Imaging of Basalt and Underlying Structures in the Faroese Offshore Area

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Úrtak

Á Norðuratlantsleiðini mynda Føroyar og landgrunnurin uttan um Føroyar part av einum tí størst agosøkinum frá tertier-tíðini. Stórar nøgdir av basalttilfari vórðu trýstar út um hetta økið í paleocentíðini. Hetta tilfar legði seg oman á jarðfrøðiliga bygnaðin, ið var frammanundan og forðaði væl og virðiliga fyri, at hetta økið kundi kannast jarðalisfrøðiliga. Serliga, tí eingin jarðfrøðiligur borur til henda dag er farin ígjøgnum hetta gostilfar.

Men nýggj framstig frá 1994 og 1995, tá ið jarðalisfrøðiligar staðroyndir skulu fáast til vega og viðgerast, hava borið við sær, at mongdir av nýggjum, nógv bøttum staðroyndum eru útvegaðar. Mongdirnar av hesum staðroyndum geva eina mynd av tí, sum er í og undir basalteindunum á teimum økjunum, ið eru meir at kalla lægdir. Harafturat eru skrásetingar av royndum frá hesum mátingum, sumsiga frá, hvussu víðan vinkul, tær endurspegla, sundurgreindar til tess at tálma snarleikamynstrið á tertier-strekkinum, sum liggur omaná, og at kanna snarleikaatburðin í sjálvum basalteindunum. Hetta fer at geva nógv neyvari metingar av, hvussu djúpar tær eindirnar eru, ið liggja niðriundir.

Hetta arbeiðið hevur víst, at á serligum økjum ber til seismiskt at sleppa ígjøgnum basalteindirnar, sum eru út fyri føroysku strondunum og lýsa jarðfrøðiliga bygnaðin, ið liggur undir. Hetta hevur við sær, at tað ber til at gera oljukanningar á Føroyaleiðini.

Abstract

The Faroe Islands and associated shelf area, located on the western European continental margin between Iceland and Scotland, are representative of one of the major Tertiary Igneous provinces of the North Atlantic region. Significant amounts of basaltic material was extruded over this area in the Paleocene, superimposing itself upon the preexisting geological structures and presenting a substantial barrier to geophysical exploration in the area, particularly as this volcanic material has not been penetrated by geological drilling to date.

However, recent advances in geophysical data acquisition and processing in 1994 and 1995 have resulted in the production of new, substantially improved data sets which allow imaging of intra and sub basalt units in the more basinal areas. Further, shot records from these surveys have been analysed for their wide angle reflection information in order to constrain the velocity model for the overlying Tertiary section and to study the velocity behavior of the basalt units themselves. This will allow a greatly improved accuracy in the calculation of depth estimates for underlying units.

This work has shown that, in certain areas, it is possible to seismically penetrate the basalt units present in the Faroese offshore environment and define underlying geological structures, resulting in a greatly improved viability for petroleum exploration applications in the Faroese region.

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Introduction

The Faroe Islands form part of the Faroe Platform area, a region of the North Atlantic Ocean beween the United Kingdom, Norway, and Iceland which is characterized by a voluminous Paleocene-Eocene basalt cover. This basalt consists mainly of subaerially extruded plateau basalts (Rasmussen and Noe-Nygaard, 1970; Waagstein, 1988). It is believed that this early Tertiary volcanism is associated with lithospheric extension which preceded the continental breakup between the Faroe-Rockall Plateau and Greenland (Smythe et al, 1983; Roberts, Morton, and Backman, 1984) by the opening of the North Atlantic Ocean (Fig.1) and therefore forms part of the Northeast Atlantic volcanic passive margin.

The presence of Tertiary oceanic crust can be observed to the north and west of the Faroe Islands (Figs. 1 and 2) ie, the Faroe-Iceland Ridge. (Nunns, 1983; Andersen, 1988) The oceanic basalt – a different age and type from that forming the Faroe Islands Platform – has formed since magnetic Chron 24 (Fig. 2) and has the age of early Eocene and younger (Nunns, 1983.) Oceanward dipping reflectors, or steeply dipping piles of subaerially erupted basalt flows which may be interbedded with sediments, are also found to the north and west of the Faroes, before the contact of oceanic crustal rocks. These oceanward dipping reflectors are thought to be indicative of the transition from oceanic to continental crustal rocks (Smythe et al, 1983; Roberts, Morgan, and Backman, 1984; Spence et al, 1989).

To the east and south the Faroe Platform is bounded by a broad, deep, structural basin known as the Faroe-Shetland Channel (Fig. 1). The basalt cover thins substantially into this basin and apparently vanishes before the basin axis is reached. To the south and west the Platform is bordered again by a broad, deep structural basin called the Faroe Bank Channel and Basin which appear to have basalt cover throughout (see Interpretation and Discussion). This basin is bounded on its southern and western edges by the Wyville-Thompson and Ymir Ridge systems, which are thought to represent Tertiary compressional features (Boldreel and Anderson, 1993, 1995).

Another particularly prominent feature of the area is the Munkagrunnar Ridge, which extends the Faroe Platform southwards from the Island archipelago (Figs. 1 and 2). This Ridge has bathymetric, magnetic, and gravity expression (R. Morgan, personal communication) but its origin remains enigmatic.

The primary challenges to geophysical investigations within the area have been to explore beneath this substantial Tertiary basalt cover, which acts as a barrier to exploration and effectively masks the underlying features which have controlled the genesis of the area. The purpose of this study has been to attempt to »see« through the basalts, utilizing primarily the seismic method, to determine what geological and structural elements lie below

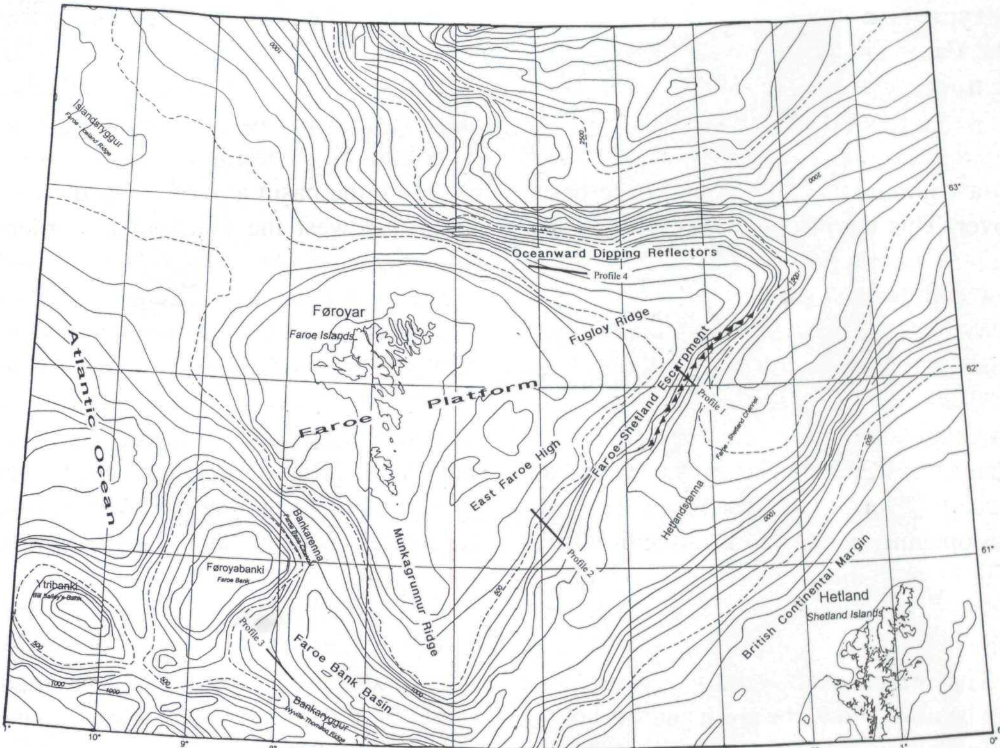

Figure 1. Major Features of the area with profile locations shown.

Methods and Data Base

During 1994 and 1995, Western Geophysical Corporation acquired approximately 12,000 km of non-exclusive seismic data within Faroese waters. Prior to this acquisition, the only data available was, again, Western Geophysical non-exclusive data, but acquired using the techniques current at the time but unfortunately not particularly suited to penetrating the Faroese basalt layer.

The 1994 and 1995 surveys utilized state of the art acquisition techniques and was designed in particular to maximize bandwidth, signal to noise ratio and signal penetration and resolution at depth.

The seismic data processing flow was designed to optimize the acquisition parameters and targeted to minimize multiple attenuation effects. All data was processed to the full acquisition two way travel time of 8 seconds. All seismic data shown is courtesy of Western Geophysical; the interpretation is the Authors' own.

During 1995, World Geoscience Gorporation conducted a non-exclusive SAM (Sedimentary Airborne Magnetometer) Survey over the Faroese area. 42,000 line km of data were collected; to the east of the Islands flight line spacing was 1.5 km, and

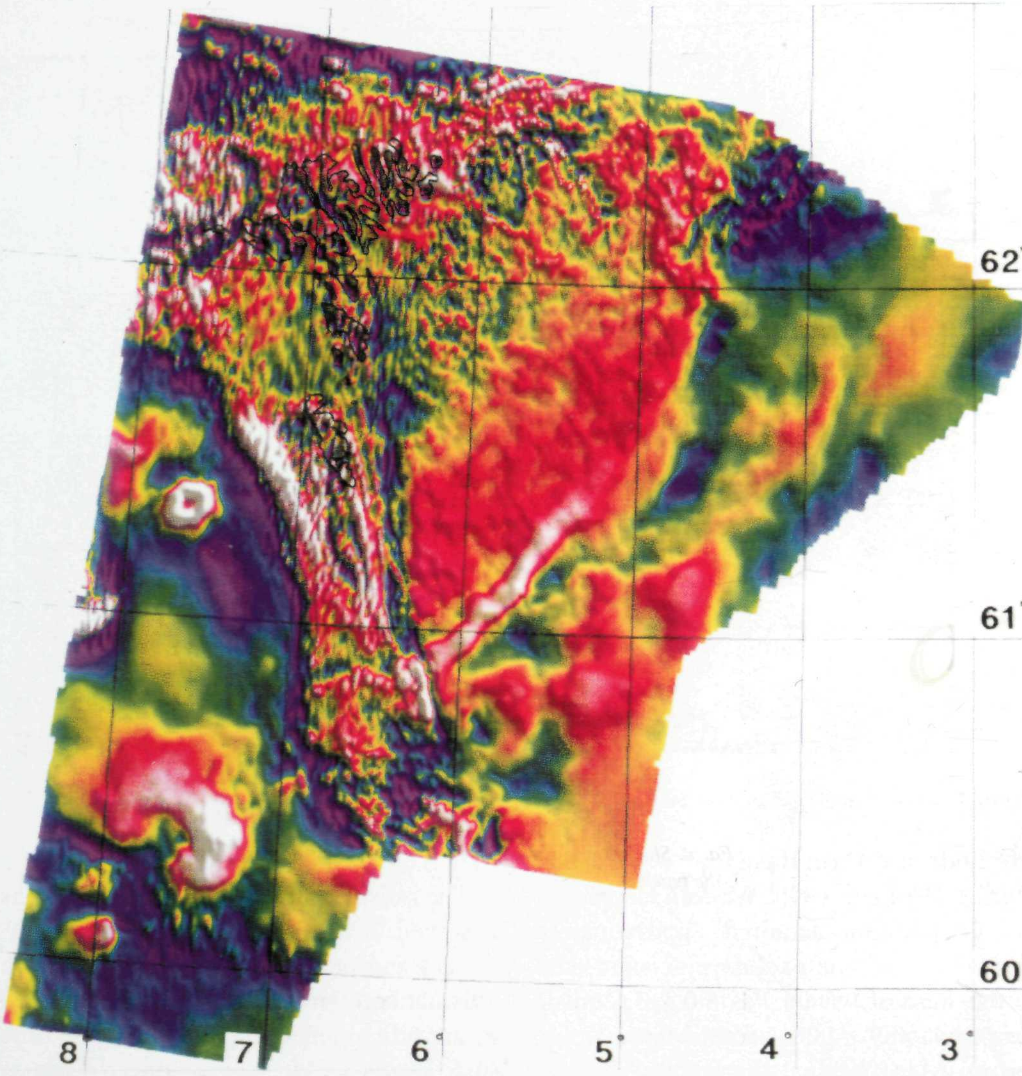

Figure 2. SAM (Sedimentary Airborne Magnetometer) Total Magnetic Intensity Map, IGRF removed. Oceanic crustal rocks (Chron 24) are represented by the purple area in the north; the broad structural basin bordering the Faroese Platform is shown by the orange-red NE-SW trending area, overprinted by the Munkagrunnur Ridge. The Wyville-Thompson Ridge is shown by the blue-green linear feature in the SW (Map supplied courtesy of World Geoscience Corporation).

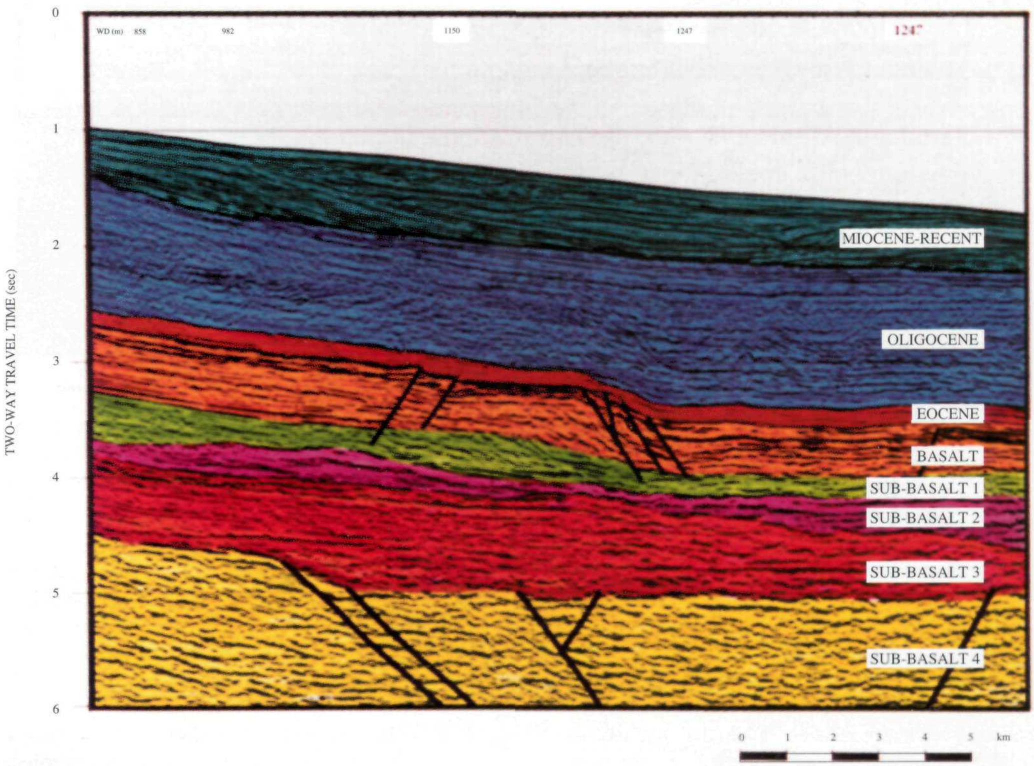

Figure 3. *Profile 1, crossing the Faroe-Shetland Escarpment (wd 1100) and the Faroe-Shetland Channel (wd 1247). This section can be used as the type section for units seen throughout the area.*

to the west of the Islands 3.0 km. Sensor height was 80 m. The Total Magnetic Intensity Map shown has had all standard corrections applied, including diurnal variations, removal of IGRF, reduction to pole and microlevelling applied. This data is shown with the permission of World Geoscience Corporation.

Seismic Interpretation

The profiles selected for display in this study represent in form the different types of features found in the more basinal areas surrounding the Faroe Platform.

Profile 1 (Figs. 1 and 3) traverses the northern arm of the Faroe-Shetland Channel and crosses the Faroe-Shetland escarpment. Further, this line displays particularly well the units which have been mapped throughout the area:

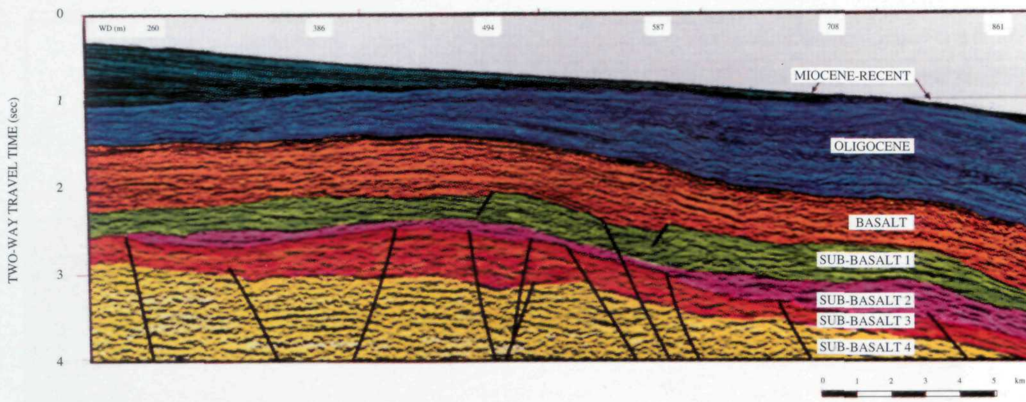

Figure 4. *Profile 2, crossing the East Faroe High and descending into the Faroe-Shetland Channel. Description of major geophysical features given in the text. Also notable is the relative thinning and thickening of the Miocene and Oligocene units, possibly representative of the interactions between uplift, subsidence, and sediment supply.*

1. Miocene to recent sediments are the shallowest unit mapped (blue-green color); although refelctors tend to be long and continuous, this interval displays the characteristics typical of Neogene bottom contour current effects (Boldreel and Anderson, 1995).
2. The Oligocene period is represented by the blue interval and tends to consist of short, disrupted reflector segments, possibly due to the incompetent or high velocity environment present during deposition; its upper boundary with the Miocene may be taken as a diagentic horizon.
3. The Eocene unit (dark orange) is well layered where present, strongly reflective, and mainly conformable with the basalt rocks which it overlies. As this unit is highly positive in its magnetism, it may represent eroded volcanic material. It appears to correlate with the Andrew Formation found West of Shetlands and in the North Sea, where it is a known hydrocarbon producing unit.
4. The basalt (orange) rocks are delineated from the overlying units by a sharp, strong acoustic impedance boundary which is readily recognized and can be correlated throughout the Tertiary Igneous Province (Wood, Hall, and Doody, 1988). The internal structure is signified by a rather continuous, parallel bedded nature which is characteristic of subaerially extruded plateau basalts (Smythe et al, 1983; Wood, Hall, and Doody, 1988, Boldreel and Anderson 1993).

   This line crosses the Faroe-Shetland Escarpment at wd 1150. The Faroe-Shetland Escarpment is thought to represent the location of the paleocoastline at the time of formation of the basalt (Jones and Nelson, 1970; Smythe et al, 1983; Boldreel and Anderson, 1994) where the basalt flows have built outwards when they are cooled by contact into water. The basalt flows within the escarpment here have a slope of 19 degrees when reduced to zero vertical exaggeration and appear to be quite faulted. It can also be observed that the basalt unit thins basinwards of the escarpment; this might represent the transition from the presence of all three Faroese basalt units as described in outcrop (Upper, Middle, and Lower Series, Waagstein 1988) to Lower Series only within the basin (Smythe et al, 1983; Anderson, 1988).
5. The green unit interval denoted as Subbasalt 1 is interpreted as the uppermost unit underlying the basalt. This unit may, in fact, represent older basalt but there are several factors which preclude this interpretation:
   a. The unit does not display the same genetic plane parallel bedded character shown in the overlying orange basalt unit, believed to be subaerial in nature of formation;
   b. Reflector segments are shorter,stronger, infills the geometries of its basal unit, and shows onlap, downlap, and truncation features.
   c. Internal clinoform segments are steep (in the

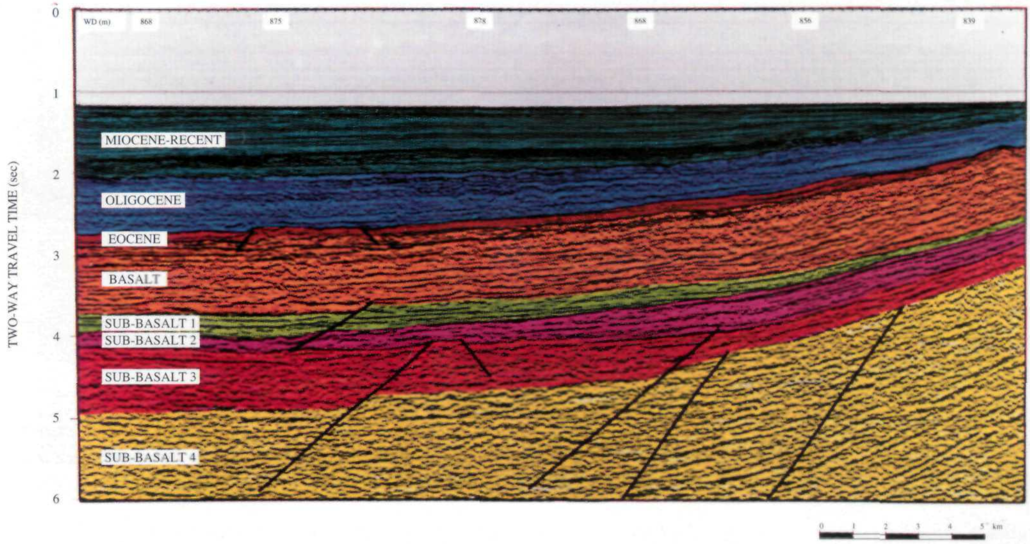

Figure 5. *Profile 3, in the Faroe Bank Basin and rising onto the Faroe Bank Channel Knoll Volcanic Feature. Note the thickening of the Basalt unit apparent relative to Figs. 3 and 4, and the thickening of Subbasalt 2 Towards the Knoll.*

region of 25 degrees) unless highly brecciated, basalts cannot support this geometry (Trewin and Hole, personal commmunication).

d. The upper contact terminates towards an erosional unconformity.

Because of these factors, we have concluded that this unit is most probably sedimentary in nature with an age older than that of the basalt which overlies it.

6. The underlying unit, Subbasalt 2 (bright pink) displays characteristic mounded structures upon which the older unit stratigraphically terminates as described above. Reflectors are strong with both broad peaks and troughs which seem to be indicative of this unit.
7. The dark pink interval (Subbasalt 3) forms the surface upon which Subbasalt 2 was clearly deposited; Subbasalt 2 infills its highs and lows but lies conformably upon its planar surfaces as well (note respectively characteristics at wd 858 and wd 1247. This unit is more massive than the overlying units and discrimination of its boundary with Subbasalt 4 can be difficult, usually depending on difference in geometry, dip, and reflection character.
8. The deepest unit interpreted is that of the yellow horizon, Subbasalt 4, which is generally taken as representing acoustic basement or the basin floor. This unit can also be heavily block faulted. Some indications of internal form may be detected with this unit (ie, wd 858 at a twt of 5.6 seconds) but these events are discontinuous, cannot be correlated, and may well represent artefacts.

Profile 2 (Figs. 1 and 4) lies farther south along the Faroese Margin and crosses the East Faroe High before descending into the Faroe-Shetland Channel. The interpreted units display the characteristics as described above, as well as the following notable features:

1. Subbasalt 2 is seen to form a large, depositional mound against the channelward fault edge of the East Faroe High (EFH) fault block. This unit thins over the EFH to terminate again against an upfaulted block near WD 260.

Figure 6. *Profile 4, located to the north of Fugloy Ridge immediately inland from the Oceanward Dipping Reflector Sequence. The overlying Miocene and Oligocene units are particularly uniform.*

2. Conversely, the underlying Subbasalt 3 (dark pink) unit thickens appreciably over the high, indicating that uplift and erosion took place between Subbasalt 1 and 2 rather than in earlier times, probably during a reactivation event.
3. The yellow Subbasalt 4 interval is substantially faulted and these faults appear to control the structure of the East Faroe High.

Profile 3 (Figs. 1 and 5) lies in the Faroe Bank Channel Basin, to the west of the Munkagrunnur Ridge. Again, the regionally interpreted structure is apparent and the following additional observations can be made:

1. The interpreted orange basalt unit is thicker than that found to the east of the Munkagrunnur Ridge (see figs. 3 and 4). This increased thickness is prevalent throughout the entire basin.
2. The interpretation of Subbasalt 1 is more difficult in this basin, due to the similarity in character with that of the plane-parallel bedded basalt. However, Subbasalt 1 is even more strongly bedded and still displays onlap, downlap, and infill with the underlying Subbasalt 2 so we believe that the intepretation, again, of a pre-basalt unit still holds.
3. The interpretation of Subbasalt 4 is, in this basin, highly tentative and proceeded primarily on character differences, as the difference in reflection strength is small and processing artefacts are strong. We interpret this horizon boundary as tentatively representative of basin form.

Profile 4 (Figs. 1 and 6) lies in a quite different environment to the north and east of the Faroe Islands and Platform, immediately southwards of the Oceanward Dipping Reflector (ODR) sequence, which is thought to be representative of the continent-ocean transition (Spence et al, 1989; Roberts, Morgan, and Backman, 1984). Other than the Miocene, Oligocene, and yellow Subbasalt 4 units, it is not possible to correlate from this north side of the Fugloy Ridge across the Platform to the Faroe-Shetland Channel.

1. The basalt seems to subdivide into two units, the light brown Basalt and yellow-brown ?Basalt. The division between these two units has been based upon the apparent thickening of the light brown unit in the region of wd 755 and thinning near wd 784; this thinned area appears to have been uplifted and eroded, as the surface is rough rather than smooth and the substantially plane parallel bedded character prevalent between wd 739 and wd 786 has been removed.The underlying ?Basalt is more constant in thickness but still retains a plane parallel nature. Onlap and downlap terminations with the basal brown unit are absent.
2. The brown Subbasalt A unit displays a strong reflection boundary with the overlying ?Basalt unit. The brown series displays bedded to massive character and does infill its basal Subbasalt B light yellow layer. It also thins over the high in the regon of wd 810.
3. Subbasalt B is a very thick, again massive to bedded unit, with very strong basal reflectors. Little internal structure is seen but the unit again thickens over the high.
4. The deep yellow Subbasalt 4 displays the strong reflection boundary typical of this unit, some internal form characteristics, and strong block faulting. These faults seem to control the uplift which has created the high over which the overlying units thins. The relative presence or absence of thinning most probably represents reactivation of existing trends over time. The basin itself displays indications of subsidence, typical of an area which is being loaded and downwarped prior to the continent-ocean transition.

Discussion

Upon examination and mapping of the seismic data, it became evident that the Faroese offshore area could be divided into two different geophysical environments: those regions where it was possible to seismically image within and beneath the basalts, and those areas where imaging was not currently possible.

Broadly speaking, in the shallower water areas, where there is little Tertiary sediment cover and where the basalt itself either outcrops, or approaches outcrop, of the sea floor, it has not proven possible to either discretely penetrate the basalts or to coherently discriminate the recorded signals from recorded noise and artefacts. These artefacts might be either geophysical acquisition system related (source overshooting; multiple generation; poor signal to noise ratio; source/receiver pattern effects, etc.) or geologically related (geologically induced ringing; Q factors of the various rock units; earth induced multiple generation; scattering of incident wave energy by disrupted surfaces, etc.); in any case, the cause of this phenomena is unclear. The end result is that discrete reflector sequences cannot be determined either within or below the basalt in these areas, which roughly correspond to the 300 m bathymetric contour along the Faroese Platform area.

However, in the more basinal environments where water depths are deeper and the amount of Tertiary sedimentation increases, imaging within and below the basalt can be accomplished as reflected seismic energy is both transmitted and received discretely. This allows observation of coherent reflector packages throughout the area which can be regionally identified and correlated.

Imaging capability also appears to be related to thickness of the basalts within these basinal areas. Where the basalt »icing« is thin, or the subaerial flows are interfingered with sedimentary units, it is possible to define with a certain degree of confidence the underlying basin form itself and the margin faults which control it. The converse argument is also of assistance: if deep structures are clearly visible, than volcanic presence is thin. These affects are particularly apparent in the area of the Faroe-Shetland Channel and the adjacent Faroese volcanic platform, where the basalt cover thins (Fig. 3), interfingers, then vanishes towards the basin axis.

In the Faroe Bank Channel Basin to the west of the Faroe Islands (Fig.1) the basalt cover is in general thicker than that observed in the basinal areas to the east of the Munkagrunnur Ridge (Compare Fig. 5 with Figs. 3 and 4). It has not been possible to determine the underlying basin margin characteristics in this region, possibly due to the increased basalt cover present.

Interestingly, what appear to be the same subbasalt units appear in both areas with equal clarity. However, the strong clinoform, mounding, or so-called channel features typical of these units in the eastern area (Figs. 3 and 4) are not so apparent in the west (Fig. 5).

In the confined basin to the north of Fugloy Ridge (Fig. 6) subbasalt units can be again defined, although the intepretation of the base basalt itself is quite enigmatic. One argument in favor of a thinned basalt interpretation over the high is the relatively high degree of definition in the deeper basin structures. It has already been stated that, other than Subbasalt 4, the units to the north of Fugloy Ridge cannot be correlated to units within the other basins; one of the determining factors for this lack of correlation was the apparent absence of the sedimentary structures visible within the southerly basins. The primary significance of this line is that it indicates that basinal elements exist in other areas, away from the Faroe Shetland Channel and Faroe Bank Basins.

Because of the lack of sound geological information, it has not been possible to identify the subbasalt units within the area. More control is possible in the southeastern part of the area due to extrapolated control from the West of Shetland area, which may be a conjugate margin. It may be possible to speculate Jurassic-Cretaceous units within this basin, with the basin fabric itself being of, perhaps, Permo-Triassic age with Mesozoic fill. This broad basin borders the Faroese platform to the SE, SSE, and SW, with the Munkagrunnur Ridge apparently superimposed upon and subdividing it. This basin trend is the same as the Caledonian trends of north Scotland and may be related to continental breakup away from Greenland.

Conclusions

The interpretation of the recently acquired non-Exclusive seismic data has shown that, in the more basinal environments, seismic energy can penetrate the basalt layers predominant in the Faroese region and that intra and subbasalt imaging is possible.

Basin elements may be defined as well. The Faroese Volcanic Platform area is bounded along its more southerly margin by a large basin, possibly Permo-Triassic in age, with a speculated Mesozoic fill. This basin has a trend equivalent to the Caledonian and may be related to original, East Greenland features pre-dating continental breakup.

Improvements in the imaging capability and seismic resolution of features indicates that structures attractive for hydrocarbon exploration are present and that, indeed, this exploration is now feasible.

Acknowledgements

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