

Early opening history of the North Atlantic – I. Structure and origin of the Faeroe–Shetland Escarpment

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Summary. Marine geophysical surveys show that the Escarpment is the buried feather-edge of a thick pile of flood basalts of early Eocene age, overlying a thinner, more widespread layer of basalts of late Palaeocene age. The Escarpment does not, therefore, define the continent–ocean boundary in the southern Norwegian Sea, but instead marks the contemporary shoreline separating terrestrially erupted basalt flows in the north from a restricted shallow-water shelf to the south. The basalts overlie 5–6 km of Mesozoic sediments, which have completely buried a large conical flat-topped seamount of similar dimensions to Anton Dohrn and Rosemary Bank. We call this newly postulated body the Brendan seamount. The Mesozoic sediments are at least as old as early Cretaceous in age, therefore precluding the possibility that the mid-Cretaceous seafloor spreading episode (supposed by some to have created the Rockall Trough) could have also created the thin crust inferred to underlie the Faeroe–Shetland Trough and Møre Basin.

1 Introduction

The structure and plate tectonic evolution of the Norwegian Sea were first described in detail by Talwani & Eldholm (1972), who identified from seismic reflection records two features which they called the Vøring Plateau Escarpment and the Faeroe–Shetland Escarpment. These escarpments are interpreted by Talwani & Eldholm as defining part of the NW European continental margin. The escarpments form three NE–SW trending lineaments (the Faeroe–Shetland Escarpment being in two parts), with the continental margin between the two regions being marked by a NW–SE trending transform fault, the Jan Mayen Fracture Zone. The escarpments are defined by the abrupt termination of a strong acoustic reflector which appears to be continuous with Tertiary oceanic crust to the NW, and which on the Outer Vøring Plateau has been proved by drilling to be from the top of a layer of basalts (DSDP Scientific Staff 1975). This result apparently corroborates the hypothesis that the reflector marks the top of oceanic layer 2.

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The main corollary of Talwani & Eldhom's hypothesis concerning the escarpments is that a large area of the eastern Norwegian Sea is underlain by subsided continent, with the further implication that bathymetry, structural level of basement, crustal thickness, Moho depth, etc., are no use in determining whether a particular region is of continental or oceanic origin. Several aspects of their archetypal Norwegian margin model have subsequently been invoked in the interpretation of other passive margins, including those of Angola (Rabinowitz 1972), Southern Africa (Talwani & Eldholm 1973), South Australia (Talwani 1976; König & Talwani 1977; Talwani *et al.* 1978) and the western North Atlantic (Rabinowitz 1974).

Leaving aside the problematic nature of 'subsided continent' in general, the specific problems which arise as a direct result of Talwani & Eldholm's eastern Norwegian Sea model include the following:

(1) The pre-drift fit of Greenland against Europe. Talwani & Eldholm's (1977) reconstruction shows a continuous 50–70 km wide continental overlap along the 1000 km length of margin between NE Greenland and Svalbard, despite their attempt to minimize the overlap by assuming that the Greenland continental margin lies landward of the 500 fathom isobath by up to 50 km.

(2) Early Tertiary North Atlantic reconstructions. Talwani & Eldholm's (1977) spreading history for the Norwegian Sea, when combined with similar interpretations for the central North Atlantic and Labrador Sea, results in mutually incompatible reconstructions of Greenland and North America relative to Europe around the time of anomalies 21–23 (Kristoffersen & Talwani 1977).

(3) The Rockall Trough. The geophysical evidence available to date is consistent with a normal oceanic crustal structure for the Trough south of about 58°N, with the Moho at 12–14 km (Scrutton 1972). Nevertheless, the Trough is assumed by Talwani & Eldholm to be underlain by subsided continental crust.

(4) The Faeroes Plateau. The crustal structure here has been shown (Bott *et al.* 1974) to be: (a) consistent with that of normal continental type and thickness, and (b) significantly different from the anomalous oceanic crust of the adjacent Iceland–Faeroe Ridge (Bott, Nielsen & Sunderland 1976). It is, however, interpreted as oceanic by Talwani & Eldholm since it lies to the west of the continent–ocean boundary supposedly defined by the Faeroe–Shetland Escarpment.

A more general inference which follows from adoption of Talwani & Eldholm's interpretation of the Norwegian Sea is that rigid plate tectonic theory can now only supply a first-order explanation of the evolution of the North Atlantic. The history of passive marginal areas prior to and during the early stages of rifting is now presumed to be dominated by the gross modification of large areas of continental crust and/or the adjacent oceanic crust. We propose to challenge these views by showing that the Faeroe–Shetland Escarpment has no direct relevance to the location of the continental–ocean boundary in the southern Norwegian Sea. Our alternative explanation for the structure and origin of the Faeroe–Shetland Escarpment is, we suggest, equally applicable to the currently less well-explored Vøring Plateau Escarpment.

A major difficulty in open scientific debate about these, and many other, marginal areas is the large amount of confidential commercial geophysical data now in existence. Since it is only permissible (and practicable) to publish a small fraction of these data, we feel that a full discussion of the already published data is necessary, in the context of the original and the new hypotheses. An acceptable method of circumventing the confidentiality problem, which we shall try to adopt here, may be: (a) to show that the new hypothesis is compatible with the newly published and the previously published data, whereas (b) the old hypothesis is not, and (c) to assert, necessarily without proof, that the rest of the unpublished data

corroborates the new hypothesis (that it may also corroborate the old hypothesis is irrelevant). This approach is methodologically sound, since it requires only that the crucial pieces of evidence, to be used in refuting a particular hypothesis, need be published. It does, however, require a more critical appraisal of previously published work than is usually thought necessary (Ziolkowski 1972; see also Rochester *et al.* 1975, p. 673).

2 Talwani & Eldholm's Faeroe–Shetland Escarpment

Fig. 1(a) shows the location of the eight profiling lines S1–S8 used by Talwani & Eldholm (1972) to identify the escarpment. The data, comprising single channel airgun, gravity, magnetic and bathymetric profiles are reproduced in Talwani (1974). The southern segment of the escarpment is defined principally from the bathymetry and profiling data (S1–S4) whereas the northern segment is defined principally by a characteristic magnetic anomaly on profiles S3–S8 attributed to an edge effect (Talwani & Eldholm 1972, fig. 12). The gravity and magnetic profiles on S5 are redrawn in Figs 10 and 11, respectively, where the magnetic edge-effect anomaly can be seen at 180–200 km in Fig. 11.

2.1 SOUTHERN SEGMENT

The reflection profile S1 shows no evidence either for the strong reflector or for a buried escarpment, although the extrapolated escarpment feature (Talwani & Eldholm 1972, figs 2 and 5) suggests that it is expected to be present; in the atlas of the Norwegian–Greenland Sea (Grønlie & Talwani 1978, fig. 6) the escarpment is depicted as extending to just south of 61°N.

The strong reflector on profile S2 (Talwani & Eldholm 1972, fig. 10) dips SE at about 3° to a point where it is obscured by the seabed multiple at about 2.4 s TWT. Penetration to the same reflection is lost on S3 at about 2.4 s TWT, where the dip is of the order of 4°. Similarly on S4, the strong reflector dips SE at about 3° from 3.0 to 3.5 s TWT, at which penetration is lost.

2.2 NORTHERN SEGMENT

On profile S4 the escarpment is located at the positive peak of the supposed edge-effect magnetic anomaly, but this position does not correspond to any break in the strong acoustic reflector seen here; on the contrary, the escarpment must lie at least 25 km to the SE, where penetration to this reflector is lost at about 2.3 s TWT. On profile S3 there is a data gap on the airgun record where the northern segment of the escarpment might be expected. On profile S5 there is another reflection profile data gap at the crucial section, where a heat flow station was observed. The escarpment here is located by a magnetic anomaly (Fig. 11, 180–200 km along profile). The feature on this reflection line reproduced in the atlas (Grønlie & Talwani 1978, fig. 7, section 9) as the Faeroe–Shetland Escarpment has been mislabelled. Neither the line drawing (Talwani & Eldholm 1972, fig. 10) nor the photograph of the reflection profile S6 (Talwani 1974, Part E, p. 159) shows any sign of an escarpment.

On S7 the escarpment is clearly identifiable on the reflection profile, but is about 20 km NW of the position defined by the magnetic feature. The dip of the strong reflector defining the escarpment is of the order of 10°, SE of which the strong reflector is still visible up to the point where it is obscured by the seabed multiple.

On S8, the most northerly profile, the reflection data show only an irregular strong reflector around the area defined by magnetics as the escarpment, varying from 0.2 to 0.8 s TWT beneath the seabed.

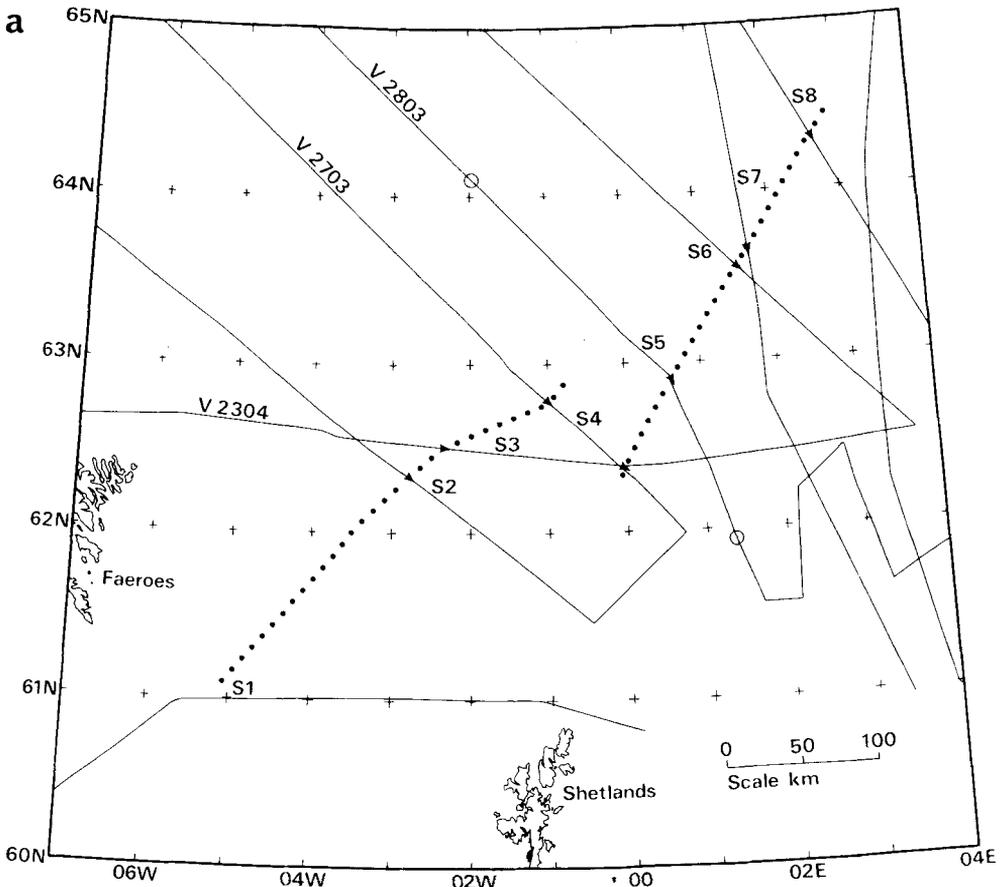


Figure 1. (a) The eight profiles S1–S8 used by Talwani & Eldholm (1972) to identify the Faeroe–Shetland Escarpment (dotted lines). Open circles on S5 locate ends of profile reproduced in Fig. 10. (b) Commercial geophysical data obtained since 1972. Solid lines – multichannel seismic profiles (mainly 24-fold); round the Shetlands and south of 62°N the density of lines is too great to be shown. Dots – commercial wells drilled in the West Shetland area and northern Viking Graben. Wavy line – limit of commercial aeromagnetic data. Dashed line – area of published aeromagnetic map ($\bar{A}m$ 1970).

2.3 DISCUSSION

The published data referred to above do establish the presence of a structural high in the 'acoustic basement' (as defined by the single-channel analogue-recording airgun records obtained more than a decade ago), apparently continuous with both the oceanic crust to the NW, and in the south with the offshore extension of the Faeroes basalts (Talwani & Eldholm 1972, p. 3583). There is also a general association of magnetic anomalies with the presence of the reflector, which can therefore reasonably be attributed to a basaltic layer. However, the geophysical evidence for the identification of the two linear segments of the Faeroe–Shetland Escarpment, supposedly terminating the basement high, is both inadequate and internally inconsistent. A convincing escarpment-like feature is only seen on one reflection profile (S7); the others show, at most, the disappearance of the gently SE dipping reflector 1–2 s below the seabed, an effect due more to the limitations of the profiling system than to subsurface geology. The identification of the edge-effect magnetic anomaly as the escarpment mismatches the reflection data in every case; on profile S4 the seismic

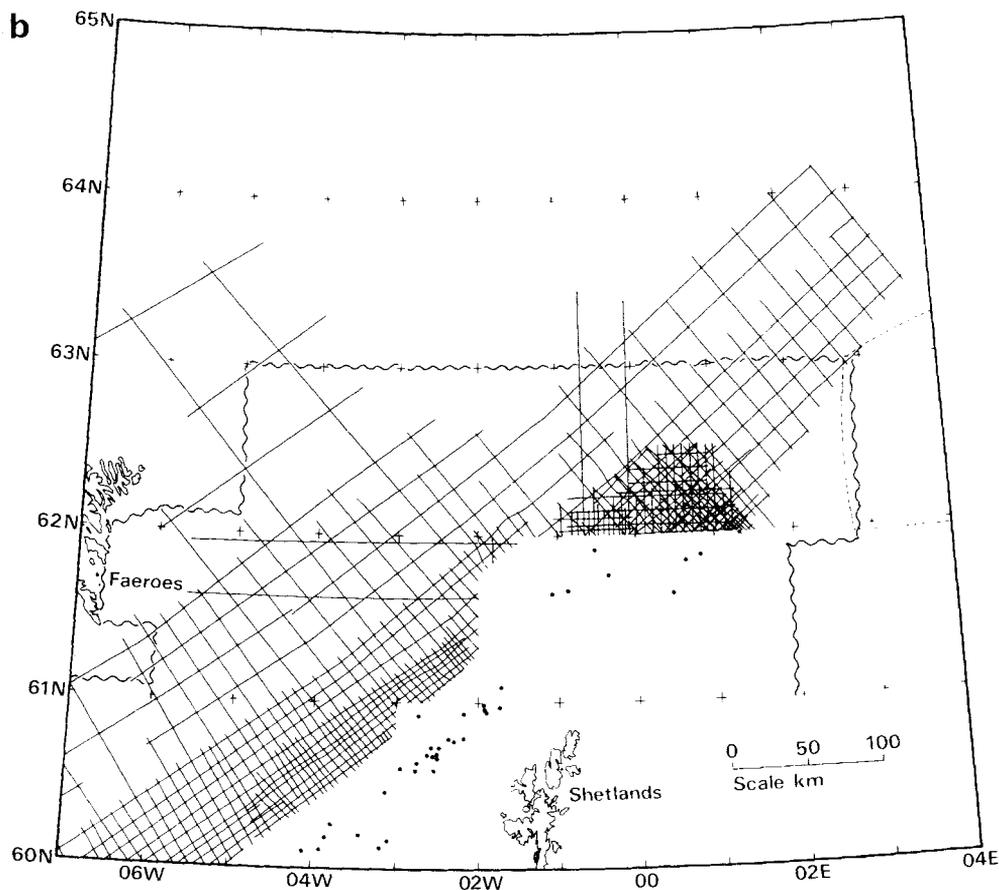


Figure 1 – continued

line demonstrates that the magnetic anomaly cannot be due to the postulated edge-effect. The gravity data are similarly inconsistent – the seaward increase in gravity on profiles S3, S4, S7 and S8 over the northern segment of the escarpment is regarded as ‘especially significant’ (Talwani & Eldholm 1972, p. 3584), whereas the landward gradient on S5 (see Fig. 10, 130–200 km along profile) is attributed to unspecified local irregularities. There are no comparable gradients at the southern escarpment segment crossings (S1–S4), nor on S6. We shall show below that the gradients referred to on profiles S3 and S4 are merely a local effect, being on the flank of a large circular gravity anomaly.

Talwani & Eldholm’s (1972) conclusions on the Faeroe–Shetland Escarpment are that it is the ‘combined weight of all these (geophysical) data which enables us to establish the presence of this feature’ (p. 3584). We suggest, on the contrary, that the only reasonable conclusions that can be drawn from the data presented by them and discussed above, are as follows:

- (1) The basaltic strongly reflective horizon forms a sinuous structural high extending NE from the Faeroe plateau, flanking the Tertiary crust of the southern Norwegian Sea.
- (2) The gentle ($3\text{--}10^\circ$) eastward dip of this reflector to the east of the high zone may be referred to as an escarpment, which is relatively well-developed in the north, but probably dies out in the south between 62° and 61°N .

(3) There is a strong supposition that the basaltic layer continues east of the escarpment, as suggested by reflection profile S7 and by the presence of magnetic anomalies within the so-called magnetic quiet zone (Talwani & Eldholm 1972, fig. 5).

(4) A contour map of the basaltic reflector, in isochrons of two-way reflection time shows that the escarpment feature swings round in a Z-shaped loop in the area of profiles S3 and S4, and that the two apparently separate segments are more likely, in fact, to be one continuous sinuous structure.

(5) The great variability in the 'regional' features of the gravity and magnetic profiles from one line to the next shows that there is *unlikely* to be a major crustal feature, such as the continent–ocean boundary, present at depth below the escarpment.

3 Geophysical data on the Faeroe–Shetland Escarpment

3.1 COMMERCIAL DATA AVAILABILITY

Fig. 1(b) shows the commercial geophysical data which have become available in the region since 1972. The seismic lines shown all belong to speculative seismic surveys shot by several major contractors. Nearer to the Shetlands the density of seismic data, which includes also many client-commissioned surveys as well as speculative surveys, is too great to be shown. These data tie in to the wells shown in Fig. 1(b), of which there are now more than 35 in the West Shetland region. The positions of the most northerly of the wells in the Viking Graben, NE of the Shetlands, are also shown.

Most of the seismic data are 24-fold, with routine processing, although some of the more recent surveys are offered with migrated stacked sections as well. Since about 1975 the contractors have simultaneously recorded gravity and magnetic field measurements along the seismic lines; the results of these, in the form of reduced profiles, magnetic tapes and compilation maps, are usually offered as part of the survey package.

The area marked by the wavy line on Fig. 1(b), extending as far as the Faeroes and 63°N, is covered by commercial aeromagnetic surveys with an east–west flight-line spacing of 4–6 km. These link to the published aeromagnetic map of the Norwegian shelf (Åm 1970), the southerly limit of which is shown by the dashed line in Fig. 1(b).

Wells drilled in the UK sector become available for release 5½ years after the completion date; at present, however, only a few of those shown in Fig. 1(b) have been released by the Department of Energy. IGS is empowered to publish eventually the commercial aeromagnetic maps. The coverage shown in Fig. 1(b) will become publishable during 1983–84.

3.2 OPEN FILE DATA

Seismic-reflection, gravity and magnetic data were acquired by IGS in 1974 along the survey lines shown in Fig. 2(a). The interpretation given here includes three lines from the Lamont–Doherty Survey of the World Ocean (Talwani 1974), and part of a 24-fold seismic reflection line obtained by Seismograph Service Ltd during a speculative commercial survey of the area in 1973. During the IGS survey, a wide-angle reflection line R and four reversed refraction lines A–D were also observed. Of these, lines A and C did not give useful results, so only lines B and D will be discussed. Lines R, B, D and the Lamont–Doherty refraction line V27–42 (Talwani & Eldholm 1972) are located in Fig. 6(a). Navigation was by Decca Main Chain OE, which in this area probably has a fix error of less than 200 m, relative to geographical coordinates. Our Magnavox integrated satellite system, with Doppler sonar dead-reckoning, was not used, because the sonar is limited to sea-bottom tracking in depths of 400 m or less, but satellite fixing integrated with Loran C was used for the wide-angle reflection line R, in which a very rapid rate of position fixing was required.

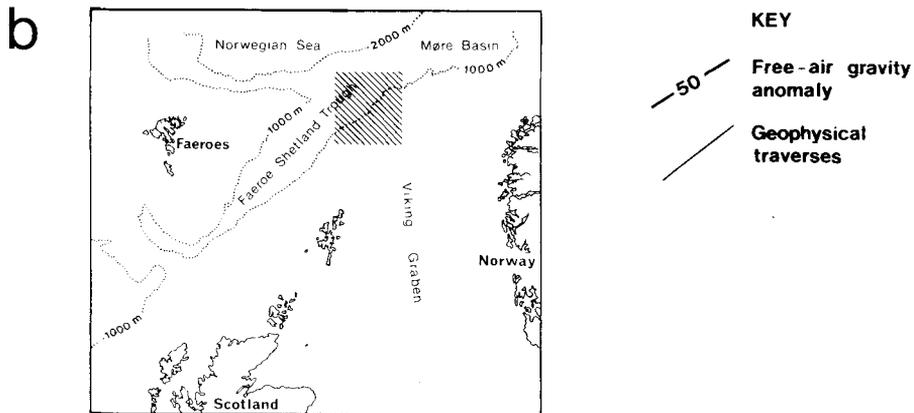
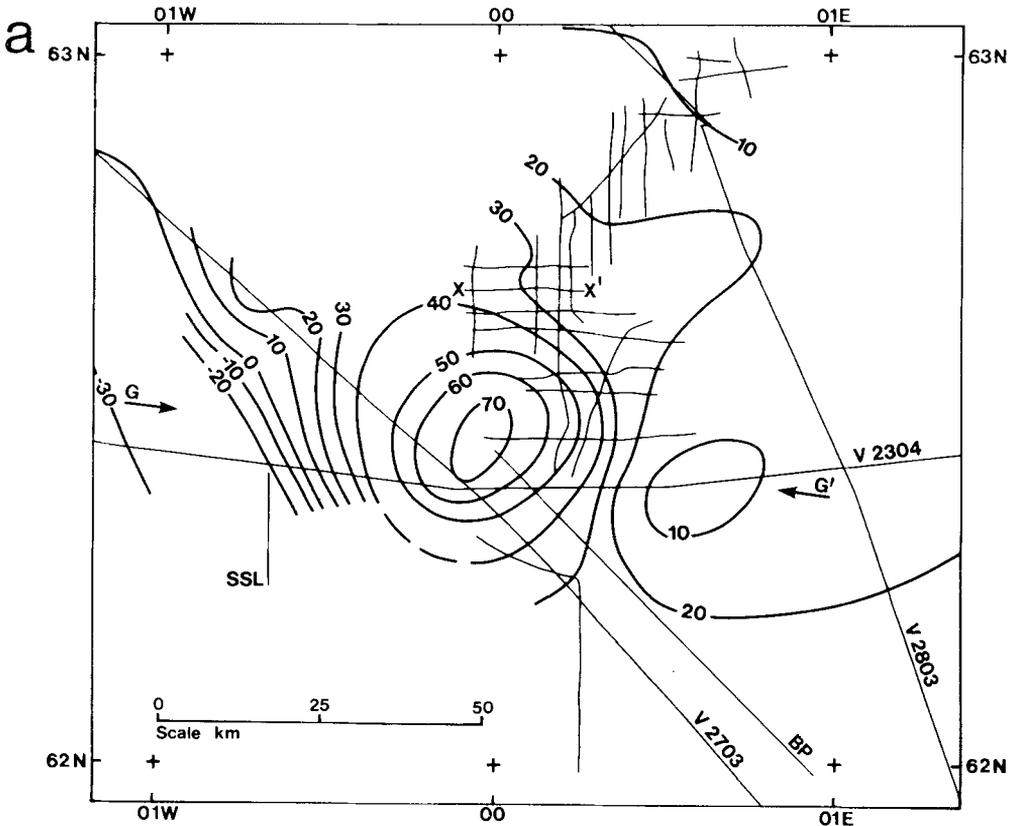


Figure 2. (a) Free-air gravity anomaly map compiled from data on geophysical traverses shown (UTM projection). Lines labelled V are Lamont-Doherty Geological Observatory surveys (Talwani 1974). Line labelled SSL is part of a multichannel seismic reflection survey of the area by Seismograph Service Ltd, reproduced in Fig. 5(a). Line labelled BP is BP reflection profile 75-39, reproduced as a line drawing in Fig. 7. Other lines are IGS survey tracks; airgun reflection record XX' is reproduced in Fig. 3. Line GG' is used in gravity modelling (Figs 8 and 9). Gravity anomaly contours are in mGal. (b) Shaded rectangle shows area of (a) (Mercator projection).

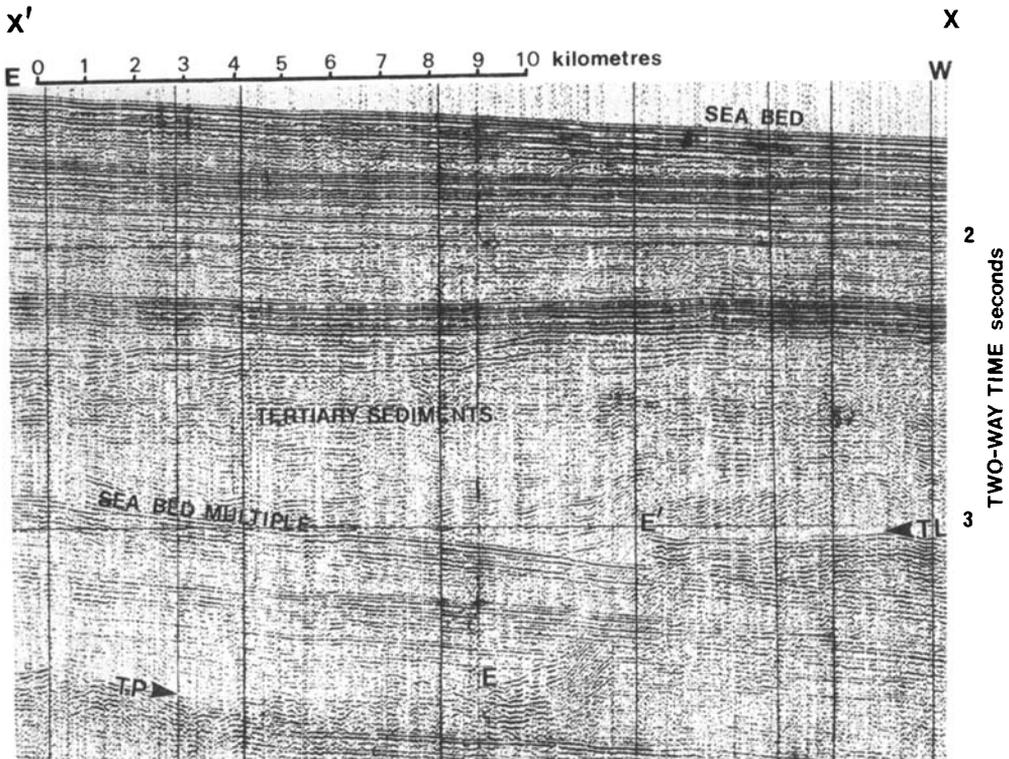


Figure 3. IGS single-channel seismic reflection line (XX' located in Fig. 2). TL is the smooth reflector mapped as the top of the upper basalts of probable early Eocene age, wedging out at EE', the Faeroe-Shetland Escarpment. TP is approximately the Top Palaeocene reflector traced northwards from wells in the Viking Graben (Fig. 2b). Here it is believed to mark the top of a layer of basalts of late Palaeocene age.

Fig. 3 is a sample of the IGS single trace seismic reflection lines (XX' in Fig. 2a) obtained with a 40 in³ airgun at 2000 psi as an energy source. TL is the reflector which Talwani & Eldholm identify as the top of oceanic layer 2, and the abrupt termination of this reflector, as at EE' in Fig. 3, they have named the Faeroe-Shetland Escarpment. The area underlain by the smooth reflector TL is shown in Fig. 7, as is the subcrop of the escarpment, which evidently bears little similarity to the apparently linear feature interpolated by Talwani & Eldholm between the three relatively widely spaced Lamont-Doherty survey lines, also shown in Fig. 2(a).

Refraction line B (Fig. 4) lies over the area of reflector TL, to the NW of the escarpment (Fig. 7a). There are several refractors with velocities below about 2 km s⁻¹, and the strong first arrival, $V_p = 4.4$ km s⁻¹, is shown from the results of wide-angle reflection line R to be from the same interface as that giving rise to reflector TL on the vertical reflection profiles. This refractor is observed to a range of about 20 km in both directions, with no sign of the faster first-arrivals to be expected within this range, if a typical oceanic crustal layering were being observed. However, a late arrival, with an apparent velocity of 5.6 km s⁻¹, is observed in one direction only, and will be discussed in Section 5.2.

Refraction line V27-42 (Talwani & Eldholm 1972, table 1) also lies just NW of the escarpment (Fig. 7a). This unreversed line was shot up-dip, as can be seen from the accompanying airgun reflection profile (Talwani 1974), so it is not surprising that the

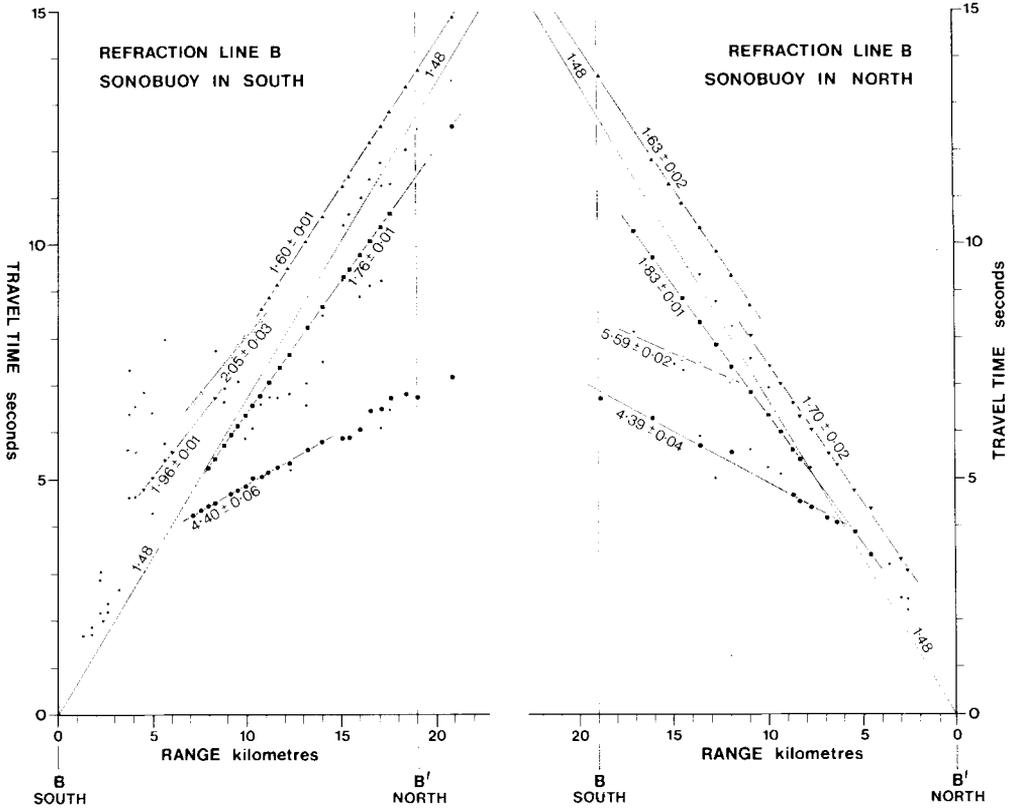


Figure 4. Refraction line B. Numbers are velocities in km s^{-1} with standard deviations, obtained by least-squares fitting of the straight lines running through the large symbols. Small dots indicate unclassified or dubious arrivals. Ranges are derived from the water-wave arrival using an assumed velocity of 1.48 km s^{-1} . Navigation is by satellite integrated with Loran C. Sixty-four shots were fired in total.

apparent velocity of $V_p = 4.65 \text{ km s}^{-1}$ observed for the refractor is slightly higher than that obtained from our reversed line.

Refraction line D lies to the SE of the escarpment (Fig. 7a). Good arrivals to a range of 18 km were observed in both directions, but none of the refractors have velocities greater than 2.2 km s^{-1} . This result is consistent with the termination of the interface TL at the escarpment.

A short section of the SSL 24-fold seismic reflection survey is shown in Fig. 5(a). This survey was originally shot and processed in 1973, and suggested that primary reflections could be observed from below the strong reflector TL. In order to demonstrate the reality of these deeper reflections, by proving that they were unlikely to be multiples, a section over the escarpment was reprocessed by SSL in 1975, with the assistance of one of us (DKS), using our refraction velocities as a guide. Compared with the original processing, the main difference in the reprocessing (which was carried out from the common depth point gather stage of the original data tapes) was the use of interval velocities of about 4.8 km s^{-1} for the section below the reflector TL, in the normal move-out (NMO) correction before 24-fold stacking. Fig. 5(a) shows the reprocessed version. The group of reflectors below the horizon TP clearly continues to the north beneath the strong reflector TL, and the depth-converted line drawing of the section (Fig. 5b) demonstrates that these reflectors are flat-lying beneath TL. Note that the minor fault downthrowing the underlying group to the north does not

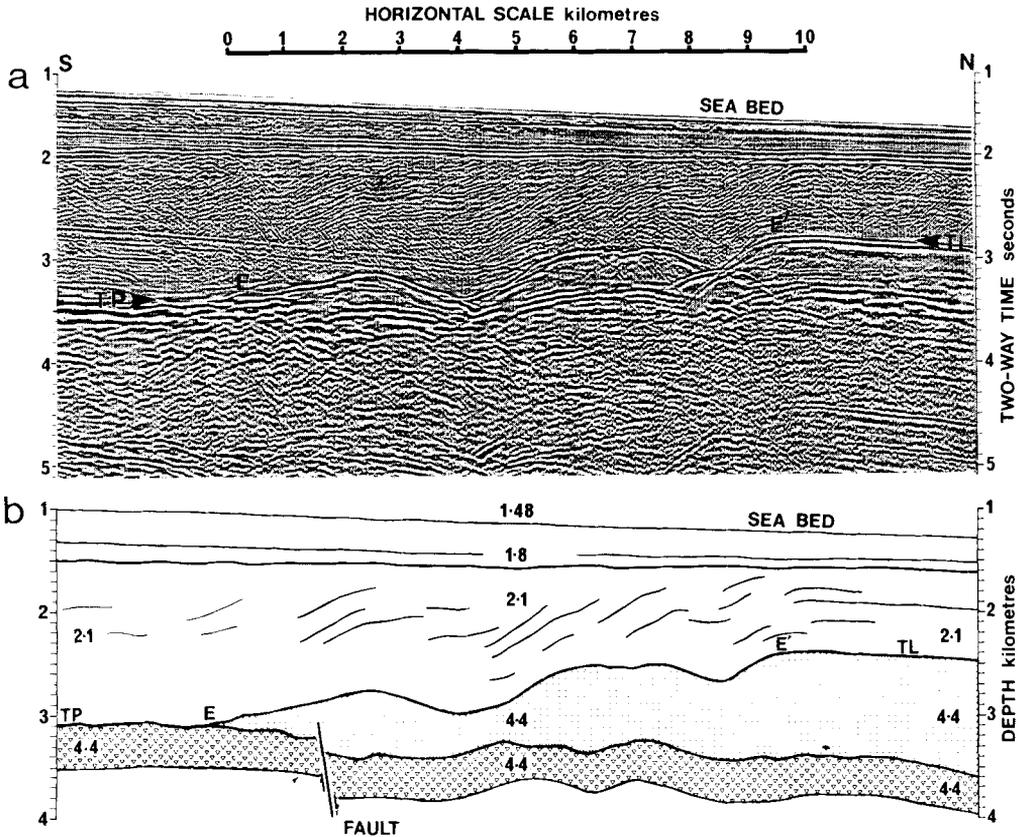


Figure 5. (a) Seismograph Service Ltd 24-fold seismic reflection line (SSL in Figs 2 and 6). Labels as in Fig. 3. (b) Line drawing of the reflection section, depth-converted using the interval velocities (km s^{-1}) shown. V-ornament indicates interval interpreted as early Eocene basalts, triangular ornament shows layer of strong reflectors interpreted as late Palaeocene basalts.

affect TL. Comparison of Figs 5(a) and 5(b) further supports the inferred high velocity of the interval TL–TP, from the ‘pull-up’ effect on TP beneath TL, seen in the two-way time section. The slightly higher interval velocity of $\sim 4.8 \text{ km s}^{-1}$, rather than the observed TL refractor of 4.4 km s^{-1} , was chosen for the NMO correction in order to eliminate any trace of multiples after stacking. However, the depth conversion is made with the observed velocity of 4.4 km s^{-1} .

Gravity measurements on the IGS surveys were carried out using an Askania GSS 3 meter mounted on an S. G. Brown gyro stabilized platform. Twenty lines were surveyed in the area with a mean mistie of track intersections of 2 mGal. The IGS data were combined with the three lines surveyed by Lamont–Doherty Geological Observatory to produce the free air anomaly map shown in Fig. 2(a). The values have been calculated against the International Gravity Formula of 1967 (GRS 67) and are referred to the UK National Gravity Network of 1973.

4 Reinterpretation of the Faeroe–Shetland Escarpment

4.1 STRUCTURE

Extrapolation from commercial exploration wells in the northern Viking Graben (Fig. 1b) along seismic reflection lines into the area north of 62°N shows that horizon TP is laterally

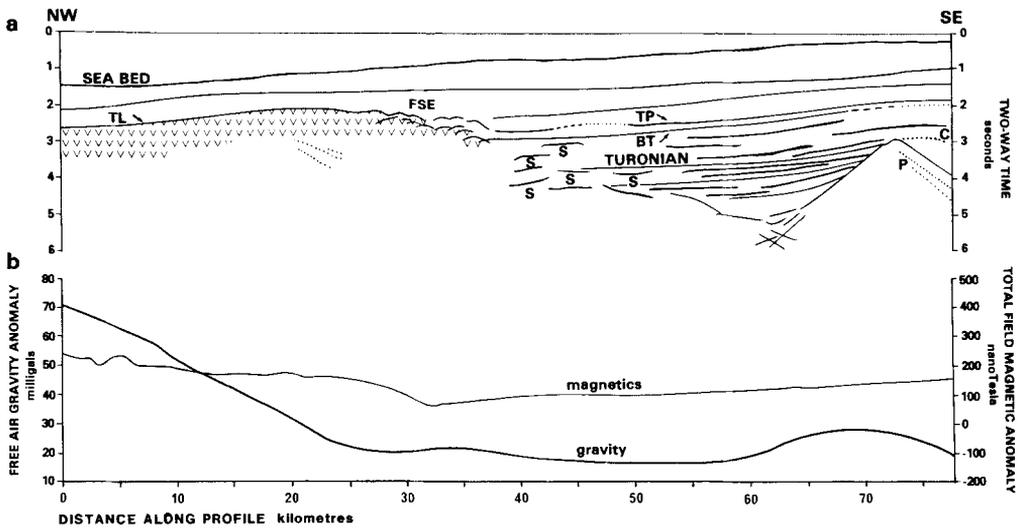


Figure 6. (a) Line drawing of BP 24-fold unmigrated reflection section 75–39 (BP in Figs 2 and 7). TL – top of early Eocene lavas (V-ornament) as in Figs 3, 5 and 7. FSE – Faeroe–Shetland Escarpment. Top Palaeocene (TP), Base Tertiary (BT) and Turonian reflectors are dated by correlation to wells in the Viking Graben. C (dots) – Cimmerian (late Jurassic–early Cretaceous) unconformity. P (dots) – Permian below the ENE trending sub-Cimmerian ridge. S – early Tertiary sills intruding Mesozoic sediments. (b) Free-air gravity and total field magnetic anomaly profiles along the BP reflection section.

equivalent to the Top Palaeocene ‘Ash Marker’ horizon of the North Sea (Jacqué & Thouvenin 1975). Fig. 6, which is a line drawing of a 24-fold reflection line shot for British Petroleum in 1975, illustrates the correlation of the Top Palaeocene (TP) and Base Tertiary (BT) horizons with the foot of the escarpment. Some reflection profiles (e.g. Fig. 5) show that reflector TP continues north-westwards below the strong reflector TL without significant tectonic disturbance, and the wedging-out of the TP–TL interval in the southward or eastward direction is due to an abrupt change of dip of the interface TL, from flat-lying, to a 10–20° dip south or east. Thus there is no evidence that the termination of reflector TL at the Faeroe–Shetland Escarpment is due to large-scale faulting, and the lack of diffractions on the reflection records, the absence of appreciable gravity gradients over the scarp (Fig. 2a) and the sinuous subcrop of the scarp itself (Fig. 7a) all support this inference. However, the subcrop of reflector TL, which is at around 2 km below sea-level, is marked by strong high-frequency magnetic anomalies, of the order of 50–200 γ in amplitude and 5–20 km in wavelength. The reflector is continuous with the top of the basalts of the Faeroes (Talwani & Eldholm 1972), so we conclude that the area of subcrop of TL (Fig. 7) is underlain by a pile of basalts of around 1 km in thickness, which terminates at the sinuous Faeroe–Shetland Escarpment. Sinuosity is probably also present on a small scale, as suggested by the apparently more complex structure of the Escarpment seen on the section of Fig. 5. This section trends N–S at a very acute angle to the local trend of the Escarpment, which has been mapped here (Fig. 7a) using other commercial seismic reflection lines (Fig. 1b).

The strongly reflective, irregular group of horizons immediately below TP (Figs 3 and 5) is quite unlike the ‘smooth’ character of the ‘Ash Marker’ further south (see, for example, Parker 1975; Deegan & Scull 1977). Although no arrivals corresponding to a refraction along this horizon were obtained on line D, we interpret the group of reflectors as a lower and thinner, but areally more widespread, series of basalts, for the following reasons:

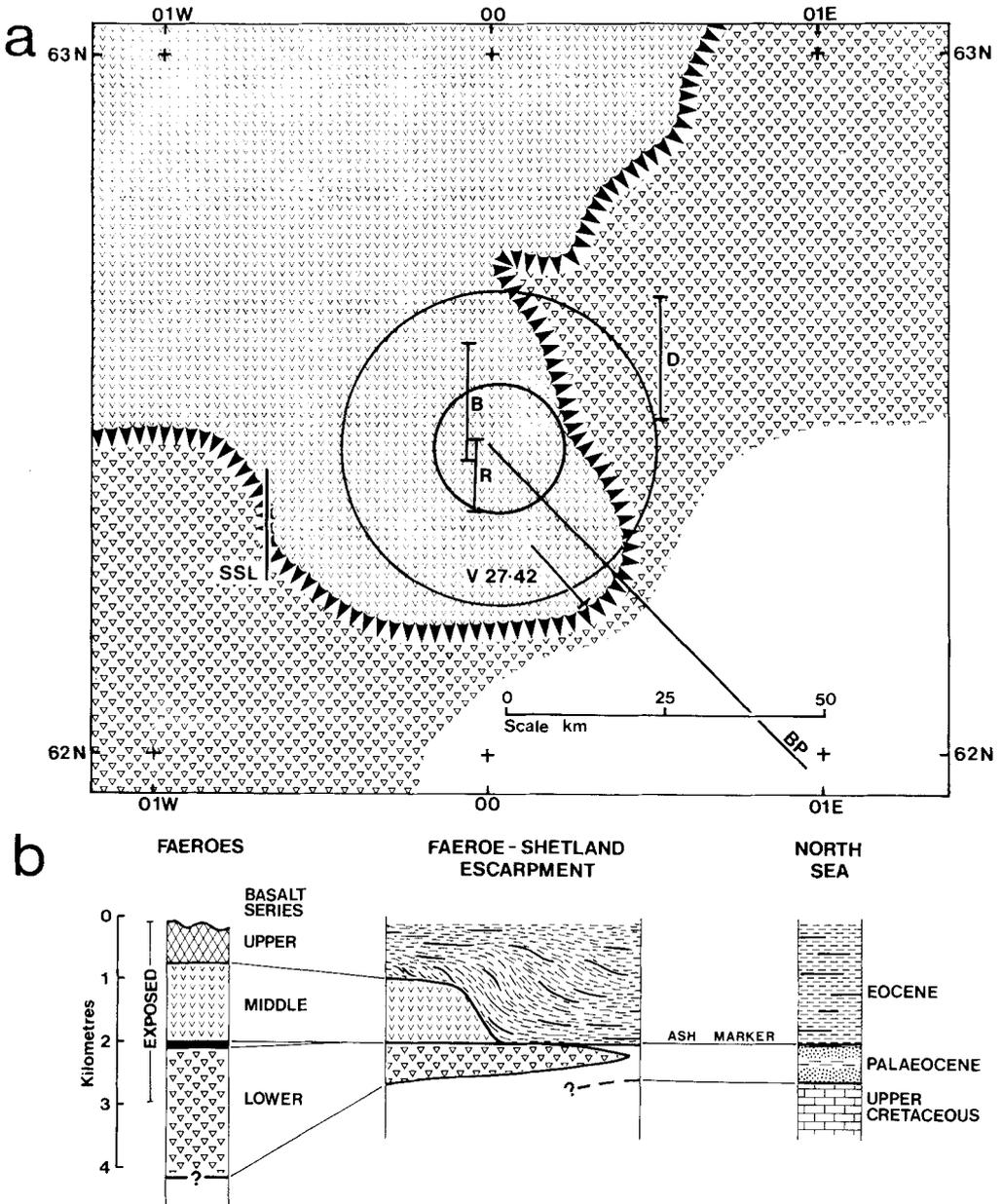


Figure 7. (a) Subcrop map (UTM projection) showing location of the Faeroe-Shetland Escarpment (hachures). Subcrop of smooth reflector TL (Figs 3, 5 and 6) is shown by V-ornament, interpreted as the top of a sequence of early Eocene basalts. Subcrop of irregular reflector TP, interpreted as the top of the late Palaeocene basalts, is shown east of the Escarpment by triangular ornament. Concentric circles show position of top and base of pluton of Figs 8 and 9. Lines B and D are IGS reversed refraction lines; V 27-42 is unreversed refraction line of Lamont-Doherty Geological Observatory (Talwani 1974). Line R is IGS wide-angle reflection line. (b) Diagrammatic geological correlation from the Faeroes through the area of detailed study at the Faeroe-Shetland Escarpment to the North Sea. Depth scale is schematic. Proportion of succession exposed on the Faeroes is indicated; remainder of Lower Series of basalts is inferred from refraction surveys (Pálmason 1965). Black band separating Lower and Middle Series represents 10 m of coal-bearing sediments, overlain by 100 m of tuffs and agglomerate. The Eocene clays and siltstones over the Escarpment are strongly cross-bedded (see Figs 3 and 5) and suggest a north-westerly source.

(1) Mapping of the Escarpment SW into the Faeroe–Shetland Trough using commercial reflection data shows that it gets progressively more subdued, and dies out in the region of 60°5 N, 3°5 W, where horizons TL and TP become effectively continuous (Smythe 1983).

(2) The group of strong irregular reflectors extends SE from the foot of the escarpment, to pinch out some distance to the SE, where the uppermost reflection passes laterally into the ‘smooth’ Ash Marker. The subcrop of the pinchout is irregular in plan, and there is no gravity gradient or magnetic anomaly marking it. No consistent reflections can be seen below the irregular reflectors, but this is explicable simply as a lack of deeper acoustic penetration, and not as an indication of ‘basement’ just beneath.

(3) The same group of reflectors extends, locally, across the Faeroe–Shetland Trough on to the West Shetland shelf, where, in the area of the Erlend igneous complex, the basalts predicted by Chalmers & Western (1979) have since been drilled (Ridd 1983).

(4) The absence of an expected high velocity arrival from this horizon on line D (and on other refraction lines observed in the region) can be ascribed to the dissipation of seismic energy along a thin high-velocity layer, whereas ‘basement’ underlying Tertiary sediments would be expected to give strong arrivals without difficulty.

(5) Our postulate of two groups of basalt in the region is consistent with the stratigraphy of the Faeroes, discussed below.

Our interpretation of these results, as two basalt groups, is shown in the depth converted drawing of Fig. 5(b).

4.2 AGE

The lower basalt series of the Faeroe Islands is separated from the middle and upper series (Fig. 7b) by a coal-bearing sedimentary sequence underlying a tuff-agglomerate zone (Rasmussen & Noe-Nygaard 1969, 1970). Microflora from the coal were originally dated as Eocene (Laufeld 1965), but recent work gives a late Palaeocene age (Lund 1983). The K–Ar ages of the lower and middle series of basalts (Tarling & Gale 1968; Fitch *et al.* 1978) lie, respectively, just beneath and just above the Palaeocene–Eocene boundary on the time-scale of Hardenbol & Berggren (1978).

The biostratigraphic assignation of the main ‘Ash Marker’ of the North Sea (Jacqué & Thouvenin 1975) has been altered slightly to calc nannoplankton zones NP9 (upper part) and NP10 (Kockel 1980; C. E. Deegan, private communication), thus placing it also at around the Palaeocene–Eocene boundary. We suggest, therefore, that coal-bearing tuff-agglomerate zone of the Faeroe Islands correlates with the end-Palaeocene Ash Marker of the West Shetlands and North Sea (Fig. 7b). The late Palaeocene lower series of Faeroese basalts therefore correlates with the lower thin series below and SE of the Faeroe–Shetland Escarpment, whereas the Faeroese middle series is probably equivalent to the thicker upper series forming the Escarpment.

The upper series of the Faeroe Islands is presumably more locally developed. An alternative correlation of the basalts at the escarpment with the upper Faeroese series, with the presumption that it is the middle Faeroese series which is absent at the Escarpment, we find less appealing, because the seismic reflection characters of the two groups at the Escarpment is markedly different (e.g. Fig. 5a). The ‘layered’ reflection appearance of the lower series at the Escarpment corresponds to the strongly rhythmic character of the layering of the Faeroese lower series. It follows that the acoustically ‘transparent’ upper basalts at the Escarpment (Fig. 5a) should therefore correspond to the structurally and morphologically ‘massive’ middle series on the Faeroe Islands (e.g. Rasmussen & Noe-Nygaard 1970, pp. 74–79), rather than to the upper Faeroese series, which, like the lower Faeroese series, is rhythmically layered.

4.3 ORIGIN

Our interpretation of the evidence presented above shows that the Faeroe–Shetland Escarpment has no direct relevance to the location of the continent–ocean boundary of NW Europe, other than the general and long-established association of Faeroese volcanism with the onset of seafloor spreading in the early Tertiary. The Escarpment is not a tectonic feature, but must therefore owe its origin to a depositional and/or erosional process.

We postulate the following sequence of events to account for the development of the Faeroe–Shetland Escarpment. We refer to the geomagnetic polarity scale of Hailwood *et al.* (1979), linked to Hardenbol & Berggren's (1978) biostratigraphic scale, but updating these for the recommended radiometric decay constants (Steiger & Jäger 1977):

(1) Terrestrial eruption of tholeiitic fissure basalts in the Faeroes region in late Palaeocene time, around 57–56 Ma. There may be a thickness of 2 km or more below the Faeroes (Pálmason 1965), of which the uppermost 1 km is exposed. Some 200–300 m thickness at the base of the exposed succession is normally magnetized (Tarling & Gale 1968), possibly during anomaly 25 time (c. 57 Ma). The basalts thin out southwards and eastwards, and in the Faeroe–Shetland Trough terminate in some localities at a small escarpment, elsewhere as an ill-defined feather-edge. The subcrop of this escarpment or feather edge may mark the contemporary shoreline, SE of which deltaic and fluvial sediments were being deposited in the Viking Graben and in a restricted basin west of the Shetlands.

(2) Cessation of volcanism was followed by a short interval of erosion, but with local areas of terrestrial deposition of clays and lignites, for example in the Faeroes and in the Moray Firth (Deegan & Scull 1977). A period of explosive volcanic activity followed, represented in the Faeroes by about 100 m of pyroclastics, and in the North Sea region by the deposition of several tens of metres of tuffaceous shales. This episode occurred around the Palaeocene–Eocene boundary at 55 Ma.

(3) The North Sea region subsided in the early Eocene, and terrestrial eruption of basalts began again in the Faeroes region. We infer that the latter region had also subsided, since the area of extrusion of this second phase of basalts was more limited, as defined by the location of the Faeroe–Shetland Escarpment. We postulate that terrestrial flows are abruptly halted at the contemporary shoreline, essentially by 'freezing'. In detail, the individual flows would be stopped by explosion and fragmentation on contact with the sea-water, with the ash debris being deposited seaward after near-immediate erosion (G. M. Brown, private communication). How the profile of the escarpment develops would depend upon whether subsidence kept pace with growth of the lava pile. A maximum slope of the face of the escarpment would result from subsidence falling behind deposition of flows, so that an increasing cliff height would be accompanied by a build-up at its foot of explosive debris and subaerially eroded material. This would account for the maximum observed dip of the escarpment, which is of the order of 25°, and which would correspond to the angle of rest of the debris.

(4) The middle basalt series of the Faeroes and its postulated eastward extension to the Escarpment built up a pile of around 1 km in thickness, over a period of, perhaps, 0.5–1 Myr. Extrusion of the upper basalt series then followed in the Faeroes area after a short interval, but we have no evidence for the offshore extension of this series, which is characterized by a very low *P*-wave velocity of 3.9 km s⁻¹ (Pálmason 1965). Both the middle and upper series are reversely magnetized, consistent with formation in the reversed epoch preceding anomaly 24.

It is apparent that the structure of the Tertiary basalts pile outlined above has no direct relevance to the continent–ocean boundary in the region of the NW British continental

margin. However, since the basalts are continuous with the oceanic basement to the NW, created by seafloor spreading in the early Tertiary, this boundary must lie somewhere beneath the pile. The simplest modification to Talwani & Eldhom's hypothesis is that the continent–ocean boundary lies somewhere towards the NW corner of the area of Fig. 7(a), and that the lobate thick pile of basalts extending SE overlies subsided continent continuous with that conjectured by these authors to exist below the Møre Basin and the Faeroe–Shetland Trough (Fig. 2b). It is likely also that the thick pre-Tertiary sediments known in these two basins will occur beneath the region of the present study, although as we have seen, there is no direct evidence for their existence from the seismic reflection or refraction surveys discussed above. Interpretation of the free-air gravity of the area (Fig. 2a) discussed in the next section, has a bearing on this problem.

5 The Brendan dome and Brendan seamount

5.1 GRAVITY MODELS

The subcrop of the uppermost series of basalts in the area of our detailed study forms a SE-facing lobe (Fig. 6a). The top of these basalts (horizon TL, Figs 5a and 7a) forms a closed structural high called the Brendan dome (named after St Brendan the Navigator; T. J. Wheatley, private communication). This structural high in the basalts can, however, only account for a small part of the observed free-air gravity anomaly, contours of which in the area of our detailed survey are shown in Fig. 2(a). The field shows a regional decrease from values of about +20 mGal in the east, to around –30 mGal in the west, superimposed upon which there is a circular high of over +70 mGal. Cross-section GG' is used in the gravity modelling. First, the gravity effects of the water layer and thick wedge of basalt are removed from the observed anomaly, using semi-infinite 2-D slabs having appropriate density contrasts relative to the Tertiary sediments. This leaves a 'semi-residual' anomaly, due to 4–4.5 km of Tertiary sediments of density $\sim 2.3 \text{ g cm}^{-3}$, overlying unknown denser rocks. Next, a planar regional is removed, leaving an almost symmetrical peak of $\sim 70 \text{ mGal}$ in amplitude, on the assumption that the density gradient within the Tertiary sediments and/or the underlying material has a small horizontal component due to the regional dip to the NW. Finally, we model the 70 mGal positive residual anomaly by taking the mean of the two sides of the anomaly, and constructing models with radial symmetry around a vertical axis, using combinations of concentric vertical cylinders and annuli.

The only likely geological explanation for the large radially symmetric residual gravity anomaly is that it is due to a large mafic or ultramafic igneous intrusion. It is therefore reasonable to place the following geometric constraints on the model: (a) the top must lie at or beneath the base of the basalts, at 4 km depth, and (b) the model should be bounded by a single closed surface (cylinders with separate annuli around them, for example, are geologically unrealistic). The assumed density contrast is also kept constant throughout the body. There are two simple geological models which will produce a sufficiently large gravity anomaly:

(1) the pluton could be mafic to ultramafic ($\rho \sim 3.1 \text{ g cm}^{-3}$) intruded through subsided continental crustal basement ($\rho \sim 2.8\text{--}2.9 \text{ g cm}^{-3}$), in which case a density contrast $\Delta\rho \sim 0.25$ will persist down to the lower crust, of the order of 30 km beneath sea-level.

(2) the mafic pluton ($\rho = 2.8\text{--}3.1$) is intruded through Mesozoic or older sediments ($\rho = 2.3\text{--}2.6$), the resulting density contrast of $\Delta\rho \sim +0.5$ accounting for all the observed anomaly, and with the contrast between the continuation at depth of the pluton and the surrounding basement rocks being negligibly small by comparison.

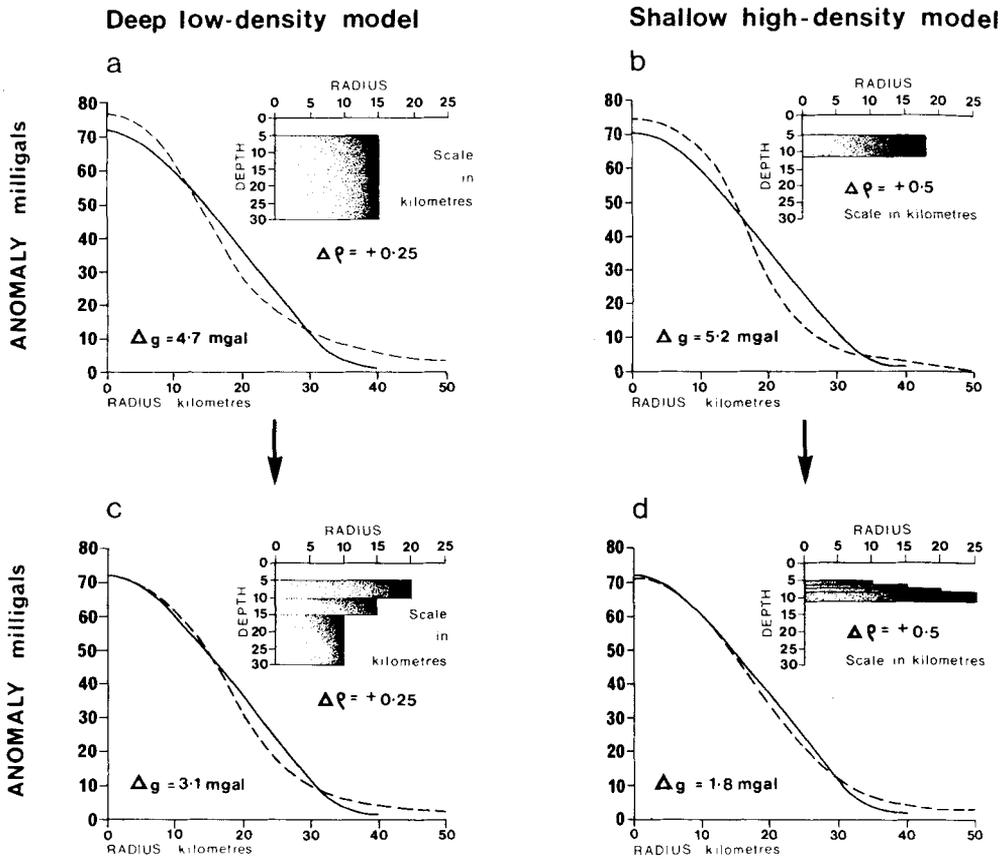


Figure 8. Radially symmetric observed residual gravity anomaly (solid lines), and anomalies (dashed lines) calculated from concentric vertical cylinders (insets). (a, b) Single cylinder. (c, d) Multiple concentric cylinders developed from (a) and (b), respectively. $\Delta \rho$ is density contrast in g cm^{-3} . Δg is rms misfit of calculated anomaly to observed anomaly using values at 0, 5, ... 40 km radius. Note that model (c) is geologically unrealistic. Model (d) is used in Fig. 9.

Preliminary modelling with a single cylinder shows that a rough fit of the model anomaly to the observed anomaly, to within 10 mGal, can be obtained both with: (a) the top and bottom at 5 and 30 km, respectively, radius 15 km, $\Delta \rho = 0.25$ (Fig. 8a), and (b) the top and bottom at 5 and 11 km respectively, radius 18 km, $\Delta \rho = 0.5$ (Fig. 8b). These two correspond to the two geological models (1) and (2) above, respectively. However, further refinement of the low-density contrast 'deep' model can only achieve a better fit (Fig. 8c) to the near-conical character of the sides of the observed anomaly using the geologically unusual inverted cone geometry, whereas a more satisfactory fit can be obtained in the 'shallow' high-contrast model with an approximation to a truncated cone tapering upwards (Fig. 8d).

Fig. 6 shows a section through the SE flank of the circular gravity anomaly, from 0 to 25 km along the profile, in relation to the deep pre-Tertiary sedimentary sequence observed to the SE. Although these sediments cannot be readily identified below the intrusions and basalts, the nearly flat gravity and magnetic anomalies imply that 'basement', more than 8 km deep in the SE, is unlikely directly to underlie the basalts. Furthermore, sub-basalt reflections, such as those between 20 and 25 km distance in Fig. 6, can be seen on the multi-channel commercial lines; they reveal a radially outward-dipping structure generally consistent with the gravity model of Fig. 8(d). We therefore reject the intra-basement, low-contrast

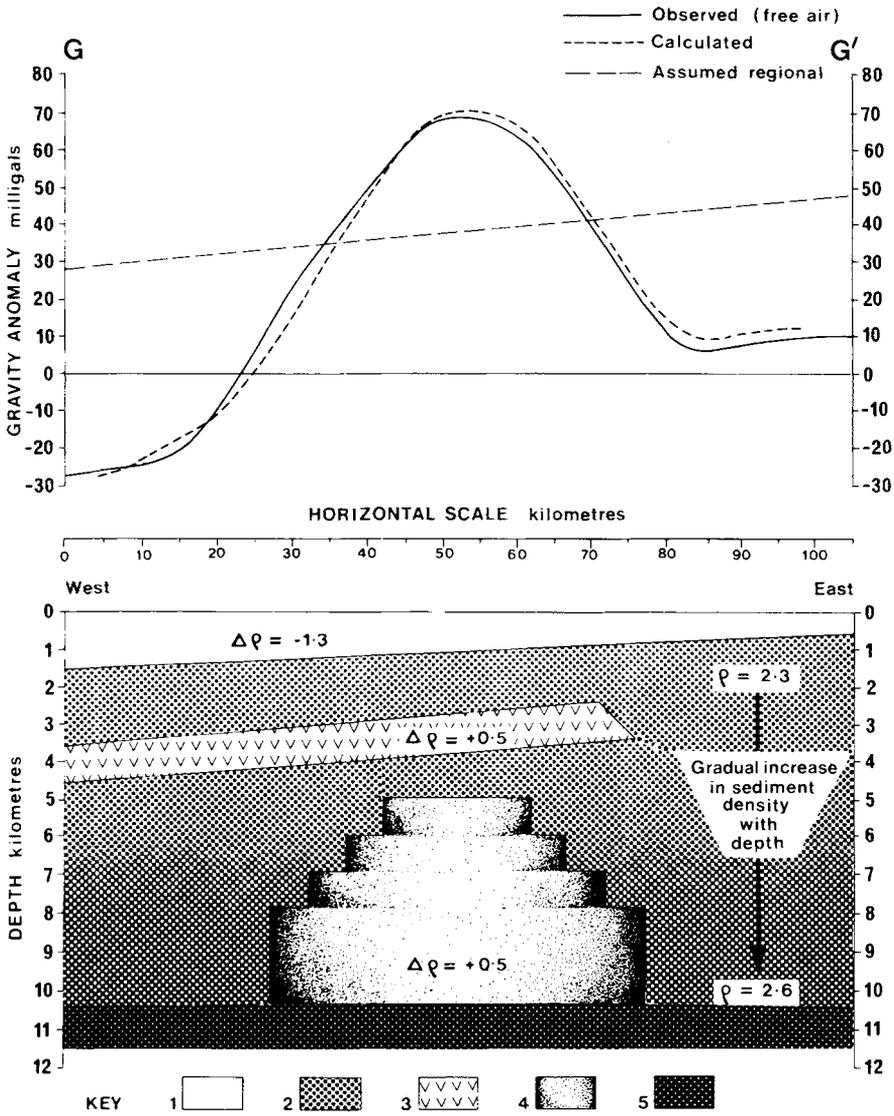


Figure 9. Observed and calculated gravity anomalies (upper figure) along profile GG' of Fig. 2. Lower figure is model used to calculate gravity anomaly, and is combination of semi-infinite 2-D slabs and concentric vertical cylinders (see text). Key: 1, sea layer; 2, sediments with density (g cm^{-3}) increasing downwards; 3, Tertiary basalts; 4, volcanic pluton model, from Fig. 8(d); 5, basement. Density contrasts $\Delta\rho$ are with respect to the sediment layer. Note that the assumed linear regional is apparently high because it is removed from a 'semi-residual' anomaly obtained by correcting the observed free-air anomaly for the effect of replacing the water and basalt layers by sediments.

type of model, in favour of the upright conical type. The complete gravity model adopted, using the version of Fig. 8(d) for the circular anomaly, is shown in Fig. 9. The dip of the conical side of the pluton is about 11° .

5.2 THE BRENDAN SEAMOUNT

Independent corroboration of the gravitational pluton model is provided by the 5.6 km s^{-1} late arrival on refraction line B, mentioned above. No unique solution to this event is

possible, first, because it is observed in one direction only, and secondly, because the velocity inversion (implicit in the chosen densities) postulated to occur beneath the basalts means that the underlying pre-Tertiary sediments will be a 'hidden layer' in the refraction interpretation. However, ray-tracing methods applied to simple models show, first, that the basalts here are about 0.5 km thinner than further SW (for example, Fig. 5b), and secondly that the dip of the refractor must be very low. A good fit ($|\text{model arrivals} - \text{observed arrivals}| < 50 \text{ ms}$) can be obtained with a planar refractor of $V_p = 5.2 \text{ km s}^{-1}$ dipping north at $2^\circ 3'$, at 5.5–6.0 km below sea-level. This corresponds very well to the top of the pluton postulated by gravity modelling in Fig. 9. The positions of the refraction lines in relation to the sub-crops of the basalts and the pluton model are shown in Fig. 7(a).

We interpret the plutonic body as a buried seamount, because the gently radially outward dips of its flanks, together with its roughly flat top implied by the planar refractor model, are inconsistent with intrusion of a large body through the pre-Tertiary sediment pile, whereas the shape of the body, which we call the Brendan seamount, is rather similar to the other large seamounts in the same region, Rosemary Bank and Anton Dohrn.

5.3 AGE OF THE BRENDAN SEAMOUNT

The obvious spatial association between the lobe of thick early Eocene basalts forming the Brendan dome and the underlying Brendan seamount (Fig. 7a) might suggest that the seamount is also early Tertiary in age. Modelling of the available aeromagnetic data at present (Fig. 1b), in an attempt to determine the magnetization of the body, is not feasible, due to the ill-determined effect of the overlying basalts. However, the following inferences lead us to conclude that the seamount is probably pre-Tertiary in age:

(1) The seamount, being a relatively rapid submarine or subaerial growth feature, must effectively pre-date the sediments surrounding and burying it. Whether the flat top is an original feature (Simkin 1972) or a product of later wave-cut planation, the 1–2 km of pre-Palaeocene sediments between the top of the body and the base of the basalts (Fig. 9b) suggests that the seamount is at least as old as late Cretaceous.

(2) Although correlation of dated reflectors right up to pinch-out against the flanks of the body is not possible, due to the prevalence of intrusives, it is likely that these sediments are at least as old as Turonian (see Fig. 6). The seamount is therefore early Cretaceous or older in age.

(3) Analogy with Anton Dohrn seamount, which is pre-Maastrichtian in age (Jones *et al.* 1974) suggests that the Brendan seamount might be of a similar age.

The spatial association of the basalts and a seamount inferred to be at least 20 Myr older can be explained as follows. The seamount, which at a depth of below 8 km or so (Fig. 9) is likely to be a cylindrical intrusive body of mafic or ultramafic rock extending well into the upper mantle, is likely to have stood high while the thick pile of surrounding sediments gradually compacted. Thus the land area of the Faeroe plateau, over which the second series of flood basalts erupted, may have included a peninsula above the old buried seamount, surrounded by shallow sea to the NE, SE and SW. This would account for the lobate extension of the basalts over the area underlain by the pluton (Fig. 7a), if our mechanism for the growth of the Faeroe–Shetland Escarpment is correct.

6 Crustal structure in the region of the Faeroe–Shetland Escarpment

6.1 GRAVITY MODELS

The 'prominent gradient in the isostatic gravity profiles' noted by Talwani & Eldholm (1972, p. 3583 and fig. 5, profiles S3, S4, S7 and S8; see also Fig. 1a above) over the

supposed position of the escarpment, is highly variable in amplitude and wavelength. We have accounted for two of these 'gradients' (profiles S3 and S4) as arising mainly from a buried pluton. The gradients on profiles S7 and S8 are not particularly striking features of the gravity field and have not been observed as linear or continuous in any way. Gravity data therefore provide little extra support for Talwani & Eldholm's proposals for the position and mode of origin of the Faeroe–Shetland Escarpment. Our model predicts a gravity gradient over the escarpment due to the lateral density contrast between Tertiary basalt and Tertiary sediments. This anomaly should have an amplitude of about 20 mGal km^{-1} height of the escarpment, and a slope length of up to 30 km, depending on the breadth and the depth of burial of the escarpment. Such a feature is generally obscured by larger anomalies, but it can be seen on Talwani & Eldholm's profile S6, where the sharp gradient above the escarpment can be modelled by an escarpment with a scarp face length of 5 km, a height of 800 m, a depth of burial of 2.1 km (seaward side), and a lateral density contrast of 0.6 g cm^{-3} .

There is only one published regional gravity model across one of the buried escarpments (Talwani & Eldholm 1972, fig. 19). This model of the Vøring Plateau Escarpment purports to show that the gravity data are generally consistent with their hypothesis of the escarpments as continent–ocean boundaries, but the apparently good fit depends on two highly dubious assumptions. First, their assumed regional has wavelengths similar to those of the gravity features they are attempting to model: this 'regional' is really nothing more than a smoothed misfit over the crucial area. Secondly, the density contrast between basement and pre-Tertiary sediments is assumed to be 0.12 g cm^{-3} . Donato & Tully (1981) have calculated average densities for sedimentary rocks in the North Sea, based on *in situ* measurements in 42 deep boreholes. Average densities for the Cretaceous (excluding deeply buried chalk) and Jurassic are about 2.35 and 2.45 g cm^{-3} respectively. Realistic average oceanic or continental crustal densities ought to lie in the range 2.75 – 2.85 (Worzel 1974). The approximate contrast between pre-Tertiary sediments and basement ought, therefore, to lie in the range 0.3 – 0.5 g cm^{-3} . Had Talwani & Eldholm adopted these more realistic densities their modelling would have shown that:

(1) Their inferred structure for the Vøring Plateau Escarpment implies a much larger gravity gradient than is observed.

(2) Their already serious problem with highly abnormal crustal thicknesses would be exacerbated, particularly under the thick pre-Tertiary basins, due to the Airy isostatic compensation which they have assumed.

(3) Their 'outer high' would produce a large misfitting gravity anomaly.

(4) The postulated 'high density belts' would have a density of more than 3.2 g cm^{-3} , i.e. of the order of upper mantle rocks (perhaps the large positive anomaly could be modelled more satisfactorily by invoking intrusions *within* the pre-Tertiary sediments).

We have attempted gravity modelling across the Faeroe–Shetland Escarpment along a slightly straightened section of part of Lamont–Doherty profile V2803 (S5, located in Fig. 1a). The gravity data (Fig. 10a) are taken from Lamont–Doherty data (0–120 km along profile) and from unpublished detailed Admiralty free-air gravity maps (120–290 km along profile). A correction of -8 mGal has been made to the Lamont–Doherty data. There is insufficient geological control along this profile to produce a definitive model; the function of the model (Fig. 10b) is to show merely that our reinterpretation of the structure of the Faeroe–Shetland Escarpment allows us to model the gravity data without having to apply *ad hoc* regionals or invoking grossly abnormal crustal thicknesses, such as thin continental crust juxtaposed with thicker oceanic crust.

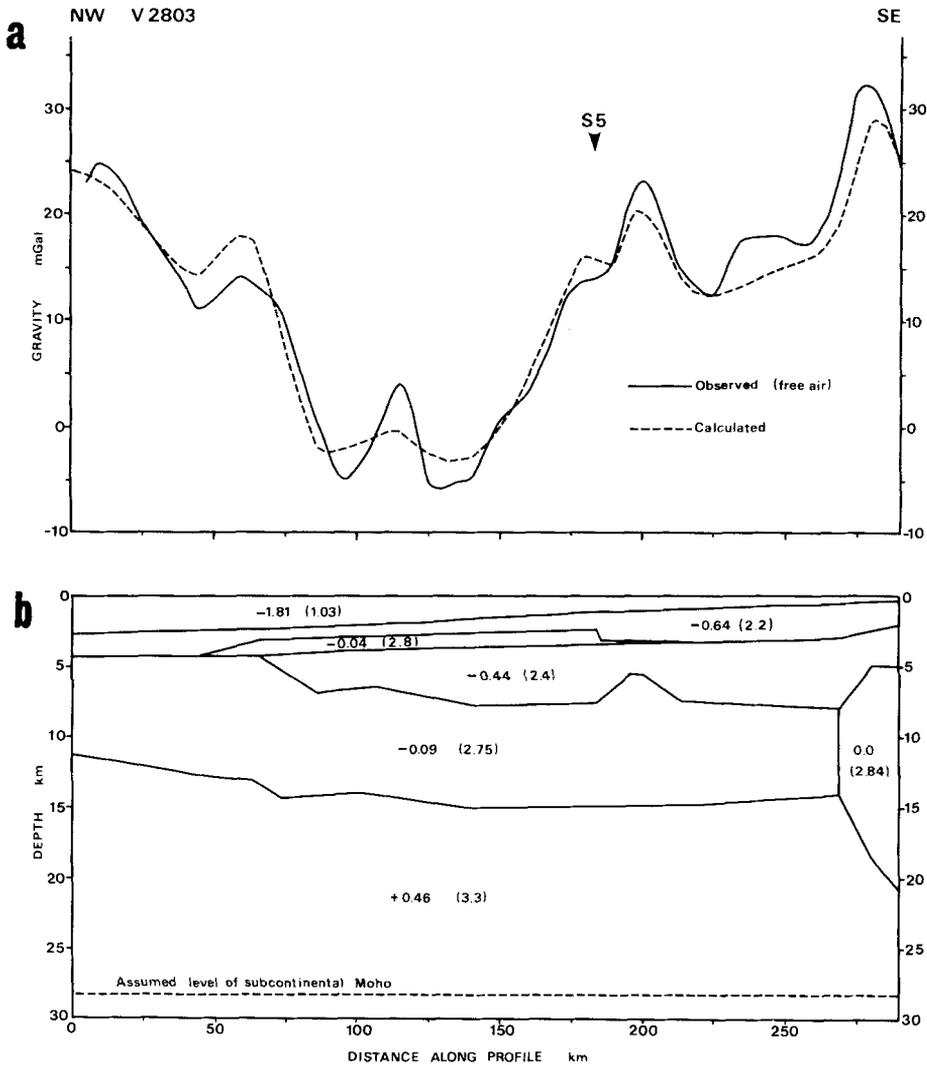


Figure 10. (a) Observed (free air) and calculated gravity anomalies. The profile runs close to Lamont–Doherty line V2803 (Figs 1a and 2a). S5 is the position of the Faeroe–Shetland Escarpment identified by Talwani & Eldholm (1972, fig. 5) and corroborated by us (Figs 2a and 7a). (b) The 2-D crustal model used to calculate the anomaly in (a) above, using infinite horizontal prisms. Density contrasts relative to 2.84 g cm^{-3} and absolute densities (in parentheses) are shown within each unit. The $+0.46$ density contrast of the mantle is applied down to 28.2 km, the level of the Moho in the assumed ‘standard’ continental crust off to the right of the profile (see Section 6.1 for discussion). The deep structure is tentative due to the lack of independent constraints, but the model shows that the available data are consistent with crust of normal oceanic thickness.

The constraints that we do have are as follows:

- (1) The water depth and thickness of Tertiary sediments are known.
- (2) There is Tertiary oceanic crust at least as far along the profile from the NW as 50 km, as demonstrated by the known geomagnetic reversal anomalies (Fig. 11b).
- (3) Commercial multichannel reflection data establish a minimum depth to basement of 8 km at around 260 km along the profile, and locate the Faeroe–Shetland Escarpment at 184–186 km along the profile; the escarpment here is about 800 m high.

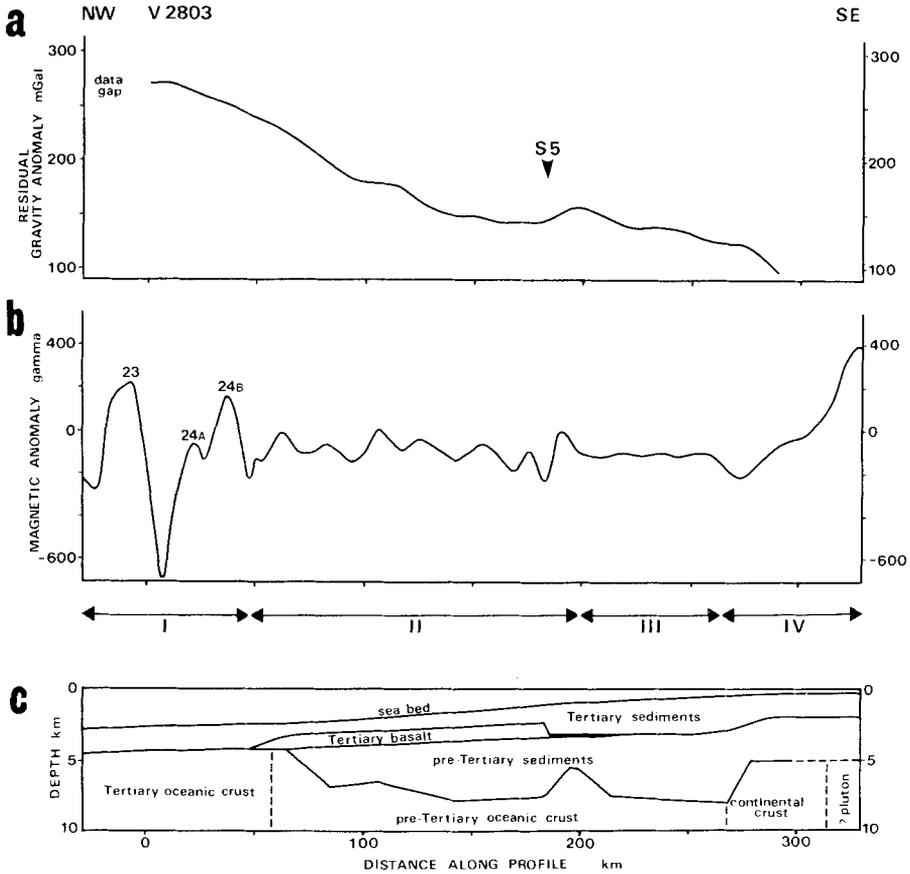


Figure 11. (a) Residual gravity anomaly after removal of the effects of the water, Tertiary sediments and basalt layers (Figs 10b and 11c) from the free air anomaly (Fig. 10a). (b) Magnetic anomalies on profile V2083. Oceanic stripe anomalies 23, 24A and 24B comprise zone I. Zone II–IV correlate respectively with Tertiary basalts, deeply buried crust and continental crust. (c) Uppermost 10 km of the gravity model of Fig. 10(b) with geological labels. The profile is the same as in Fig. 10, but has been extended along V2803 at each end.

We have assumed that the Tertiary basalts NW of the escarpment are 1 km thick, although they may well be thicker than this. Densities were assumed as shown in Fig. 10 (Worzel 1974; Donato & Tully 1981). The 2.75 oceanic crustal density represents a combination of 2.55 g cm^{-3} layer 2 and 2.86 g cm^{-3} layer 3. A standard continental crustal thickness of about 28 km was assumed. Using this assumption it was possible to estimate depth to the Moho where depths to basement were known, so as to preserve an approximate mass balance; this could be done at 260 km and over the area of known Tertiary oceanic crust. Depths to the Moho and the pre-Tertiary sediment thickness from 50 to 260 km were estimated by assuming a constant crustal thickness of about 7 km and assuming a rough mass balance. The structure at the SE end of the model is highly schematic, the location of the continent–ocean boundary is rather arbitrary, and the depths to basement are minima. The model was subsequently adjusted slightly in order to fit the observed gravity to an accuracy of $\pm 5 \text{ mGal}$. In the final model the density contrast of the upper mantle relative to continental crust was extended down to depth of 28.2 km, in effect to apply a small ‘DC shift’ to the calculated anomaly. The basement high centred at 200 km models a small residual linear gravity high, which, on the Admiralty free-air anomaly map, appears to extend NE from the

Brendan seamount gravity high described above: this postulated linear basement high and the seamount may therefore be related.

Our model and Talwani & Eldholm's model should be in broad agreement on the thickness and densities of the water layer and Tertiary sediments, and on the *minimum* thickness of Tertiary basalt NW of the escarpment. Using density contrasts relative to 2.84 g cm^{-3} (continental crust) the effects of these upper layers can be stripped from the observed free-air gravity (Fig. 11a). The residual gravity anomaly calculated in this way is dominated by a steep gradient ($\sim 1 \text{ mGal km}^{-1}$) from 0 to 140 km and a more shallow gradient ($\sim 0.2 \text{ mGal km}^{-1}$) from 140 to 280 km along the profile. We have accounted for these gradients by assuming a roughly constant crustal thickness across the area, raising the Moho and thus thinning the pre-Tertiary sediments. Note the absence of any steep gradients or changes in gradient over the Faeroe–Shetland Escarpment. If there are no pre-Tertiary sediments NW of the escarpment, then, using our density and mass-balance assumptions, the oceanic crust there would have to be 15 km thick, whereas the 'continental' crust to the SE of the escarpment would be only 10 km thick.

Gravity data therefore provide no positive support for Talwani & Eldholm's contention that the Faeroe–Shetland Escarpment is a linear feature marking the boundary between Tertiary oceanic crust and subsided continental crust. In order to model the gravity data using Talwani & Eldholm's hypothesis it is necessary to invoke one or more of the following: (1) grossly abnormal crustal thicknesses; (2) small density contrasts between pre-Tertiary sediments and oceanic or continental basement; (3) *ad hoc* crustal and upper mantle density variations. In contrast, our model is consistent with the observed gravity without requiring any abnormal conditions.

6.2 REGIONAL MAGNETIC ANOMALIES

The magnetic anomaly profile along line V2803 is typical of the magnetic profiles across the Faeroe–Shetland Escarpment, and has been subdivided into four zones of distinctive magnetic character (Fig. 11b, zones I–IV). Zone I contains large amplitude positive and negative anomalies which can be correlated with the well-known Tertiary marine magnetic anomalies up to and including anomaly 24B. Zone II comprises anomalies of much smaller amplitude caused, in our view, by the $> 1 \text{ km}$ thick Tertiary basalts. Talwani & Eldholm (1972) do not recognize this change in character, although it is obvious on their profiles S4–S8. Our model predicts a small negative magnetic anomaly on the immediate NW of the escarpment and a smaller positive anomaly on the SE side assuming that the Tertiary basalts are reversely magnetized: the observed anomalies above the escarpment fit such a model in a general way. South of 63°N , however, the commercial aeromagnetic map (Fig. 1b) shows that simple edge-effect anomalies like this are often obscured, due presumably to the presence of Tertiary and earlier intrusions.

Magnetic zone III is quiet, due to the 8 km depth to magnetic basement which, if oceanic as we believe, suggests that the seafloor spreading occurred during a single geomagnetic polarity epoch. The magnetic lineations within the quiet zone postulated by Talwani & Eldholm (1972, figs 5 and 20) north of 63° do not exist on our commercial aeromagnetic map covering the area south of 63°N . Zone IV is dominated by a large positive magnetic anomaly, which the IGS ship-borne magnetic map of the area shows is sub-circular in plan. This 'Magnus' anomaly is one of those in the North Sea on which 3-D modelling has been used to postulate the presence of a plutonic body of ?Permian age (Beamish, Glen & Smythe 1980).

Thus although we agree with Talwani & Eldholm (1972) that the Faeroe–Shetland Escarpment marks the edge of a magnetic quiet zone, we do not agree that this is necessarily

indicative of a major crustal boundary. The boundary between zones I and II (Fig. 11b) is, in our opinion, just as striking, and seems more likely to mark the SE limit of Tertiary oceanic crust. There seems to be no locality where either the magnetic or the gravity anomalies are more consistent with Talwani & Eldholm's views than with our own.

6.3 OCEANIC OR SUBSIDED-CONTINENTAL CRUST?

There are no crustal seismic refraction lines in the area of the present study, nor in the Faeroe–Shetland Trough to the SW and the Møre Basin to the NE, which are relevant to the interpretation of the crustal structure beneath the thick sediments of this part of the NW European continental margin. Gravity interpretation alone as a means of estimating crustal thickness is inconclusive, since the thin-crust model which can be derived from the gravity data in this area (Fig. 10) depends on the *a priori* assumption of Airy isostasy, whereas other mechanisms of compensation could equally well satisfy the gravity, but imply instead crust of continental thickness. Talwani (1976, p. 347) has illustrated this point with a gravity model of the south Australian margin incorporating what 'could be regarded as an oceanized continental block'.

The Faeroe–Shetland Trough and Møre Basin form the central section of a zone of deeply buried pre-Tertiary crust extending from the Rockall Trough in the south to the eastern Norwegian Sea (Inner Vøring Plateau) in the north. It has been suggested (Roberts 1974; Bott 1975) that if the Rockall Trough is oceanic in origin, then on geometrical grounds oceanic crust of the same age is likely to underlie the whole zone to the north as well. The geometrical requirement, which follows from the assumption that the Greenland and European plates are rigid, has been demonstrated graphically using an oblique Mercator projection (Russell & Smythe 1978). It could, however, apply equally well to the subsided continental origin postulated for the region by Talwani & Eldholm (1972, 1977), if continental thinning, subsidence and 'oceanization' is accompanied by separation of the two plates. The question of the origin of the crust below the Inner Vøring Plateau or the Rockall Trough, for example, cannot therefore be considered in isolation from that of the whole region taken together.

At present the evidence for crustal structure in the region is equivocal; the apparently transitional crustal structure derived from refraction data in the Inner Vøring Plateau (Hinz 1972; Talwani 1976) can be satisfactorily re-modelled with an ocean-like crustal structure (D. K. Smythe, unpublished work). The refraction data in the Rockall Trough (Scrutton 1972) are not complete enough to exclude the possibility of some sort of 'subsided continent'.

The age of formation of the crust must clearly pre-date the overlying sedimentary cover. Seismic stratigraphic dating methods applied to reflection data from the Møre Basin north to the Inner Vøring Plateau suggest that there are pre-Cretaceous rocks present (Jørgensen & Navrestad 1981). However, there is a possibility that their interpretation of tilted fault-blocks below a supposed 'late Cimmerian' unconformity is wrong, and that the reflectors in question are instead due to sills cross-cutting the Cretaceous succession, as is common in the Faeroe–Shetland Trough. A good example of one of the seismic reflection lines, rather than just a line drawing interpretation, needs to be released (*cf.* Section 1), so that the published interpretations can be better evaluated.

There are at least 2–3 km of pre-Turonian sediments in the Faeroe–Shetland Trough and Møre Basin, as shown by the correlation of seismic reflectors (e.g. Fig. 6) with wells on the shelf. On the outer flank of the Rona Ridge more than 1 km of Lower Cretaceous rocks have been drilled (Ridd 1981, p. 422), enabling a satisfactory correlation and mapping of 'Top Lower Cretaceous' and probable 'Top Jurassic' reflectors to be made some way out into the

Faeroe–Shetland Trough (*cf.* Ridd 1981, fig. 7). Gravity modelling (assuming Airy isostasy) shows that the underlying crust here thins abruptly from an assumed normal continental thickness below the West Shetland shelf (with the Moho at 28 km) to less than 10 km in thickness below the Trough.

It is thus well established that there are rocks of Albian (and probably much older) age resting on the thin crust below the Faeroe–Shetland Trough and Møre Basin. The possibility that this crust was created during a phase of seafloor spreading in post-Albian, pre-Maastrichtian time (~100–70 Ma), as is conjectured by some authors to have occurred in the Rockall Trough (Roberts 1974; Roberts, Masson & Miles 1981), is clearly precluded here. Leaving aside any 'fixist' explanations, employing only vertical movements, for the generation of the 'proto North Atlantic' strip of deeply buried crust, we can draw no definite conclusions about its origin, but we can say that it was in existence before the end of the early Cretaceous. This conclusion is based on the stratigraphic evidence from the Faeroe–Shetland Trough discussed above, which we consider to be more trustworthy than that based essentially on correlation and modelling of supposed linear oceanic magnetic anomalies in the southern Rockall Trough, apparently implying a post-Albian phase of spreading (Roberts *et al.* 1981).

7 Conclusions

We conclude that the structure of the Faeroe–Shetland Escarpment in the region due north of the Shetlands has no relevance to the position of the continent–ocean boundary at the European shelf edge, as postulated in the model by Talwani & Eldholm (1972). We have proposed, instead, that the Escarpment was formed by the build-up of a pile of early Eocene terrestrial flood basalts erupted throughout the Faeroes region, as successive flows were chilled on reaching the contemporary shoreline. We have dated these basalts and the underlying late Palaeocene group of basalts by stratigraphical correlation with the Faeroes and with wells in the North Sea.

Our inferences from gravity modelling, although not conclusive, suggest that there is a buried seamount, of similar dimensions to Anton Dohrn and Rosemary Bank, below the basalts. Like them, our newly postulated Brendan seamount appears to rest roughly axially upon a 200 km wide zone of deeply buried thin crust. The sediments which have buried the thin crust and the seamount are at least as old as early Cretaceous (pre-Albian; ~110 Ma) in age, and therefore preclude an origin for the crust by a mid-Cretaceous episode of seafloor spreading.

These results do, however, permit alternative hypotheses invoking either seafloor spreading, or a phase of intra-continental rifting, stretching, and subsidence, of pre-mid-Cretaceous age. We favour the first of these alternatives, on the grounds that seafloor spreading is at once a more elegant, but at the same time a more rigorous, hypothesis than the 'subsided continent' theory.

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