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Crustal Structure of the Iceland-Faeroe Ridge

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Abstract. Knowledge of the crustal structure of the Iceland-Faeroe Ridge is based on results from the North Atlantic Seismic Project of 1972 supplemented by earlier short refraction lines and reflection, gravity and magnetic surveys. The main 5.7 km/s upper crustal layer is locally overlain by lower velocity layers of variable thickness. The upper crust is interpreted as being predominantly basaltic, comprising lavas, regions of pyroclastic rock and intrusives including ring complexes. A 6.7 km/s lower crustal layer underlies the upper crust at a depth of between about 4 and 8 km along the Ridge; this layer is present also beneath the Icelandic shelf but not beneath the Faeroe shelf. A deeper 7.8 km/s refractor interpreted as the Moho occurs at about 30–35 km depth beneath the south-eastern part of the Ridge, shallowing to about 28 km towards the north-western end of it. A significant increase in velocity with depth within the main 6.7 km/s layer has not been detected but may occur, in which case the Moho would be somewhat deeper. The seismic crustal results are consistent with a gravity profile across the Ridge, which indicates approximate Airy isostatic equilibrium. The crust beneath the Ridge, which is of a thickness more typical of the continents than the oceans, is believed to have been formed by sea-floor spreading during the period 55 to 40 Ma ago.

Key words: Iceland-Faeroe Ridge – Crustal structure – Seismic refraction.

1. Introduction

The Iceland-Faeroe Ridge (Fig. 1) forms an upstanding bathymetric feature of NW-SE trend which connects the Iceland Block containing the active spreading centre to the Faeroe Block of probable continental origin. It is about 400 m deep along its smooth crest, and is separated from the Iceland and Faeroe shelves by short, sharp bathymetric scarps. It appears to form the oldest part of the aseismic Icelandic transverse ridge which crosses the north-eastern Atlantic, having originated by seafloor spreading starting about 55 Ma ago during the initial stages of separation of Greenland from the Rockall-Faeroe microcontinent. The shallow bathymetry in relation to the adjacent Norwegian and Reykjanes basins indicates a highly anomalous underlying structure for an oceanic region. Prior to the present investigation, gravity and seismic investigations (Bott et al., 1971) indicated that the elevation of the Ridge probably arises because of an underlying crust with a thickness more like that of continental than oceanic regions. This paper describes the investigation of the anomalous crustal structure of the Ridge by the North Atlantic Seismic Project (NASP) of 1972, incorporating the earlier shorter seismic lines of Bott et al. (1971).

An earlier study of the crustal structure of the Iceland-Faeroe Ridge based on NASP data has been presented by Zverev et al. (1975). They interpreted the crust as being 30–35 km thick in agreement with our interpretation, but they regarded the crust as being in structural continuity with that of the Faeroe Islands in disagreement with us.

2. The North Atlantic Seismic Project

The North Atlantic Seismic Project (NASP) was a sea-to-land explosion seismology crustal refraction investigation of the structure between North Scotland and Iceland taking place in July and early August 1972. Shots were fired at sea from MV *Hawthorn*, these consisting mainly of 300 lb (136 kg) or 600 lb (272 kg) charges of geophex fired along a series of lines shown in Fig. 1 (inset) using long burning fuses. A few 1,200 lb (544 kg) shots were also fired. Most of the shots detonated at about 180 m depth or on the seabed where shallower than this. Of relevance to this paper is the shot line A which stretches from the Faeroe Islands to Iceland and runs along the crest of the Iceland-Faeroe Ridge. About 70 main shots were fired along this line, and a number of smaller shots (23 and 12 kg) were fired in the vicinity of the recording ship *Mikhail Lomonosov* and on the Icelandic shelf. The shots numbered A7 to A38 were situated on the main line along the Iceland-Faeroe Ridge itself and consisted of 600 lb (272 kg) charges, spaced on average at about 10 km interval. A further short subsidiary line of shots was fired on the Ridge to the north-east of the main line along the region of high gravity; this consisted of five 600 lb charges numbered between A75 and A84.

The shots were recorded at seven stations situated on the Faeroe Islands, six of these being provided by Aarhus University in cooperation with Hamburg and Kiel Universities (F1 to F6) and one by Durham University (DU4). A total of fifteen recording stations were situated on Iceland; station M1 was a six-seismometer L-shaped array operated by the National Energy Authority of Iceland and M2 was provided by Lamont-Doherty and operated under the supervision of Dr. P. Einarsson. Station DU5 was provided by Durham University. Stations R1 to R6 were provided by the Institute of the Physics of the Earth, Moscow, and were operated under the supervision of Dr. S.M. Zverev, and stations S1 to S6 along the south coast of Iceland were provided by La-

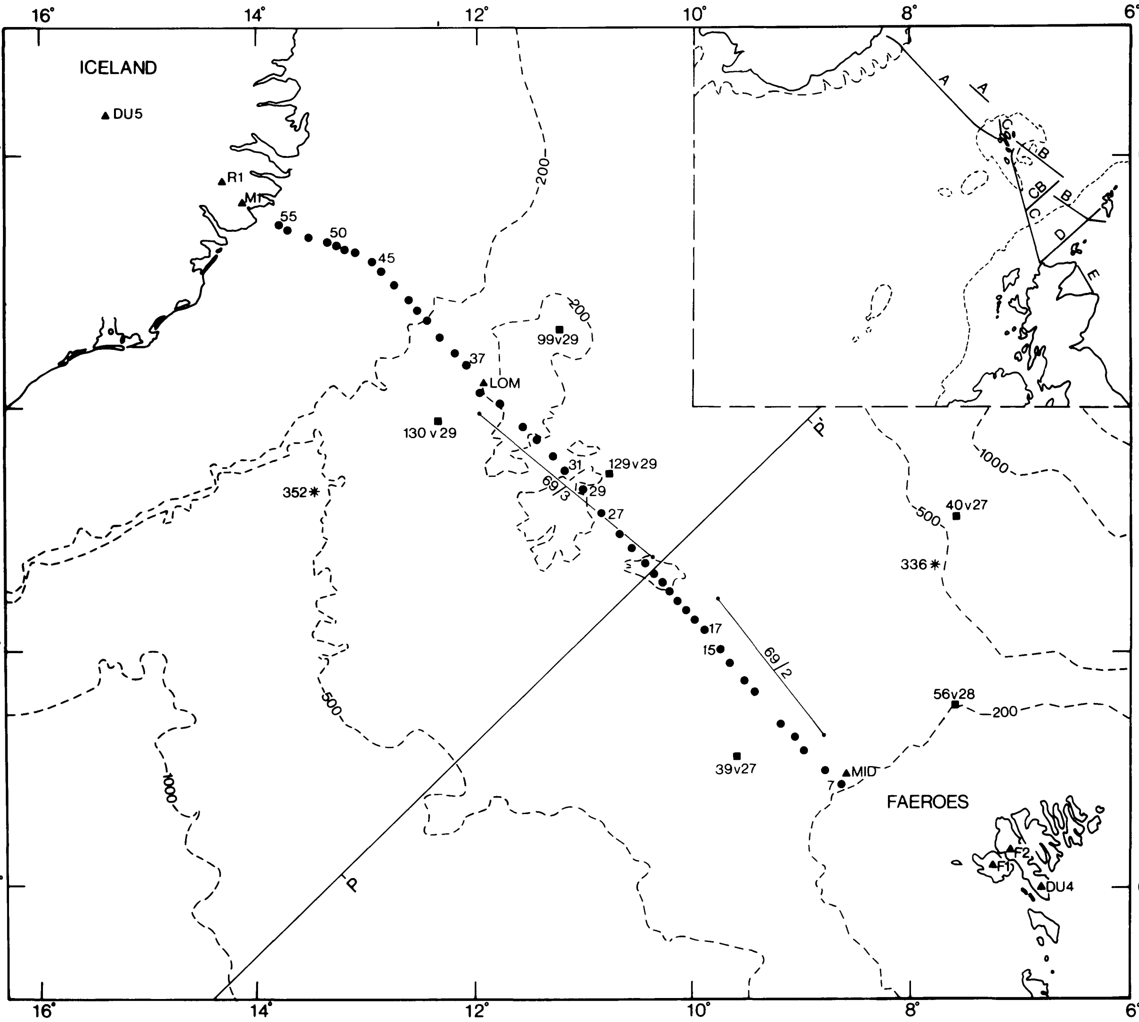

Fig. 1. Map showing shot positions (*solid circles*) and seismic recording stations (*triangles*) used in the determination of crustal structure beneath the Iceland-Faeroe Ridge. *Refraction lines 69/2* and *69/3* are from Bott et al. (1971), sono-buoy refraction lines *99299* etc. from Grønlie and Talwani (1978), and DSDP holes 336 and 352 are shown. Bathymetric depth contours are shown in fathoms, and the overall shot lines of the North Atlantic Seismic Project are shown on inset

mont-Doherty Geological Observatory. Shots were also recorded at sea by the Soviet research vessel *Mikhail Lomonosov* which operated an underwater seismometer station near the north-western end of the line A on the Ridge and by MV *Miranda* which occupied two stations along line A, one of these near the south-eastern end of the Ridge and the other about two-thirds way along it towards the Icelandic shelf.

In this paper we describe an analysis of the crustal structure of the Iceland-Faeroe Ridge based on arrivals from shots A7 to A39 on the Ridge and A40 to A50 on the Iceland shelf. Recordings were used from *Lomonosov* (LOM) and one *Miranda* station (MI(D)) on the ridge, stations DU4, F1, and F2 on the Faeroe Block, and stations M1, R1, and DU5 on Iceland.

3. Upper Crustal Structure

We define the upper crust as the region above the 6.7 km/s main crustal layer which starts at about 7 km depth. This has been studied by reflection profiling, gravity and magnetic surveys, and Leg 38 DSDP drilling. The layering has been investigated by two ship-to-ship refraction lines each of about 100 km length and by sonobuoy refraction lines.

Reflection profiling shows that sediments are thin or absent over most of the smooth crustal region of the Iceland-Faeroe Ridge except in local troughs such as those beneath the scarps at both ends of the Ridge (Johnson and Tanner, 1972; Fleischer et al., 1974; Grønlie and Talwani, 1978). This is borne out by the general presence of conspicuous short wavelength magnetic anomalies indicating that highly magnetic rocks crop out on the seabed or not far beneath it over most of the crestal region (Bott and Ingles, 1972). Some large amplitude circular magnetic anomalies also occur, these probably representing igneous intrusions of ring type occupying the eroded cores of ancient volcanoes (Ingles, 1971). The gravity field over the ridge crest is unusually variable for an apparently oceanic region, with some local anomalies of 20 to 40 mgal amplitude caused by lateral variation of upper crustal density (Bott et al., 1971, Fleischer, 1971, Fleischer et al., 1974). Some regions of gravity low correspond to slight bathymetric depressions. Correlation between gravity anomalies and medium wavelength magnetic anomalies is also observed, with the magnetic polarity varying from area to area (Bott and Ingles, 1972).

The seismic refraction lines 69/2 and 69/3 of Bott et al. (1971) (Fig. 1) revealed the local presence of one or more low velocity uppermost layers with velocities ranging between 3.2 and 4.6 km/s and a composite thickness locally reaching up to nearly 4 km; elsewhere these layers are thin or absent. The underlying main upper crustal layer yielded an estimated velocity of 5.7 km/s along 69/3 and 5.4 to 5.8 km/s along 69/2. The regions of thick low velocity rocks show correlation with slight bathymetric depressions and low gravity anomalies. The sonobuoy refraction results presented by Grønlie and Talwani (1978) are consistent with this picture.

During Leg 38 of the Deep Sea Drilling Project (Talwani et al., 1976) drilling sites 336 and 352 were situated on opposite flanks of the Iceland-Faeroe Ridge where sediments thicken towards the adjacent Norwegian and Reykjanes basins. At site 336 on the north-eastern flank in 811 m water depth about 30 m of oceanic tholeiitic basalts were penetrated below 515 m of sediment of upper Eocene and later age. The basalts, dated at 40–43 Ma old, show evidence of subaerial erosion indicating that the basement has subsided by at least 1,350 m since formation. At site 352 on the south-eastern flank 122 m of sediment of Oligocene and later age was penetrated but basement was not reached.

The upper crust beneath the Iceland-Faeroe Ridge thus appears to consist of highly magnetic igneous rocks of probable basaltic composition. Pockets of low velocity and low density rocks are best interpreted as regions where pyroclastic rocks (tuffs and agglomerates) predominate. Circular igneous intrusions representing the cores of ancient volcanoes are also found. As evidenced by the subaerially weathered basalt in DSDP hole 336, the crestal region probably stood about 1 km above sea level in early Tertiary time and has subsequently subsided to its present elevation as the underlying lithosphere cooled, as suggested by Bott et al. (1971) and Vogt (1972).

4. Crustal Structure From NASP

The presence of a 6.8 km/s refractor (revised by NASP to 6.7 km/s) beneath the Iceland-Faeroe Ridge at a depth of about 7 km was first detected by refraction line 69/3 (Bott et al., 1971). A short unreversed segment with apparent velocity 7.84 km/s along line 69/2 was originally interpreted tentatively as the head wave from the Moho at about 16 km depth, but the later NASP results presented here indicate that this segment probably represents arrivals from the 6.7 km/s layer where it is dipping. The NASP results indicate the presence of two main crustal refractors beneath the length of the Ridge, the 6.7 km/s refractor representing the top of the main crustal layer, and a 7.8 km/s refractor at about 30 km depth representing the Moho.

The main problem of interpreting the NASP data is that, whereas the shots were fired along the Ridge itself, most of the recording stations were situated on land on the adjacent Iceland and Faeroe Blocks which may lack structural continuity with the Ridge. Fortunately the marine stations occupied by *Lomonosov* and *Miranda* (sites D and E) were situated on the Ridge itself. Under such circumstances, the time-term method can make use of arrivals from the Ridge shots at the stations on Iceland and Faeroe Islands, provided that the travel path to a station beneath an adjacent block from a given refractor beneath the Ridge can be assumed to be identical for all relevant shots.

A serious drawback of the time-term method in crustal seismology is the substantial offset between the surface shot or recording points and the positions where the rays leave the refractor (O'Brien, 1968). This problem is particularly acute for the Moho refractor beneath the Ridge. The dip of the refractor cannot be assumed to be uniform over the cone of critical rays at a surface point, which is of the order of 50 km in radius for Moho arrivals beneath the Iceland-Faeroe Ridge. Thus the variation in time-term along the line cannot be regarded as an accurate indication of variations in depth to the refractor. We have overcome this difficulty by a modification of the time-term method developed by one of us (K.G.). To determine the depth profile of a refractor, we first assume a constant velocity layering above. The refracting interface is then defined in terms of a series of points of specified horizontal location and unknown depths (to be determined). The depths and refractor velocity are determined by iteration from an initial model, using linear inversion at each stage. This method has been applied to the interpretation of first-arrival times from both 6.7 and 7.8 km/s refractors.

The 6.7 km/s Refractor

As a first stage, a time-term solution for the 6.7 km/s layer was obtained using the shots on the Iceland shelf recorded by *Lomonosov* (LOM) and by stations R1 and M1 on Iceland. A well-determined solution UW2 was obtained yielding a refractor velocity of 6.76 ± 0.013 km/s (Fig. 2). The time-terms at LOM and shot A36 were equated to each other, being determined as 0.88 s. The time-terms determined for shots A40 to A50 on the Iceland shelf were found to be about 1.0 s but those for the shots at the NW end of the Ridge are significantly smaller at about 0.7 s.

A separate solution was obtained for the Iceland-Faeroe Ridge itself, using shots between A7 and A31 recorded at MI(D), LOM and land stations F1, F2, and DU4 on the Faeroe Islands (Fig. 2). In order to make the solution unambiguous, it was necessary to assume a time-term value of 0.88 s at LOM as obtained in solution UW2 above (LOM = A36). The approximate validity of this assumption is confirmed by the line 69/3 result and by the determined value at MI(D) being intermediate between values determined for shot points A7 and A8. The results (Fig. 2) show that the time-terms along the Ridge vary between about 1.0 s and 0.5 s, the lower values occurring in the region between shots A13 and A23. The velocity was determined to be 6.73 ± 0.04 km/s. Minus time analysis was used to verify the velocity estimate over short segments of the line.

Variation in delay time (i.e., time-term) to the 6.7 km/s refractor may arise either from lateral variation in the shallow velocity structure, or by variation in depth to the refractor, or both. There is evidence presented by Bott et al. (1971) and Fleischer et al. (1974) to show that much lateral variation does occur, but this is not yet sufficiently well defined along the line to allow for it in constructing a model. We have therefore used the iterative method we have developed to estimate the depth to the 6.7 km/s refractor between MI(D) and LOM assuming that the overlying layer has a constant velocity of 5.0 km/s. The analysis is based on arrivals at LOM, MI(D), F1, F2, and DU4. The resulting shape of the interface (Fig. 3) closely resembles the pattern of time terms, so that the offset is not a serious problem for this relatively shallow refractor This solution yielded an estimated refractor velocity of 6.72 ± 0.05 km/s which does not differ significantly from that obtained by time-term analysis. This interpretation (Fig. 3) shows the refractor shallowing between shots A11

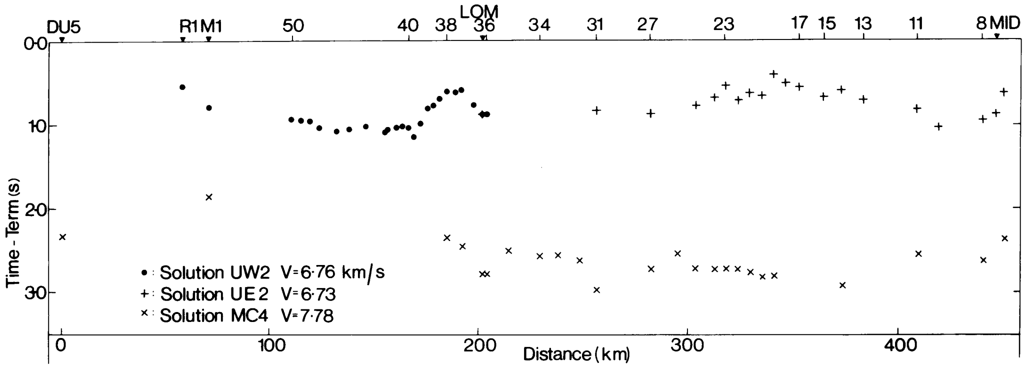

Fig. 2. Results of time-term analyses for line A shots and stations along the Iceland-Faeroe Ridge. Solutions UW2 (Icelandic shelf) and UE2 (Iceland-Faeroe Ridge) are for the 6.7 km/s refractor and solution MC4 for Moho arrivals. For shot and station positions see Fig. 1

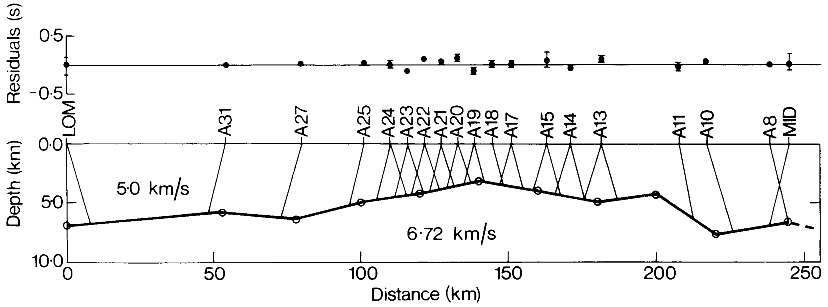

Fig. 3. Interpretation of the depth to the 6.7 km/s refractor beneath the Iceland-Faeroe Ridge along line A, using the iterative refractor mapping method described in the text. The solution uses arrivals at LOM, MI(D), DU4 and F1 but structure is only shown beneath the Ridge itself. Average residuals are shown together with their range where applicable. Ray paths are shown in the upper layer

and A25, and reaching an estimated minimum depth of 3 km beneath shot A19. Between MI(D) and A11 at the south-eastern edge of the Ridge, and between A25 and LOM towards the north-western end, the depth is about 6 to 8 km. North-west of LOM, the depth can be estimated from the time-terms. Between LOM and shot A38 it appears to average about 4 to 5 km. Assuming that the overlying average velocity also applies to the Icelandic shelf, the depth there is estimated to be uniformly about 7.5 km.

The 6.7 km/s layer beneath the Ridge does not give rise to any well-defined pattern of wide-angle reflections, this probably being attributable to inhomogeneity in the overlying layers which may be accentuated because the line perpendicularly crosses the inferred axis of spreading when the Ridge was formed.

It is of interest to note the contrast in structure of the two 'shelf' regions adjacent to the ends of the Ridge. The 6.7 km/s layer appears to be in continuity between the Ridge and the Iceland shelf, although there is an abrupt change in its depth at the boundary. On the other hand, no 6.7 km/s layer has been detected beneath the Faeroe shelf or the Faeroe Islands, the arrivals from the Ridge shots being converted to a lower velocity upper crustal phase at the boundary (Bott et al., 1976).

The Moho

The initial assessment of the Moho beneath the Ridge is based on time-term analysis of relevant arrivals from the Ridge shots (A7 to A38) recorded at F1, F2, and DU4 on Faeroe Islands, DU5 and M1 on Iceland and LOM on the Ridge itself (Fig. 2). The time-terms at LOM and shot A36 were equated to each other. The solution MC4 using 22 shots yielded a velocity of 7.78 ± 0.03 km/s and a mean time-term for the Ridge of 2.7 s. Except for some local scatter, the time-terms do not vary much along the Ridge although the values near the middle of the line (A12 to A25) are marginally higher than those near the ends.

Because of the substantial offset of about 50 km between the rays at the surface and at the Moho, the lateral variation in P_n time terms is not a good indication of variation in depth to the Moho beneath. A better solution can be obtained using our iterative programme to map the interface from the travel times, after correction for the delay above the 6.7 km/s refractor. Analyses were carried out for various combinations of the arrivals at DU5, M1, LOM, F1, and DU4 from shots along the Ridge. The resulting sub-Moho velocity estimates lie between 7.8 and 8.0 km/s and are rather higher than those obtained by time-term analysis. Two of the resulting models are shown in Fig. 4. Both models show the Moho at about 32 to 35 km depth beneath the south-eastern part of the Ridge (A7 to A29) and at a significantly shallower depth of about 25 km beneath the northwestern part of it, but they differ in the emphasis they place on the change in depth of the Moho. Great confidence cannot as yet be placed on this change in depth of the Moho, as it may be partly or wholly an artifact of the complicated structure at depth beneath the junction of the Ridge with the Iceland Block. Confirmation by refraction lines across the length of the Ridge is needed.

A coherent P_mP phase is conspicuously absent from the recordings at LOM, MI(D) and MI(E), although packets of large amplitude arrivals are observed following P_n. It is suggested that the absence of recognisable P_mP branches results from scattering by inhomogeneities in the lower crust or possibly at the Moho. Absence of the P_mP phase removes the possibility of investigation of the Moho in detail or estimation of mean crustal velocity on present evidence.

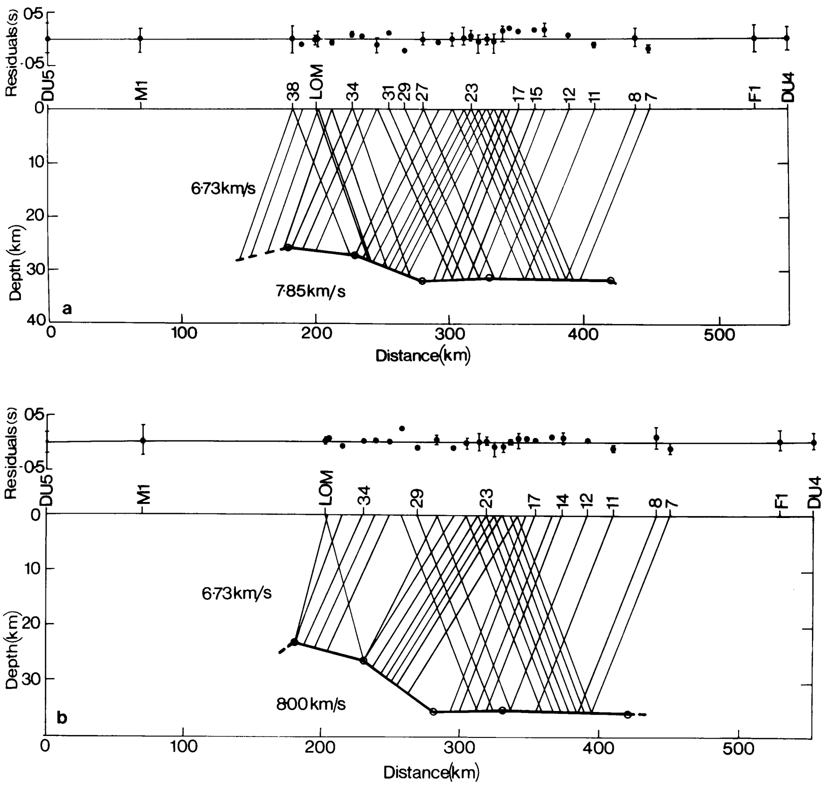

Fig. 4a and b. Interpretations of the depth to the 7.8 km/s Moho refractor beneath the Iceland-Faeroe Ridge using two separate shot-station configurations, including correction for delay in upper crustal layer as shown in Fig. 3. The main distinction between the two models is that the long distance arrivals to station F1 are included in (**a**) but not in (**b**)

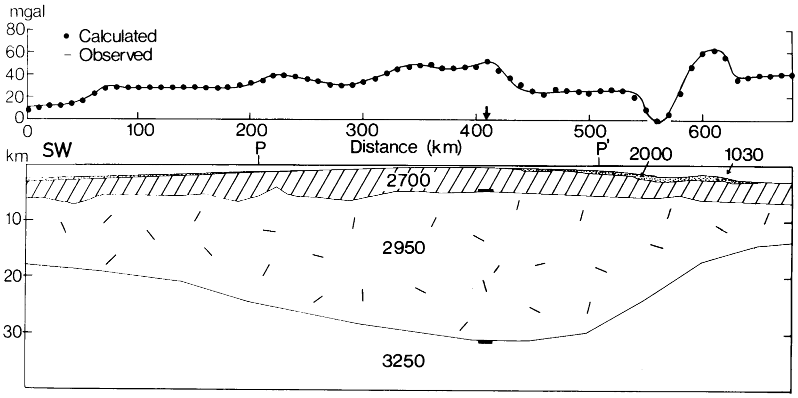

Fig. 5. Interpretation of the free air gravity anomaly profile along line PP′ (Fig. 1) and its extension to SW and NE. Densities are shown in kg/m^3 and depth to 6.7 and 7.8 km/s refractors are shown where line A is crossed

5. Gravity Structure Across the Ridge

An earlier gravity interpretation of the structure across the Iceland-Faeroe Ridge from the Norwegian Sea to the Reykjanes Basin was made by Bott et al. (1971). This demonstrated that the Ridge is in approximate isostatic equilibrium in relation to the adjacent ocean basins as a result of a thick underlying crust rather than a low density underlying upper mantle. By assuming a crust-mantle density contrast of 400 kg/m^3 and taking the depth to Moho beneath the Norwegian Sea obtained by Hinz and Moe (1971), the depth to the Moho beneath the Ridge was determined as about 22 km. We now know that this estimate is too low, and therefore we have constructed a more realistic model consistent with the new NASP estimate of crustal thickness beneath the Ridge and incorporating the better evidence on sediment thicknesses now available.

Our new model (Fig. 5) has been constructed on the following basis. Bathymetry and gravity for the whole line and sediment thickness over the crest of the Ridge have been taken from Fleischer et al. (1974). Sediment thicknesses on the flanks of the Ridge have been taken from Grønlie and Talwani (1978) and from individual VEMA profiles. Crustal structure beneath the Ridge is based on the NASP data presented in this paper. In order to produce a sufficiently large change in crustal thickness between the Ridge and the Norwegian Sea to be consistent with the refraction results of Hinz and Moe (1971), a smaller density contrast at the Moho of 300 kg/m^3 had to be used. On this basis, we estimate the Moho to be about 14 km deep at the north-eastern end of the line at the edge of the Norwegian Sea where the water depth is 2.7 km. This is consistent with the estimate of 10 km depth made by Hinz and Moe (1971) in the central part of the Norwegian Sea where the water depth is about 3.6 km. Short-wavelength discrepancies between the observed and calculated profiles have been removed by minor adjustment of the sediment thickness or depth to the 6.7 km/s interface, although these could be equally well attributed to lateral variation in the upper crustal layers.

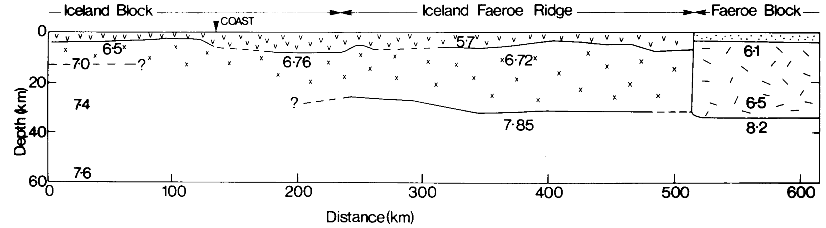

Fig. 6. Interpretation of the crustal structure of the Iceland-Faeroe Ridge along line A and its relationship to the crustal structure of the adjacent Iceland and Faeroe Blocks. The structure beneath Iceland is after Pálmason (1971) and Angenheister et al. (1979) and that beneath the Faeroe Block interpreted as continental crust is after Bott et al. (1976)

The gravity model (Fig. 5) is in good agreement with the available observations. However, there is indication from the work of Haigh (1973) that the upper mantle beneath the Reykjanes Basin is of lower density than that beneath the Norwegian Sea, so that a decrease in upper mantle density towards the south-western end of the line may occur. If so, then the crust towards the south-western end would be thinner than indicated in the model.

6. Conclusions and Discussion

The results from NASP and previous geophysical projects indicate that the main features of crustal structure of the Iceland-Faeroe Ridge are as follows (Fig. 6):

1. Sediments are thin or absent from the crestal region but thicken down the flanks towards the adjacent basins. The 4-to 8-km-thick upper crust above the 6.7 km/s refractor is interpreted as consisting of volcanic rocks which are probably predominantly basaltic. Significant lateral variations seen in short-wavelength gravity, magnetic, and seismic features and in subdued bathymetry may be attributable to regions of thick pyroclastic rocks and to the cores of ancient volcanoes.
2. A 6.7 km/s refractor at 4 to 8 km depth represents the top of the main crustal layer. This layer is apparently shallowest in the region between shots A13 and A24.
3. A well-defined refracted arrival with velocity of about 7.8 km/s is received from the base of the crust. The Moho is estimated to be 30 to 35 km deep beneath the central and south-eastern part of line A along the Ridge, shallowing by a few kilometres beneath the north-western end of it, assuming that the 6.7 km/s velocity remains constant down to the Moho. Lack of coherent wide angle reflections is attributed to scattering in the lower crust along the line which is perpendicular to the direction of the sea-floor spreading axis.
4. The upper crust appears to be similar to that beneath Iceland, with the 6.7 km/s layer apparently continuous between the Ridge and the adjacent Icelandic shelf. In contrast, the 6.7 km/s layer has not been detected beneath the Faeroe Block; 6.7 and 7.8 km/s waves from the Ridge appear to be converted to lower velocity crustal phases at the boundary between Ridge and Faeroe Block, marking a fundamental change in type of crust.

Our interpretation differs from that of Zverev et al. (1975) in the relationship of the Ridge to the adjacent blocks. Zverev et al. (1975) assumed continuity of crustal layering across the whole region. In contrast, we have found evidence for a fundamental change in crust at the boundary between the Ridge and the Faeroe Block. We attribute the relatively high delay times at the land stations on Iceland to lateral reduction in the upper mantle velocity towards central Iceland rather than to deepening of the Moho beneath Iceland.

The Iceland-Faeroe Ridge appears to be underlain by crust of Icelandic type, albeit significantly thicker than that beneath Iceland. We interpret this crust as formed by the sea-floor spreading mechanism as the north-eastern North Atlantic opened since about 55 Ma ago, the Iceland-Faeroe Ridge forming at an early stage in this evolution and Iceland itself forming at a later stage (Bott, 1974). The Icelandic type crust is much thicker than normal oceanic crust (a factor of five thicker beneath the Iceland-Faeroe Ridge, and two to three times thicker beneath Iceland). This is attributed to differentiation of a greater quantity of crustal material from the underlying mantle, possibly as a result of the high underlying temperature at the time of continental splitting and shortly after.

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