeolite facies metamorphosed flood basalts: the upper Paleocene basalts of the Faroe Islands, NE Atlantic. *In*: JOLLEY, D.W. & BELL, B.R. (eds) *The North Atlantic Igneous Province: Stratigraphy, Tectonic, Volcanic and Magmatic Processes*. Geological Society, London, Special Publications, **197**, 219–251, https://doi.org/10.1144/GSL.SP.2002.197.01.09

WALKER, R.J., HOLDSWORTH, R.E., IMBER, J. & ELLIS, D. 2011. The development of cavities and clastic infills along fault-related fractures in Tertiary basalts on the NE Atlantic margin. *Journal of Structural Geology*, **33**, 92–106, https://doi.org/10.1016/j.jsg.2010.12.001

WATTS, A.B. 1971. Geophysical investigations on the continental shelf and slope north of Scotland. *Scottish Journal of Geolocy*, **7**, 189–218.

WHITE, R.S. 1988. A hot-spot model for early Tertiary volcanism in the N Atlantic. *In*: MORTON, A.C. & PARSON, L.M. (eds) *Early Tertiary Volcanism and the Opening of the NE Atlantic*. Geological Society, London, Special Publications, **39**, 3–13, https://doi.org/10.1144/GSL.SP.1988.039.01.02

WHITE, R.S. 1989. Initiation of the Iceland plume and opening of the North Atlantic. *In*: TANKARD, A.J. & BALKWILL, H.R. (eds) *Extensional Tectonics and Stratigraphy of the North Atlantic Margins*. American Association of Petroleum Geologists, Memoirs, **46**, 149–154.

WHITE, R.S. & MCKENZIE, D. 1989. Magmatism at rift zones: the generation of volcanic continental margins and flood basalts. *Journal of Geophysical Research*, **94**, 7685–7729.

WHITE, R.S., CHRISTIE, P.A.F. ET AL. 2002. iSIMM pusher frontiers of marine seism. *First Break*, **20**, 782–786.

WHITE, R.S., SMALLWOOD, J.R., FLIEDNER, M.M., BOSLAUGH, B., MARESH, J. & FRUEHN, J. 2003. Imaging and regional distribution of basalt flows in the Faeroe-Shetland Basin. *Geophysical Prospecting*, **51**, 215–231, https://doi.org/10.1046/j.1365-2478.2003.00364.x

WHITE, R.S., SMITH, L.K., ROBERTS, A.W., CHRISTIE, P.A.F., KUSZNIR, N.J. & THE iSIMM TEAM. 2008. Lower-crustal intrusion on the North Atlantic continental margin. *Nature*, **452**, 460–464.

WILKINSON, C.M., GANERØD, M., HENDRIKS, B.W.H. & EIDE, E.A. In review. Compilation and appraisal of geochronological data from the North Atlantic Igneous Province (NAIP). *In*: PÉRON-PINVIDIC, G., HOPPER, J., GAINA, C., STOKER, M.S., DOORNENBAL, H., FUNCK, T. & ÁRTING, U. (eds) *The NE Atlantic Region: A Reappraisal of Crustal Structure, Tectonostratigraphy and Magmatic Evolution*. Geological Society, London, Special Publications, **447**.

YANG, H., WEN, B. ET AL. 2009. Distribution of hydrocarbon traps in volcanic rocks and optimization for selecting exploration prospects and targets in Junggar Basin: case study in Ludong-Wucaiwan area, NW China. *Petroleum Exploration and Development*, **36**, 419–427.

ZISKA, H. 2012. Fracture orientations onshore Faroe Islands (North Atlantic); evidence for dual rifting episodes in the Palaeogene? *In*: VARMING, T. & ZISKA, H. (eds) *Proceedings of the 3rd Faroe Islands Exploration Conference. Annales Societatis Scientarum Færoensis Supplementum*, **56**, 40–58.

ZISKA, H. & VARMING, T. 2008. Palaeogene evalution of the Ymir and Wyville Thomson Ridge, European North Atlantic Margin. *In*: JOHNSON, H., DORE, A.G., GATLIFF,. R.W., HOLDSWORTH, R., LUNDIN, E. & RITCHIE, J.D. (eds) *The Nature and Origin of Compression in Passive Margins*. Geological Society, London, Special Publications, **306**, 153–168, https://doi.org/10.1144/SP306.7