# *Marine geophysical studies between northwest Scotland and the Faeroe plateau*

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# MARINE GEOPHYSICAL STUDIES BETWEEN NORTHWEST SCOTLAND AND THE FAEROE PLATEAU

A Thesis submitted for the Degree of Doctor
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by

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## ABSTRACT

A marine geophysical survey of the northern Rockall Trough including the Banks to the north and northwest, the Wyville-Thomson Rise and the Hebridean continental shelf was carried out in 1970 and 1971.

Gravity, magnetic and seismic reflection data indicates that the central Rockall Trough is underlain by about 5 km of sediment overlying a normal oceanic crust. The sedimentary thickness decreases to about 3 km and the crust becomes anomalously thick at the northern end of the Trough. Gravity and magnetic interpretation suggests that the Faeroe-Shetland channel is also underlain by anomalously thick oceanic crust.

Gravity interpretation indicates that George Bligh, Bill Bailey's and Faeroe Bank are underlain by crust of continental thickness.

The Wyville-Thomson Rise, which connects Faeroe Bank to the Scottish continental margin, is composed of two basement ridges of pre-Lower Oligocene age shrouded by sediments up to 1.5 km thick. The northeasterly ridge is continuous from the Bank to the continental margin but the southwesterly ridge terminates about 50 km from the margin. Magnetic and gravity evidence indicates that the ridges are composed of igneous material and that crustal thickening occurs beneath the ridges. An intrusive complex of unknown age lies beneath the southwest flank of the Rise.

Gravity, magnetic and bathymetric interpretation indicates that the Hebridean continental shelf is underlain by Lewisian basement. Gravity and magnetic interpretation indicates that a NNE-SSW trending sedimentary basin about 1.5 km deep and with a partial covering of Tertiary lavas lies between Lewis and the Flannan Isles.

Tertiary intrusive complexes, recognisable by their magnetic, gravitational and bathymetric effects, are present beneath St. Kilda, below the continental slope 75 km northwest of St. Kilda and beneath the shelf 40 km north-northwest of the Butt of Lewis.

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# CHAPTER 1

# INTRODUCTION

## 1-1. The region studied

The area between northwest Scotland, Rockall Bank and the Faeroe Islands (Fig.1) forms an unusual part of the east Atlantic margin. The Scottish continental shelf in the east is separated from Rockall Bank and other shallow banks to the west and the Faeroe Plateau to the northwest by the Rockall Trough and the Faeroe-Shetland Channel which are between 1000 and 2000 m deep (Fig.2). The Wyville-Thomson Rise connects the Faeroe region to the Scottish shelf and thereby separates the Rockall Trough from the Faeroe-Shetland Channel to the north. To the south, the Rockall Trough opens into the main part of the Atlantic Ocean.

Geophysical cruises, involving a total of about 7 weeks at sea in 1970 and 1971, were planned to study the area using seismic reflection, gravitational and magnetic methods. This thesis describes the collection, reduction and interpretation of the data.

## 1.2. The geology of the region

### 1.2.1. The land geology

The oldest exposed rocks in the Scottish area are the Precambrian Lewisian complex which is found throughout the Outer Hebrides and along much of the west coast of the Scottish mainland (Fig.3). Two major orogenic events, the Scourian and the Laxfordian, have folded and metamorphosed the Lewisian rocks. Those rocks only affected by the older Scourian orogeny belong to the granulite facies and are preserved in massifs. On the mainland, three major massifs are separated by amphibolite grade gneisses of Inverian age which is an intermediate orogenic phase. Rocks metamorphosed by the Laxfordian orogeny are mainly banded biotite-gneisses containing amphibolites and foliated

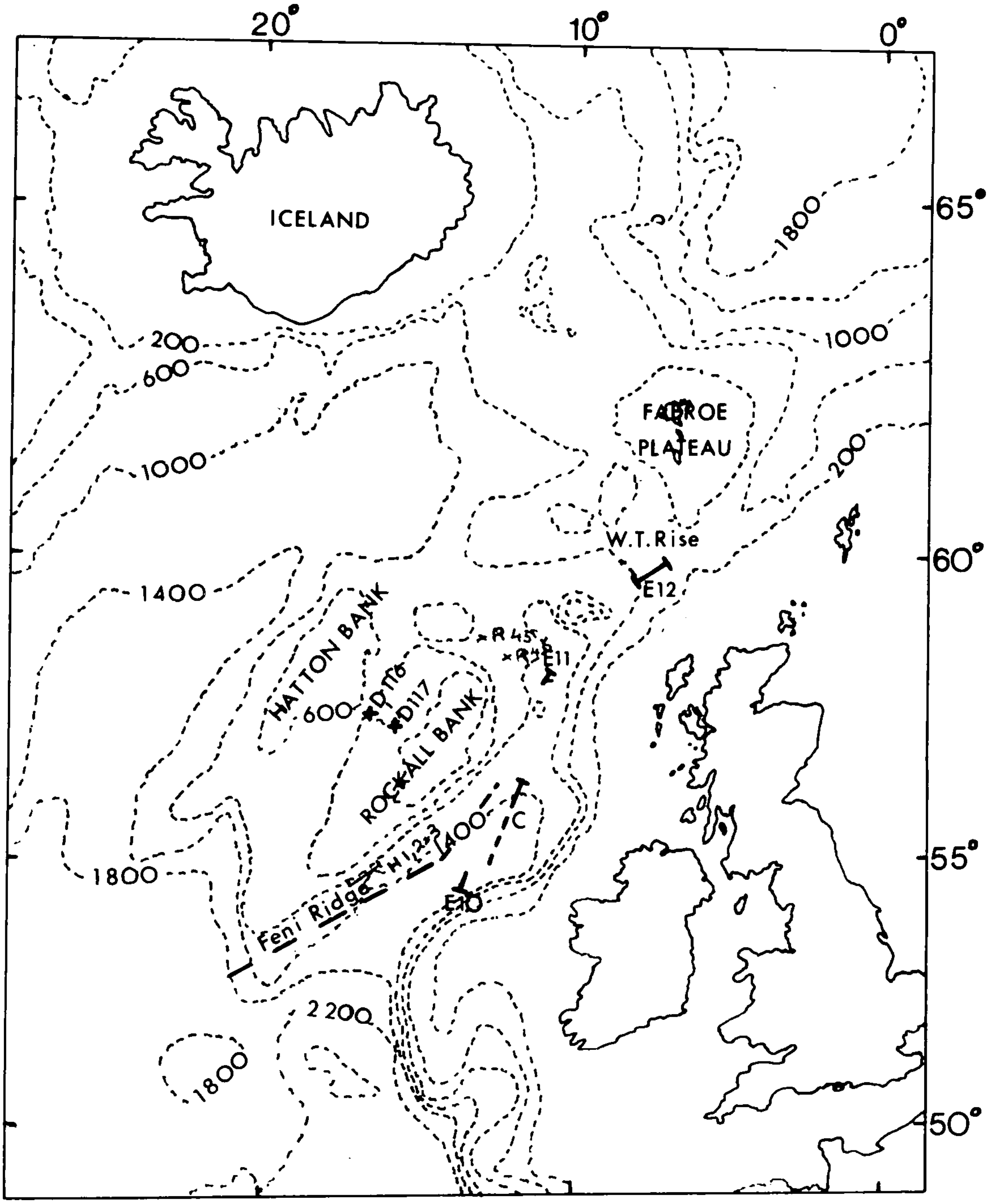


Figure 1. The northeast Atlantic.

D 116 & D117 : DSDP Holes.

E10,E11 & E12 : Refraction lines of Ewing and Ewing 1959.

C : Refraction line of Scrutton 1971.

Depths are in fathoms.

granites (Watson 1965). The Scourian occupies the central area of the Lewisian outcrops on the mainland whilst the Laxfordian lies to the north and the south (Fig.3). A similar configuration is present on the Outer Hebrides although it is less clearly defined (Dearnley 1962). Gravity and magnetic evidence suggests, however, that the Laxfordian in the north may be underlain by Scourian pyroxene-granulites (Bott et al. 1972). The Moine thrust marks the western boundary of the later Caledonian fold belt. To the east of the thrust, outcrops of remobilised Lewisian material occur as inliers in the cores of some Caledonian folds.

The Scourian granulites are significantly denser than the Laxfordian gneisses by about 0.09 $g/cm^3$ (Bott et al. 1972), and have an average magnetisation about ten times that of the Laxfordian (Powell 1970). The different complexes are therefore distinctive both gravitationally and magnetically (Bott et al. 1972, Powell 1970, Westbrook, in press).

Unconformably overlying the Lewisian is the relatively undeformed and unmetamorphosed Torridonian Sandstone (Johnson 1965) which covers large areas along the west coast of Scotland. It was probably deposited contemporaneously with the sands and shales which have since been metamorphosed and folded to form the Moine schists (Johnson 1965). The boundary between the Moinian and Torridonian rock groups now lies at the Moine thrust but the Moinian along the thrust may have been transported from some distance to the east (Watson 1963). A succession of conglomerates and sandstones near Stornoway in the north of the Outer Hebrides may represent the western limit of the Torridonian outcrops but the succession may alternatively be of New Red Sandstone age (Stevens 1914, Steel 1971).

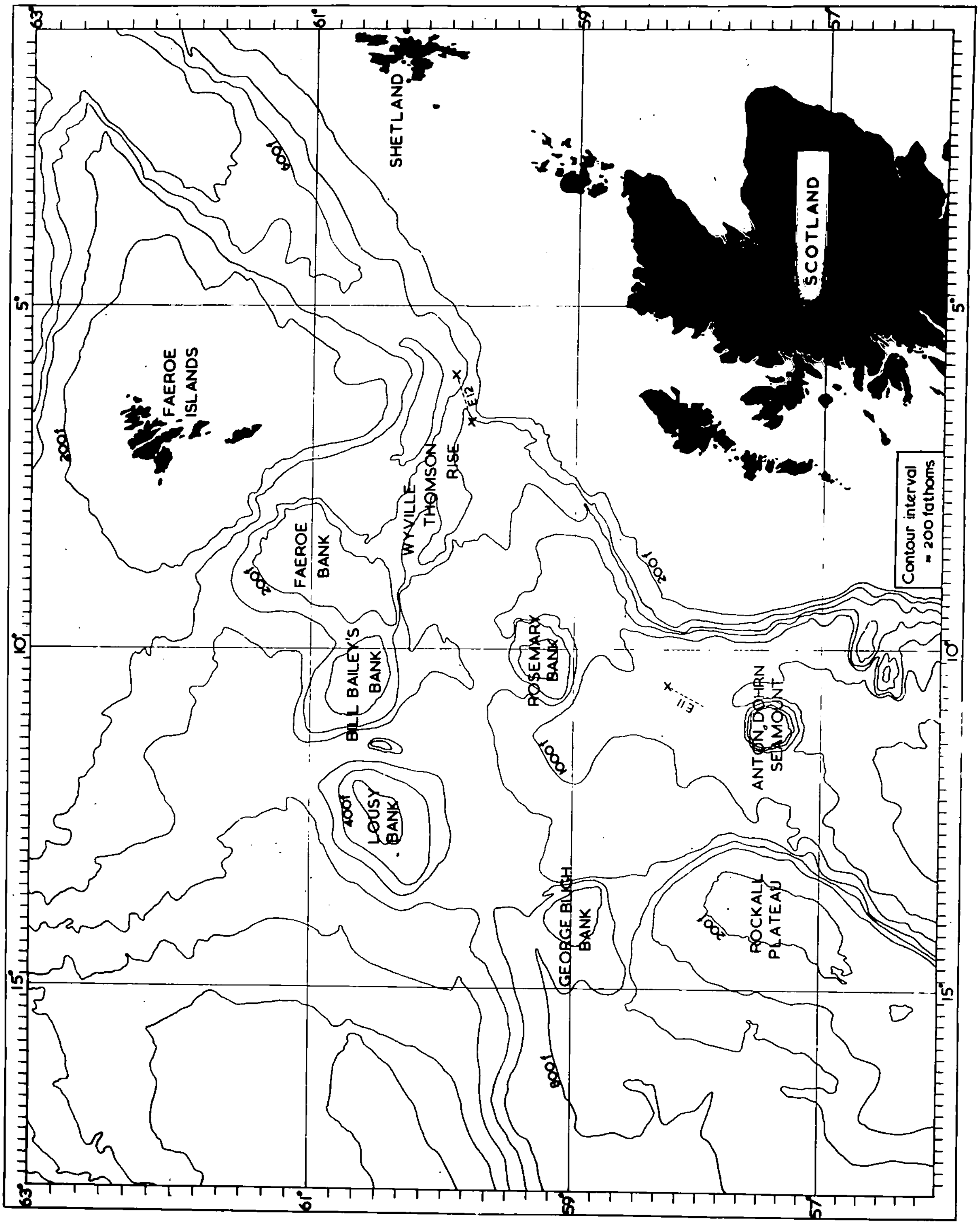


Figure 2. The Rockall Trough and surrounding regions.

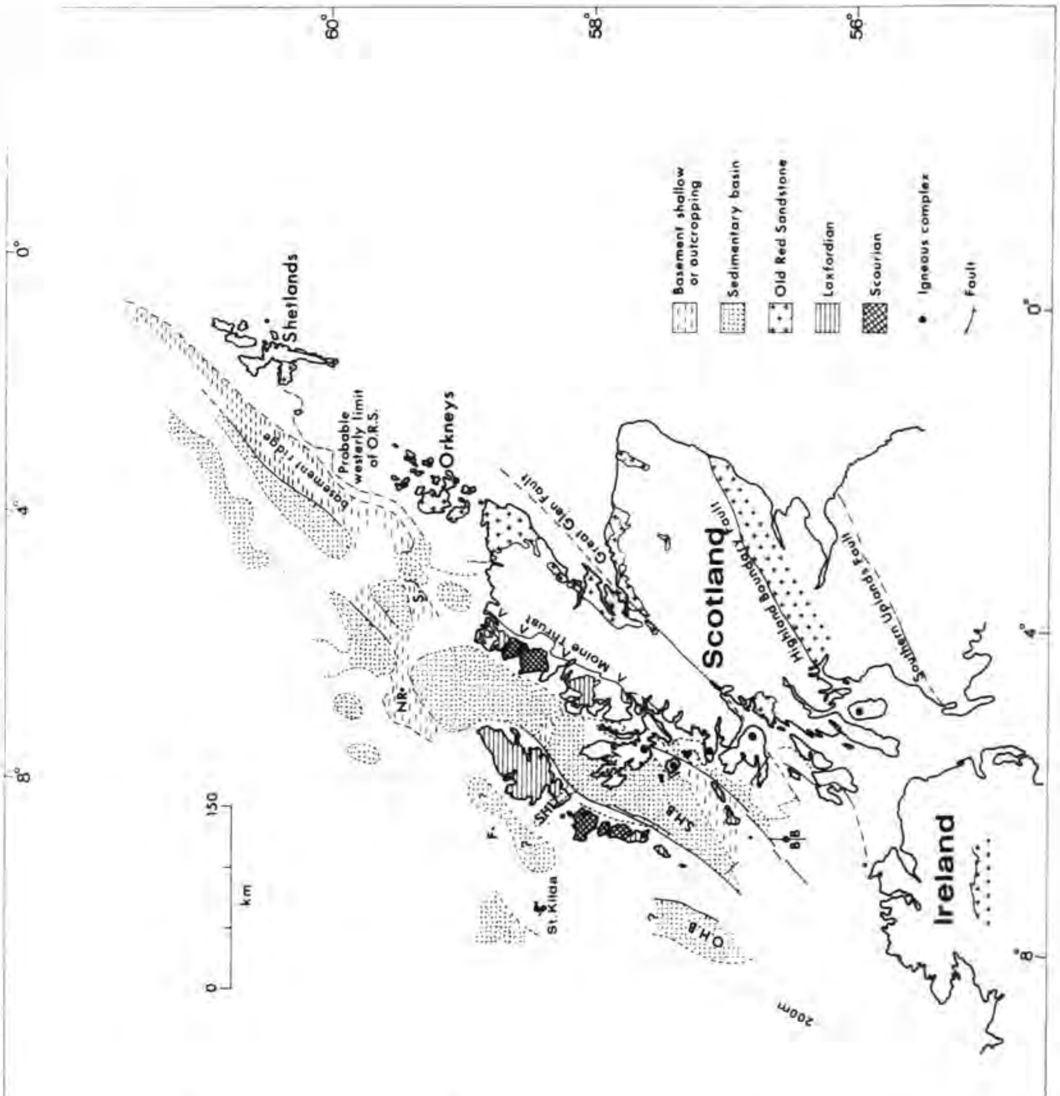


Figure 3. The geology of northwest Scotland.

NR : North Rona. S : The Skerries. F : Flannan Isles

BB : Blackstone Bank. OHB : Outer Hebrides Basin.

SHB : Sea of the Hebrides Basin. SHI : South Harris Igneous Complex.

The Dalradian succession stratigraphically and structurally overlies the Moinian to the southeast of the Great Glen fault but it is not found on the mainland north of this line. On the Shetlands, the basement is made of metasediments and metamorphosed igneous rocks which may be Dalradian in age (Miller and Flinn 1966). The polyphase metamorphic history of the rocks, which included extensive thrusting (Johnson 1965), indicates that they are part of the Caledonian orogenic belt.

Unmetamorphosed Lower Palaeozoic rocks of Cambrian and Ordovician age occur west of the Moine thrust zone in northwest Scotland (Walton 1965). A lower arenaceous sequence followed by a carbonate suite unconformably overlies the Torridonian and Lewisian rocks.

A major area of deposition of Old Red Sandstone covered much of the Caithness, Orkney and Shetland region in Middle and Upper Old Red Sandstone times (Waterson 1965, Miller & Flinn 1966, Fig.3). The Old Red Sandstone succession in Caithness is up to 6,000 m thick and unconformably overlies a Precambrian landscape of high relief.

Scattered outliers of Permian and Mesozoic sediments, which have been preserved by downfaulting and protection by Tertiary lavas, indicate that sediments of this age were deposited over much of the region (Craig 1965, Hallam 1965). A lack of Tertiary sediments, apart from minor lignite occurrences between the lava flows, suggests that the area was uplifted during much of the Tertiary.

### 1.2.2. The continental shelf.

The Lewisian basement probably extends over much of the continental shelf to the west of Scotland. Fault-bounded sedimentary basins between 2 and 5 km deep with north-northwest to south-southwest trends overlie the basement beneath the Sea of the Hebrides (McQuillin and Binns 1973), to the west of the Shetlands (Watts 1971), and possibly to the west and southwest of the Outer Hebrides (Eden, Wright and Bullerwell 1971, McQuillin and Binns 1973) (Fig.3). They are probably between 2.5 and 5 km deep and contain Mesozoic and perhaps Torridonian sediments (Watts 1971, McQuillin and Binns 1973, Browitt 1972). The basins are flanked by basement ridges which are exposed on the Outer Hebrides, North Rona (Nisbet 1961) and the Skerries (Geological Survey 1957). The basement ridges can be traced over the continental shelf by geophysical methods (Watts 1971, Flinn 1969).

Sediments, which may be up to 2.5 km thick, lie to the west of the break in slope of the continental margin (Stride et al. 1969; Watts 1971, Fig.3). These probably include sediments which are Tertiary in age.

Between the Orkneys and the Shetlands, Old Red Sandstone is present on the shelf (Watts 1971). The Old Red Sandstone basin is continuous from Caithness to the Shetlands.

### 1.2.3. The Thulean igneous province

The Thulean igneous province developed in Lower Tertiary times and extended from Northern Ireland and Lundy Island to the Faeroes and Greenland (Richey et al. 1961, Stewart 1965). The extensive outpouring of lava flows, chiefly basaltic, was followed by the development of basic and ultrabasic intrusive centres. Basaltic dykes, associated with the central complexes, were intruded during a final stage of activity.

The province is well represented in northwest Scotland where intrusive centres have been described in Skye, Rhum, Mull, Ardnamurchan and other places (Fig.3). A thickness of 2,000 m of lava is still present in Mull and about 2,000 km$^2$ of the land surface are covered by lava in northwest Scotland. Intrusive centres have also been described on the continental shelf. Blackstone Bank, to the southwest of Tiree (Fig.3) has been shown to be a centre by geophysical methods (McQuillin et al. 1973) whilst geological investigations on St. Kilda and the adjacent islands (Cockburn 1935) have shown the presence of another centre near to the continental margin.

### 1.2.4. The Faeroe Islands to Rockall Bank

The continental margin of north-west Britain is approximately paralleled to the north-west by a series of banks and rises (Fig.2). The Faeroe Rise lies to the north-east whilst the Rockall Plateau, which is composed of two elongated adjacent banks, Rockall Bank and Hatton Bank, lies to the south-west. The area between these is occupied by several smaller banks. These are Faeroe Bank, Bill Bailey's Bank, Lousy Bank and George Bligh Bank.

The Faeroe Rise is a shallow plateau area lying midway between Iceland and Scotland (Fig.2). Most of the area is at a depth of less than 200 m and its emergent parts form the Faeroe Islands. These have a northwest to southeast topographic grain and are composed almost entirely of plateau basaltic lavas which can be divided into three Series (Rasmussen and Noe-Nygaard 1970). The Lower Series is about 900 m thick and was formed by forty to fifty intermittent fissure eruptions of lava. This eruptive phase was followed by a long quiescent period when a coal-bearing shale sequence up to 15 m thick was laid down. Then a further strongly eruptive phase producing a tuff-agglomerate zone preceeded a period of lava extrusion from smaller northwest to southeast trending vents. This produced the Middle Series of lavas which has a thickness of about 1350 m. The Upper basalt Series was extruded, after a break in vulcanism, in a similar manner to the Lower Series. It has a thickness of about 675 m. The coal bearing shales are probably of Eocene age (Laufield 1965). Radiometric dating of the lavas (Tarling and Gale 1968) shows that all three Series are probably between 50 and 60 m year old but the relative ages of the individual flows could not be determined. Measurements of the remanent magnetisations of the lavas (Tarling and Gale 1968) have shown that the Upper and Middle Series are reversely magnetised with respect to the present Earth's field whereas the Lower Series shows two normal zones separated by a reversed zone of magnetisation.

Evidence on the deep structure of the Faeroes is provided by seismic and gravity surveys (Saxov and Abrahamsen 1966, Palmason 1965). Seismic refraction surveys show upper layers with P-wave velocities of 3.9 and 4.9 km/s (Palmason 1965) which have been correlated with the Upper Series and the Middle and Lower Series respectively. Palmason found a layer with a velocity of 6.4 km/s beneath the upper layers but deeper layers have not been detected. This layer could represent either oceanic or continental crust. A gravity profile from the Shetlands to the Faeroe Islands (Bott and Watts 1971) indicates that, although the crustal thickness beneath the Faeroe-Shetland channel is unknown, the thickness beneath the Faeroes is probably similar to that beneath the continental shelf adjacent to the Shetlands. The change in Bouguer anomaly between the Faeroe Islands and the Iceland-Faeroe ridge indicates that there is a lateral change in crustal density between the two, possibly caused by the Faeroes being underlain by a continental crust (Bott et al. 1971). A small bathymetric rise marks the possible continental margin. A fit of the North Atlantic continental margins which improves on that suggested by Bullard et al. (1965) also indicates that the Faeroe Plateau may have once been part of the North Atlantic continent (Bott and Watts 1971). The area between the Faeroe Islands and Rockall Plateau includes several shallow banks. George Bligh Bank rises to a depth of about 600 m and closes the northeast side of the Hatton-Rockall basin (Fig.2). Gravity and magnetic lines crossing the Bank (Roberts 1971) indicate that, although strongly magnetic lavas are probably present on the Bank, there is no evidence for a major intrusive centre. Lousy Bank, which rises to a depth of about 400 m, has been mapped bathymetrically but no other detailed investigations have been carried out on it. A dredge haul on the bank recovered small pebbles which included quartzite, amphibolite, gneiss and basalt (Carruthers et al. 1923) but the provenance of the pebbles was not firmly established. Basalt has been dredged from Bill Bailey's Bank (Dangeard 1928) which lies between Lousy Bank and Faeroe Bank (Fig.2) and rises to a depth of about 200 m . North-south magnetic anomaly lineations over the Bank (Avery et al. 1968) may be related to the trend of the vents from which lavas have been extruded as they are on the Faeroe Islands and may be on Faeroe Bank (Dobinson 1970). Faeroe Bank lies 100 km southwest of the Faeroe Islands and is separated from the Faeroe Plateau by the Faeroe Bank channel. The bank is probably covered by basic igneous rock which was extruded from north to northwest trending fissures in either a continental or oceanic crust (Dobinson 1970). The present elevation of the Bank suggests that a continental crust is more probable beneath the Bank since an oceanic island would have subsided to a greater depth since Tertiary times (Dobinson 1970).

In order to improve their fit of the pre-North Atlantic continent, Bullard et al. (1965) suggested that Rockall Plateau may be a continental fragment. The islet of Rockall, being the only protrusion above sea level of Rockall Bank, is of Lower Eocene age (Miller and Mohr 1965) and is probably part of a Tertiary intrusive centre similar to those on the Scottish continental shelf (Roberts 1969). Samples of the coarse aegerine-granite, Rockallite, contain an excess of radiogenic strontium and of unradiogenic lead indicating that, although the complex is of Tertiary age, there is probably ancient crust beneath which contaminated the igneous material as it rose through the crust (Moorbath and Welke 1969). Lead isotope measurements can be approximately correlated with those from the Skye lavas. The Skye lavas are considered to have risen through ancient Lewisian crust with an approximate age of 3100 m year therefore a similar history is likely for the Rockall material. The approximate depth to the Moho beneath the Bank is 31 km (Scrutton 1970) and although the crustal velocities are high for standard continental crust the thickness is clearly that of a continental region. The magnetic anomalies on Rockall indicate that, north of 56°25' N, basic igneous rocks cover the Bank whereas, to the south, there is a major change in the geology and a possible absence of basic igneous rocks (Roberts and Jones, in preparation). Dredge hauls have produced typical Tertiary igneous rocks from the north of the Bank (Cole 1897). Dredge hauls from the south of the Bank (Roberts et al. 1972) have recovered a poorly-sorted conglomerate containing a granulite with a similar mineral assemblage to that of the Lewisian found in the Outer Hebrides and in East Greenland. The provenance of the pebbles is probably nearby therefore Rockall may consist, at least in part, of Lewisian-type material. A sedimentary basin between Rockall Bank and the slightly lower Hatton Bank to the west (Fig.1, Roberts et al. 1970) contains sediments at least as old as Palaeocene (D.S.D.P., Scientific Staff, 1970). Three periods of sinking of the basin, approximately correlating with changes in sea floor spreading directions on the Reykjanes Ridge, have been recognised from drilling results (D.S.D.P. Scientific Staff 1970). They are Palaeocene (55 m year B.P.)., late Eocene (39 m year B.P.) and Miocene (10 - 15 m year B.P.).

### 1.2.5. The sediments and crustal structure of the basins

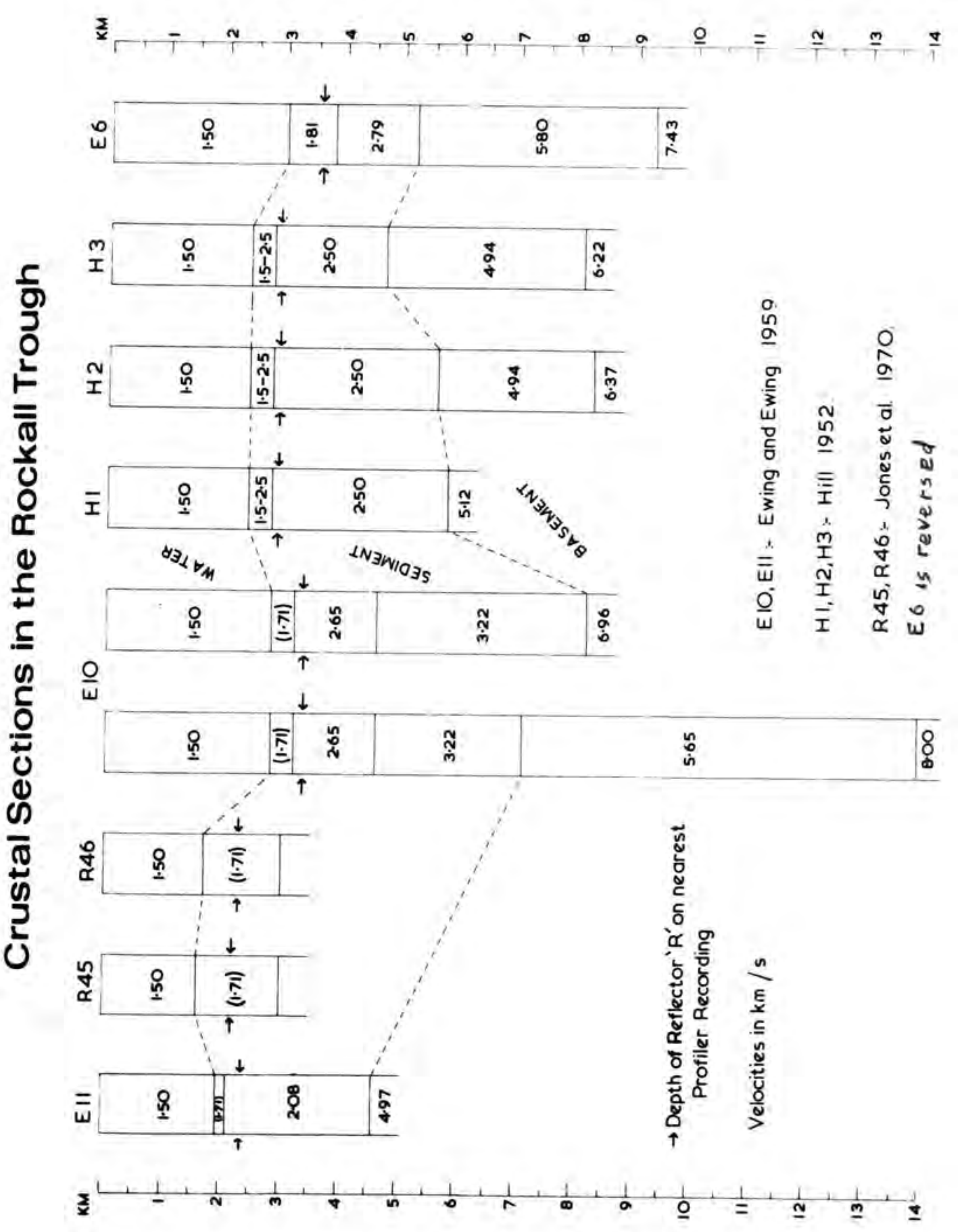
Owing to the proximity of source areas and the relatively constricted basins, the sediments in the Rockall Trough and the nearby basins are in general thick. They contain several reflecting horizons which are used to correlate and date events.

In the Hatton-Rockall Basin, five reflectors are present in about two kilometres of sediment (Roberts et al. 1970). Reflector 4 is a highly fractured, cherty limestone of Eocene age whilst Reflector 5 may be a Palaeocene basalt layer (Scrutton 1971). Five reflectors are also found in the Rockall Trough (Scrutton and Roberts 1971). The upper two reflectors are not continuous across the Trough and the bottom reflector is very bumpy and intermittent. Reflector 3 has been correlated with one of the reflectors in the Hatton-Rockall Basin (D.G. Roberts - personal communication) and is the same as reflector 'R' of Jones et al. (1970) which they have found in many parts of the Rockall Trough. Reflector 'R' has been traced into the main North Atlantic basin and found to wedge out at a Lower-Middle Oligocene magnetic anomaly as dated by Heirtzler et al. (1968) (E.J.W. Jones - personal communication). Two distinct periods of sedimentation occurred in the north-east Atlantic (Jones et al. 1970). The change between the two is demonstrated by the difference between flat lying beds, which are previous to and include reflector 'R', and current deposited ridges which developed after reflector 'R'. The earlier beds were laid down by turbidity currents at a time when bottom water flow was relatively quiet whereas, when the Norwegian Sea opened, the cold dense water from the Arctic flowed south as bottom currents and disturbed the sedimentation pattern. The factors affecting the pattern of flow are discussed later.

A total sediment thickness of 3 to 5 km is present in most parts of the Rockall Trough (Fig.4, Ewing and Ewing 1959, Hill 1952, Scrutton 1971). Two sediment layers with distinctly different velocities are present. The lower layer, which Ewing and Ewing divided into two on their line E 10, has a P-wave velocity of between 2.0 and 3.3 km/s and probably consists of semi-consolidated sediments. The upper layer is usually less than 1 km thick and has a velocity of 1.7 to 2.0 km/s. The boundary between the two sedimentary layers approximately correlates with reflector 'R' which is presumably an important lithological boundary (Jones et al. 1970, Fig.4).

The crust of the Rockall Trough directly beneath the sediments has a P-wave velocity between 4.94 and 6.96 km/s. Gravity evidence suggests that the depth to the Moho is about 12 km (Scrutton 1971) but no seismic refraction experiments have satisfactorily determined the depth. The crust may therefore be oceanic in nature which is in agreement with the original theory of Bullard et al. (1965) that Rockall Trough has formed as part of an early stage of opening of the North Atlantic.

The Moho depth in the Hatton-Rockall basin is about 22 km beneath what is probably a continental crust (Scrutton 1971). The relatively thin crust may indicate that the area is similar to a continent-ocean transition zone or to a subsiding continental margin. In the Faeroe-Shetland channel, a similar situation may exist although no refraction results have yet been described which determine either the sediment or crustal thicknesses. On the basis of gravity data, Bott and Watts (1971) suggested that there may be crustal thinning of about 5 km beneath the channel. Since the sediment thickness in the channel was unknown the model was ambiguous.



Crustal Sections in the Rockall Trough

Figure 4. Sediment and crustal thicknesses in the Rockall Trough (taken from Jones et al. 1970).

station positions on Fig. 1.

### 1.2.6. Rosemary Bank and the Anton Dohrn Kuppe

These banks rise from relatively deep water in the northern part of the Rockall Trough (Fig.2).

Rosemary Bank contains a high density igneous plug and is therefore probably an extinct volcano (Scrutton 1971). Alkali basalts dredged from the Bank are atypical of the Tertiary volcanic province therefore the Bank may have a pre-Tertiary origin perhaps connected with the opening of the Rockall Trough.

The Anton Dohrn Kuppe or Seamount has only been studied in detail bathymetrically (Dietrich and Ulrich 1961). It has steeper sides than the relatively smooth Rosemary Bank which probably indicates a lack of sediments draping the sides. An aeromagnetic profile over the Seamount (Roberts 1971) shows large amplitude, short wavelength anomalies similar to those over Rosemary Bank. The Anton Dohrn Kuppe is therefore probably an igneous centre similar to Rosemary Bank.

### 1.2.7. The Wyville-Thomson Rise

The Wyville-Thomson Rise completes the Greenland-Iceland-Scotland ridge system (Fig.1) and so has a considerable influence on the ocean current system and sediment distribution. The Rise extends from Faeroe Bank towards the southeast to join the continental shelf off the northwest tip of Scotland. The maximum depth of water along the crest of the Rise is about 400 fathoms. Rasmussen and Noe-Nygaard (1970) remarked on the parallelism of the Rise and the Faeroese fjord system and suggested that they may have connected origins.

## 1.3. Current trends and their sedimentary effects in the northeast Atlantic

Deep sea currents can have a strong influence on the type of sedimentation taking place on the ocean floor (Heezen and Hollister 1964). In the northeast Atlantic the bottom currents are dominated

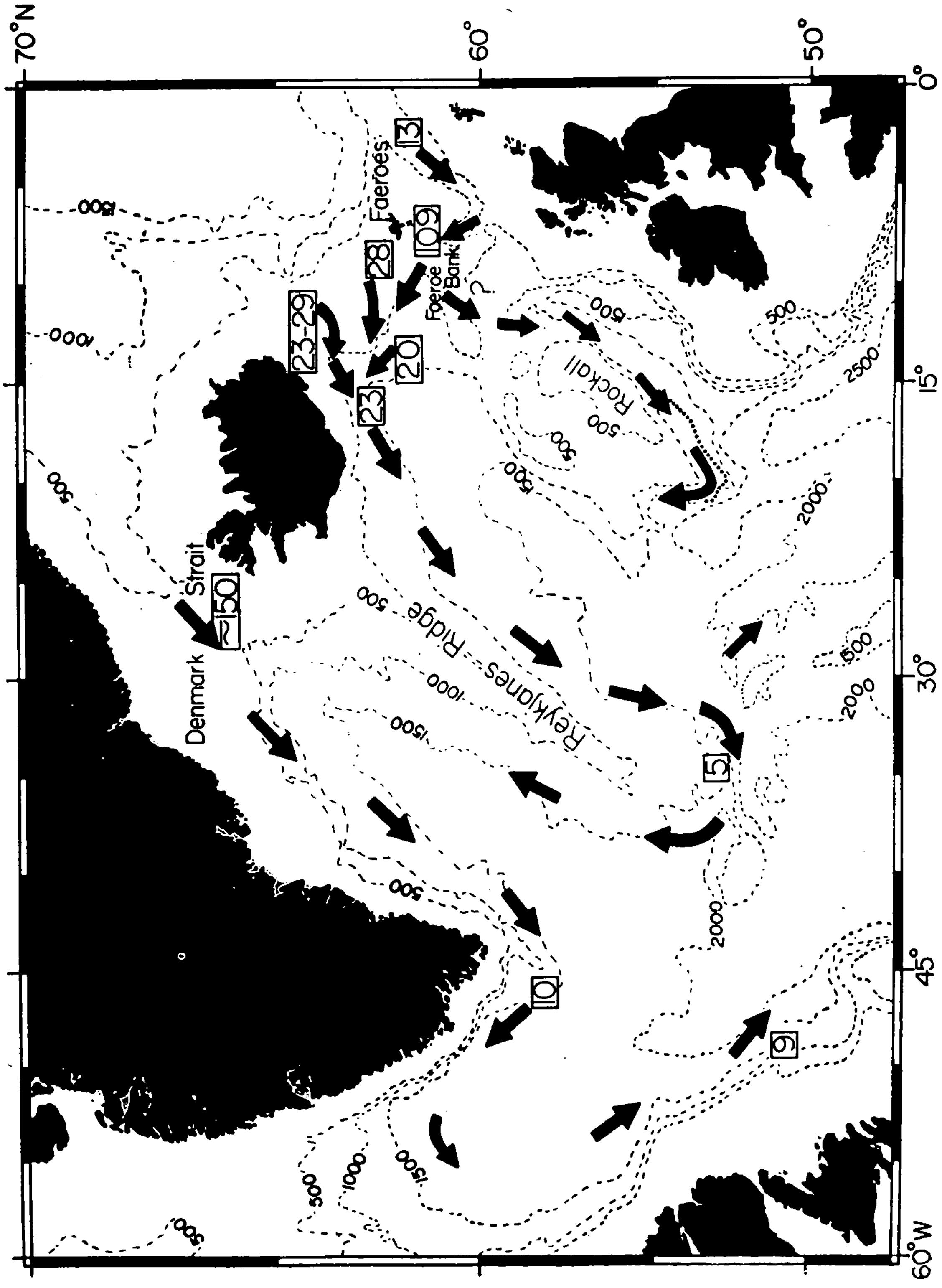


Figure 5. Seawater flow in the North Atlantic

(taken from Jones et al. 1970)

by the flow of cold Norwegian Sea water from the north and the flow of Labrador Sea water from the west (Jones et al. 1970). The currents are controlled by basement rises but are also influenced by Coriolis force which, in the northern hemisphere, tends to deflect the flow in a clockwise direction. In the Rockall Trough, a northward flow of Mediterranean water may also be of some importance. The bottom waters of the Rockall Trough are principally interfingering layers of Norwegian and Labrador Sea Water (Lee and Ellet 1965). The formation of the Feni Ridge (Fig.1) after Lower Oligocene times is caused by deposition of the sediment from the bottom waters along an interface between flows of the two types of water (Jones et al. 1970), Ellet and Roberts 1973). The Labrador Sea water passes into the East Atlantic in the vicinity of the $53^{o}$N fracture zone (Fig.5) and so presumably enters the Trough from the south. A principal source of the Norwegian Sea water into the Atlantic is through the Denmark Strait (Fig.5) between Greenland and Iceland but this flow does probably not cross into the northeast Atlantic. The other principal source involves water flowing through the Faeroe-Shetland channel and then either, turning to the west and flowing at high velocity through the Faeroe Bank channel, which provides a relatively deep passageway, or, overflowing the Wyville-Thomson Rise and flowing straight down the Rockall Trough (Fig.5, Ellet and Roberts 1973).

## 1.4. Problems for Investigation

The nature of the Rockall Trough has been investigated by various workers but there is still some doubt as to its origin. The crust beneath the sediment must be either oceanic in nature or composed of some form of continental crust. The latter case implies that, at some time, the continental crust has subsided to form a graben-like structure. Indications of this type of situation may be difficult to recognise since its existence has not been conclusively shown elsewhere. If the crust is oceanic, it is necessary to look for not only the features typical of oceanic crust but also indications as to when and from what spreading axis or axes it was formed.

It has been shown that the Rockall Plateau is continental in nature but little evidence has been presented to indicate whether the Banks further north are similar to the Plateau or whether they are volcanic seamounts similar to Rosemary Bank. Both solutions have been suggested. Gravity and magnetic traverses over the Banks should provide valuable evidence to solve this problem.

The Wyville-Thomson Rise and its relationship to the surrounding regions have previously had relatively little investigation. Although the bathymetry of the Rise and its effect on the deep sea currents have been studied, the underlying structure of the basement has not been described. Coupled with these problems are the ages and the nature of the sediments in the whole region. It is unlikely that the age of many features can be found without tracing dated sedimentary reflectors. Recent work by Jones has also shown that investigations into the sediments can indicate the existence of past and present sea-water currents.

Little work on the continental shelf west of the Hebrides has been described although a sedimentary basin has been postulated. This basin requires some investigation as does the extent of the Tertiary Igneous Province.

# CHAPTER 2

# DATA COLLECTION AND REDUCTION

## 2.1. The cruises

The data presented in this thesis was collected during two cruises organised by the Department of Geological Sciences, University of Durham. The first cruise was on board R.R.S. John Murray in the summer of 1970 and was of six weeks' duration. A reconnaissance gravity, magnetic and profiling survey of the northern Rockall Trough, the outer Banks, the southern Faeroe-Shetland channel and the Hebridean shelf and margin was the major object of the cruise. The lines carried out are shown on Fig.6. The 1970 lines are suffixed '70'. One week of the cruise was devoted to seismic refraction work on the Shetland shelf which has been described by Browitt (1971). Gravity and magnetic data was collected during this part of the cruise but it was necessary to shut down the equipment during the shooting of the charges thereby making the data spasmodic and, in the case of the gravity, unreliable. Three days of work were lost after Line 2/970 for repairs to the ship's steering gear. These were carried out at Port Glasgow. During Line 2/970 trouble was experienced with the gravimeter stabilised platform which consistently became off-level. Minor repairs were carried out at Port Glasgow but further trouble was experienced whilst on passage to the start of Line 3/970. The ship therefore put into Stornoway and the fault was traced to the output stages of a servo-amplifier. This was repaired. The remainder of the cruise was successful apart from several breakdowns in the air-gun system. Bad weather was experienced during the last few days.

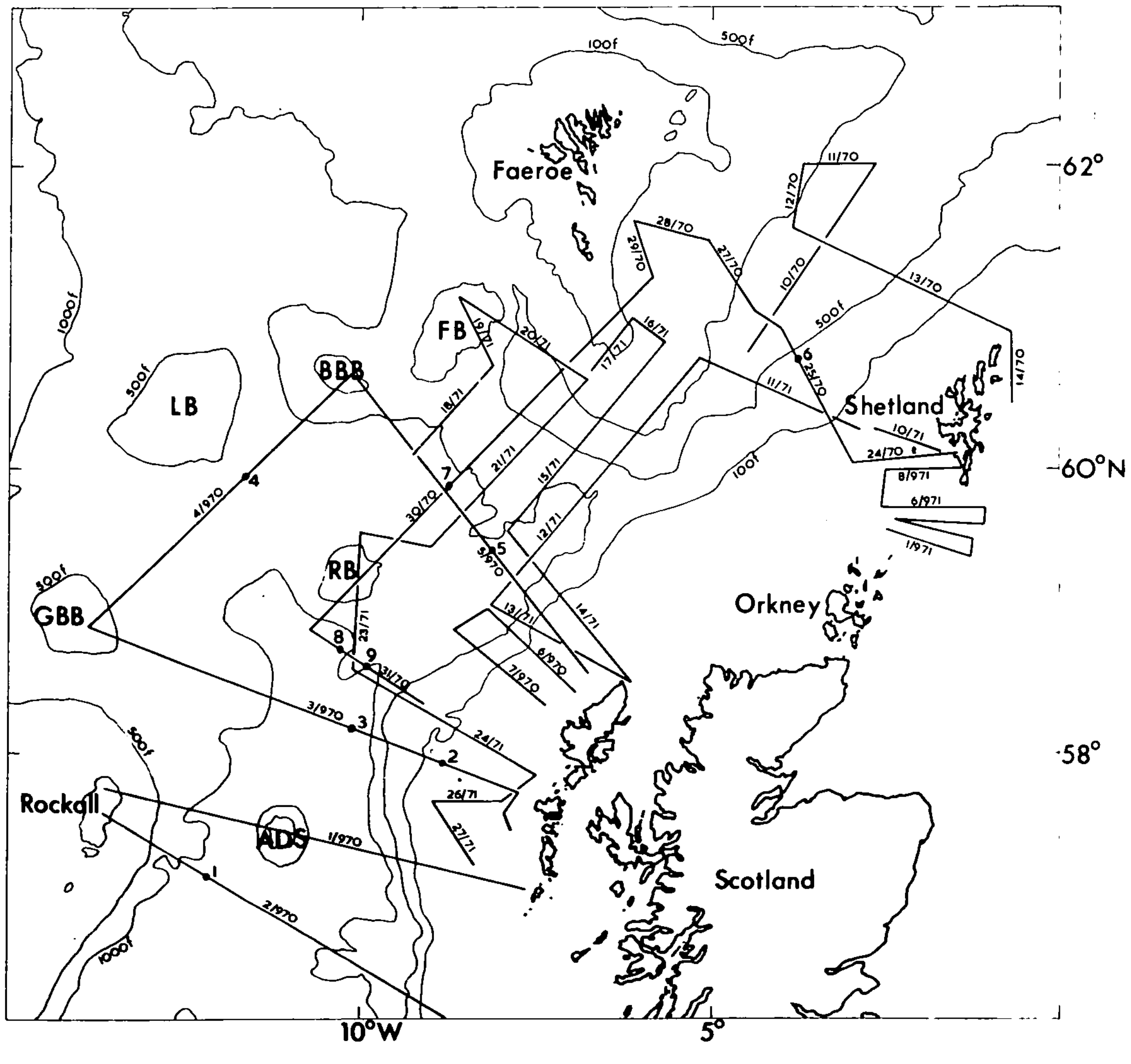


Figure 6. Track chart for the cruises in 1970 and 1971.

Single figures refer to wide-angle reflection stations.

The second cruise took place in the summer of 1971 on board M.V. Researcher. The cruise was of a fortnight's duration of which the first few days were spent investigating the area between Shetland and Fair Isle. This data is not considered here. The remainder of the cruise was devoted to a survey of the Wyville-Thomson Rise. The lines are shown on Fig.6 suffixed '71'. Gravity, magnetic, bathymetric and seismic profiling work was carried out. Short interruptions were experienced owing to equipment breakdowns. The failure of a gyroscope on the gravimeter platform necessitated putting into Lerwick to carry out repairs and the failure of drive belts on the air-gun compressor necessitated a call at Stornoway. Two days work were also lost due to storm force weather conditions during the latter stages of the cruise.

## 2.2. Navigation

### 2.2.1. Navigation systems

The navigation on both cruises relied on the Decca system, using a Mark 12 receiver working on the North Scottish chain, and on the Loran 'C' system. The former system worked well at all times but some of the Lines lay outside the area within which the system provides reasonable accuracy. The Loran 'C' system should have provided a high degree of accuracy on all the lines but on neither cruise did the receiving instrument work satisfactorily. Although the instrument could often be tuned in to and aligned with two slave stations, the tracking facility did not appear to function therefore the readings soon became erroneous.

The Decca system was therefore used over the entire area. Errors in this system can be divided into fixed and variable errors. Distortions in the position-line patterns, mainly due to the radio signals passing over ground of low electrical conductivity, cause the fixed errors. The distortions may be considerable, particularly in coastal regions, and errors in position of up to 2 km are possible.

Variable errors are caused by an unwanted skywave from a Decca station interfering with the wanted ground wave. The variable errors are usually less than 600 m during the day but at night they may be two or three times as great, particularly in areas where the position-lines cross at low angles. An individual fix near the edge of the region could therefore have a fixed error of 2 km and a variable error of about 2 km. Since many fixes are used to define a course the variable errors should be reduced slightly. The maximum error in the position of a course is unlikely to be greater than about 4 km.

### 2.2.2. Calculation of courses and velocities.

Since many of the lines carried out were over 100 km long, a simple reduction of the navigation data, assuming straight line courses, was inadequate because of the effect of tides and winds producing slight drifts in the intended straight courses. The errors of position and heading could in places be quite significant. A computer program called ANAV (Appendix A) was written which allowed for gently curving courses.

The Decca data was initially converted into latitudes and longitudes using an iterative program supplied by the National Institute of Oceanography and modified for use on the NUMAC IBM 360/67 computer. The program ANAV then determined positions, headings, and speeds at ten minute intervals along the calculated courses. The program first reads in the latitudes and longitudes and checks through them looking for large course changes and fixes which are obviously erroneous. The change in heading required to be taken as a course change must be sustained over four fixes and the actual angle, through which the heading must change to constitute a course change, can be varied depending on the scatter of the fixes.

Each course is then processed individually. Starting at one end of a course, twelve points are taken and a quadratic line is fitted through them. It is necessary to rotate the co-ordinates until the course lies at about 45 degrees to facilitate this fitting. The middle four points are then dropped perpendicularly on to the line and the resulting four positions are determined. The process is then advanced four points and four further positions are determined. The four positions at the end of a course are determined using a curve fitted through the end twelve points.

There is still likely to be error in the position of points along the line of the course. These errors are reduced by smoothing the ship's velocity over five fixes. The courses, velocities and headings are thus calculated. Eötvös corrections, for application to the gravity readings, are also calculated from the velocities, headings and latitudes. Instability in the velocities may occur at the ends of courses and on short courses because of smoothing difficulties. It has been found advisable to check the velocities calculated to ensure that they are reasonable in case unexpected stoppages or short course divergences have been carried out by the ship. The results were generally acceptable except in some instances where the initial Decca positions were too scattered for the initial smoothing carried out in the program to follow the course.

## 2.3. Bathymetry

### 2.3.1. The instruments

On the 1970 cruise a Kelvin Hughes MS 38 depth recorder was used which recorded on a wet-paper recorder. Since transducers attached to the ship's hull were being used, there were no problems with operating speeds.

An Ocean Research Equipment precision depth recorder was used in 1971. This recorded on a Gifft wet-paper recorder. A transducer fish was towed over the side which limited the safe operating speed of the ship to about 7 knots. Although this speed was satisfactory on the survey lines, the fish had to be brought inboard when the ship was proceeding to port at maximum speed.

### 2.3.2. Reduction of data.

Readings at ten minute intervals were transferred from the records to computer punched cards. Corrections for the variation of the velocity of sound in water due to variations in salinity, temperature and pressure were applied in accordance with Matthews' published tables (Matthews 1939).

## 2.4. Gravity.

### 2.4.1. Instruments and recording methods.

A Graf-Askania GSS2,11 sea gravity meter, on loan from Cambridge Department of Geodesy and Geophysics, mounted on an electrically erecting gyrostabilised platform manufactured by the Anshütz Company, Kiel was used on the 1970 cruise. An Enograph chart recorder was used to record the movements of the damped beam. The stabilised platform developed faults as described earlier but these were overcome. The recorder also required two new rheostats but worked well apart from this. A cross-coupling computer linked to the gravity meter was also installed but this did not operate satisfactorily.

In 1971 No.S40 La Coste and Romberg Shipboard Gravity Meter on loan from the Natural Environmental Research Council was used. This system includes a gyrostabilised platform and a cross-coupling computer. A simple analog computer is used to compute the cross-coupling correction from the beam position and the horizontal acceleration along the beam. The gravimeter beam is kept approximately horizontal by varying the spring tension using a slow servo-system.

Deviations of the beam from the horizontal are taken into account by calculating the differential of the displacement of the beam. A second analog computer computes this differential, filters the spring tension, filters the cross-coupling, sums the three and thereby calculates a value for the gravity. This is displayed directly on a chart recorder with the beam deflections, the spring tension and the cross-coupling. The value of the beam displacement is not used directly to calculate the gravity. There should be virtually no drift experienced with the meter over periods of weeks. This was substantiated when comparisons of the readings with those at the base stations were made. Even after a gyro failure, causing the meter to undergo violent oscillations, the drift was less than one milligal over the fortnight's cruise.

The base stations occupied on the two cruises were all set up by the Institute of Geological Sciences. The reference station used for the bases was Pendulum House, Cambridge Observatory which is a fundamental base station. The value of gravity at Pendulum House based on the Potsdam system was measured by Bullard and Jolly (1936) to be 981265.0 mgal but Cook (1953) obtained a more accurate value of 981268.5 ± 0.3 mgal. This value has been used for the present survey.

## TABLE 1

## GRAVITY BASE STATIONS

Gravity base station values are relative to the fundamental station at Pendulum House, Cambridge Observatory. (g = 981268.5 mgal).

| | |
|---|---|
| OBAN | 981642.9 mgal |
| STORNOWAY | 981830.3 mgal |
| LERWICK | 981963.4 mgal |
| BARRY | 981204.8 mgal |

A gravity value was obtained at the quay adjacent to the ship by observing gravity differences from the base station with a Worden 'Master' gravimeter. This value was then reduced to sea level and used in the computation of the gravity data.

### 2.4.2. Reduction of Gravity.

The methods of data reduction used for the two years were basically the same apart from the initial operations.

The 1970 paper chart recordings were digitised using a D-Mac Pen Follower (See Appendix B). On the 1971 cruise, the values of gravity were tabulated at ten minute intervals. The values of gravity were punched onto computer cards with their respective times. The delay in display of the readings due to filtering in the gravity meter was allowed for at this stage.

A revised version of a program called MGRED, written by Watts (1970), was used to calculate the gravity readings at the positions calculated by ANAV. The input to the program consisted of the latitudes, longitudes and Eötvös corrections from ANAV, the gravity information on punched cards, the base station values and the bathymetry values from punched cards. The program MGRED was used in a slightly different form for the two sets of data to allow for the differing forms of the gravity data and the redundancy of any drift correction in the case of the 1971 data. The drift rates for the 1970 cruise are shown in Table 2.

## TABLE 2

## DRIFT RATES OF THE GRAF-ASKANIA SEA GRAVIMETER ON THE 1970 CRUISE.

| Place | Day | Time | Drift Rate. |
|---|---|---|---|
| OBAN | 165 | 1550 | 0.553 mgal/day |
| STORNOWAY | 170 | 1110 | |
| STORNOWAY | 174 | 1500 | -2.803 mgal/day |
| LERWICK | 181 | 0700 | |
| LERWICK | 183 | 1420 | 0.151 mgal/day |
| BARRY | 191 | 1134 | |

(The large drift rate between Stornoway and Lerwick was probably due to the gravimeter being clamped for many short periods during the shooting of the seismic refraction charges).

### 2.4.3 Errors in the gravity.

Errors in the gravity are caused by instrumental errors, errors in the reduction and navigational errors. Off-levelling of the gravimeter and cross-coupling cause the instrumental errors, whilst the application of Eötvös corrections is the main source of error in the reduction.

### 2.4.3.1. Off-levelling.

Off-levelling of the gravimeter causes errorsin the readings. In 1970 the Graf-Askania gravimeter frequently became off-level due to malfunctioning of the stabilised platform particularly during the initial stages of the cruise. The steady off-levelling never exceeded 10 divisions on the spirit level connected to the table and calibrations have shown that this represents a possible error of about 2 mgal (Watts 1970). This is amall compared to other corrections and was therefore ignored. (The off-levelling error due to fluctuations in the level of the table caused by the ship's motion should also be insignificant.) The LaCoste gravimeter system used in 1971 ensured that off-levelling of the gravimeter was negligible. Coupling of off-levelling and horizontal accelerations produces errors less than 1 mgal (La Coste 1967).

#### 2.4.3.2. Cross-coupling.

Cross-coupling is an inherent error in the gravity readings caused by horizontal accelerations acting in the direction of the gravimeter beam coupled with vertical motions of the same period. Watts(1970), using a cross-coupling computer, showed that errors as large as ± 22 mgal can occur in heavy seas with the Graf-Askania meter mounted in R.R.S. John Murray. This error depends largely on the sea state and the orientation of the ship with respect to the waves. The error was corrected for on the 1970 cruise by applying cross-over corrections with 1971 data where possible but corrections could not be applied for variations in the error between the cross-over points. The LaCoste gravimeter has a cross-coupling computer built into it and the correction is automatically applied. Tests described by La Coste (1967) indicated that the accuracy of the meter was better than ± 2 mgal.

#### 2.4.3.3. Eötvös corrections.

The Eötvös correction is necessary to allow for the effect on the measured gravity of the gravimeter's motion over a curved rotating earth. The effect causes an error of approximately 7.5 cos $\phi$ milligals per knot of east to west speed (La Coste 1967), where $\phi$ is the latitude. This correction is added to the observed gravity values for eastward velocities. The correction is zero if the motion is along a line of longitude and a maximum if it is along a line of latitude. The error in east-west velocity is unlikely to exceed 1 knot; therefore the maximum error caused by the Eötvös effect after the correction has been applied is unlikely to exceed 4 mgal. Errors in the ship's heading also produce negligible errors in the gravity.

### 2.4.3.4. The application of cross-over corrections

All the gravity data, including that available from previous cruises, was plotted on a map and the cross-over errors were determined. The 1971 data, which included cross-coupling corrections, had cross-over errors with other 1971 lines and with reliable lines from previous years of no more than 4 mgal. Small corrections were made to eliminate these errors.

The 1970 data had, in many places, quite considerable cross-over errors both with other 1970 lines and with the other data. This was presumably caused by the lack of any cross-coupling correction and the rather large gravimeter drift rates. On Lines 30/70 and 31/70, where very rough weather was experienced, the errors were large and the data was discarded. Corrections were applied to the other lines to bring them into agreement with the 1971 data. At cross-overs between two lines of 1970 data the correction to be applied to either line was estimated by considering the weather conditions and the correction applied at other points on the cruise. The maximum correction applied at any point was 15 mgal which, considering the high drift values measured and the rough weather, was not unreasonable.

### 2.4.4. Display of gravity

The reduced gravity data was plotted both as profiles and on maps using the computer and an on-line 11 inch Calcomp plotter. A program called MAP was written using subroutines written by McKay (1970) which enabled maps of any scale to be plotted on a standard Mercator projection. Lines and gravity values were plotted at convenient scales and superimposed on maps of the coastline and bathymetry which were plotted using the same program. The gravity data was also plotted as profiles adjacent to the equivalent reduced magnetic profiles on a horizontal scale of distance.

## 2.5. Magnetic field observations.

### 2.5.1. Instruments and recording methods.

Proton precession magnetometers, on loan from the Natural Environmental Research Council, were used on both cruises to record variations in the Earth's total magnetic field. A Varian model was used in 1970 and a Barringer model in 1971. Both recorded analogue traces on paper chart recorders and both worked with little trouble. The fish containing the sensor head was in both cases towed between two and three ship's lengths behind the vessel.Bullard and Mason (1961) estimated that the maximum error caused by the magnetic properties of the ship when the sensor head is towed two ship's lengths behind is about ten gammas. This is well inside the errors caused by the temporal variations in the earth's field described later.

### 2.5.2. Reduction of data.

The analogue trace paper chart records were digitised at sufficiently short intervals to record all the variations using a D-Mac Pen Follower. The method used was similar to that used for the gravity records. Times and magnetic field values were punched on cards by the computer. Variations in the Earth's magnetic field measured along the profiles are caused by several phenomena. Before interpretation of the underlying structure could be carried out it was necesaary to attempt to allow for regional and temporal magnetic variations. The temporal variations can be divided into secular variation, diurnal variation and magnetic storm effects. The secular variations occur over long periods of time (measured in years) and would have no relative effect on the profiles. Diurnal variations, which are caused by solar and lunar phenomena and are affected by atmospheric and local geographic effects, can be large, particularly in regions of low latitude. The observatory at

Lerwick, Shetland generally registers peak to peak diurnal variations of between 20 and 40 gamma. On many surveys, corrections for diurnal variations are applied. These are generally calculated using stationary base stations. Hill and Mason (1962) have studied the correlation between land stations and stations on moored buoys in varying depths of water over the continental margin. Although they found reasonably good correlation between the records during magnetic storm periods, correlation between the records at other times was not obvious. They suggested that there may be some phase shifted correlation but insufficient data was available to confirm or quantify this. The variations at sea appeared to be affected by the ocean tides and were in general of a higher magnitude than those on the land.

The records of magnetic measurements during the periods of the present cruises were obtained from the observatory at Lerwick and the periods of magnetic storms were noted. The magnetic measurements taken during magnetic storm periods were discarded for purposes of interpretation since the temporal variations could exceed 100 gamma over periods of less than one hour.

The majority of the profiles were more than 200 km from the observatory. Since the difference between the diurnal variation at the profile and that at the observatory may be as great as the variation itself, there was no value in attempting to apply diurnal variation corrections to the magnetic profiles based on the Lerwick observatory. The error involved over a profile 100 km long, which is the greatest length used for modelling purposes, may be as great as 40 gamma but a more probable maximum value is about 20 gamma since a profile is unlikely to extend over a period containing the maximum and minimum daily values. The fitting of calculated to observed anomaly curves was rarely carried out to an accuracy greater than this since magnetisation values and directions were not accurately known.

Regional gradients in the Earth's magnetic field in this area may be as great as 2.5 gamma/km therefore some method must be employed to correct for these regional variations before interpretation can be carried out. Two methods of calculating a regional field are in general use (Bullard 1967).

The first involves applying what appears to be the best regional field to an individual profile. On short profiles, where a particular body or structure is being investigated, this method works well since it is usually quite clear where the magnetic effect of the body in question has become negligible. When long profiles, which may cover many changes in structure, are being considered the problem is far more complex since it is often difficult to recognise what part of an anomaly is caused by a regional effect and what is caused by the structure under investigation. The complexity is further increased in many of the present profiles by the existence of highly magnetic basaltic lavas near the ends of the profiles.

The second method used involves taking a world-wide reference field as the regional field. In 1968 an International Geophysical Reference Field was defined at Washington in terms of a series of spherical harmonic coefficients up to the eighth order (Anon 1969). The secular variation causes the coefficients to change with time. The meeting attempted to forecast the field up to 1972. A computer program, supplied by the Department of Geodesy and Geophysics, Cambridge, calculates the value of the I.G.R.F. Field at any position on the Earth at any time from 1955 to 1972. It has been shown recently that the secular variation has not occurred quite as expected and there may be a difference as great as 40 gamma between the calculated and the actual field. Although this error is important when considering data collected over many years, the errors involved over a period of one year and a relatively small area are negligible.

The field calculated by the Cambridge computer program was therefore assumed to be a reasonable regional field for the present work. In most cases the program was used as a subroutine at the beginnings of the various interpretation programs.

## 2.6. Seismic reflection profiling.

Two systems were used on both cruises. A sparker system with a simple hydrophone array was used in shallow water whereas in deep water an airgun was used as the energy source with a large hydrophone array as the receiver. The sparker system produces higher frequency energy, which gives good resolution but low penetration, whereas the airguns produced a lower frequency thereby giving greater penetration but less resolution (Hoskins 1965).

### 2.6.1. The equipment and the recording systems.

An E.G. & G. sparker profiling system was used on both cruises. A diesel generator supplied the power to the capacitor banks which were normally set to store 2, 4 or 6 thousand joules of energy. The smaller capacitor banks were used in the shallower water where penetration was of less importance than definition. Multiple reflections from the sea bottom obscure deep reflections in shallow water. In 1970, a single pair of electrodes mounted on a sledge, which was towed behind the ship, was used for the discharge but, in 1971, a brush electrode system was used. This was designed to produce a faster and therefore more powerful discharge by using numerous small wire electrodes which discharged onto a long copper rod.

A simple sixteen element hydrophone array was used to receive the reflections. An E.G. & G. Type 254 recorder both triggered the system and recorded the signal on electro-chemical sensitive recording paper. Band-pass filters filtered out unwanted noise caused by the ship's engines and the passage of the array through the water. The frequency of the firing and the time over which the signal was recorded were varied to suit the power of the generator, the depth of the water and the expected penetration of the sea bed. Penetration varied from nil, where basement rocks were exposed on the sea-bed, to about half a second, where soft sediments were present.

An airgun seismic profiling system, designed and built at Durham University by Mr. J. H. Peacock, was used on the 1970 cruise. The airgun was a dual-pressure, electrically-triggered type with a cylinder capacity of 9.4 cubic inches. The compressed air was supplied by a diesel engine driving a compressor which developed a pressure of about 2,000 lb/in$^2$. A reducing valve lowered the pressure for the low pressure air line. The gun was towed about 20 m behind the vessel at a depth of about 10 m, on a simple frame which was weighted down with large iron weights. A Géoméchanique hydrophone array, about one kilometre in length and containing two, one hundred metre long, active sections, was used as a receiver. This type of array consists of a flexible plastic tube through which is threaded a steel cable for towing purposes. The tube is filled with oil of a suitable density until the array is neutrally buoyant at a certain desired depth. This is usually about two metres. The active sections of the array contain geophones in the oil at two metre intervals. The array is towed behind the ship on a spring section of cable which has the property of decoupling the noise of the ship from the array. This type of array produces a high signal to noise ratio. The plastic tube tows through the water smoothly so reducing water disturbance noise. The ship noise is cut to a minimum by the spring section of cable and by the distance behind the ship that the active sections are towed. The large number of geophones and their spacing increases the signal picked up from below but noise travelling horizontally tends to destructively interfere with itself across the array.

The signal from the geophones was preamplified and recorded directly onto one inch magnetic tape on an E.M.I. tape deck. The preamplified signal was also passed through suitable band pass filters which were adjusted to admit only those frequencies which appeared to give the best penetration and resolution. The filtered signal was recorded on a variable-area Geospace recorder on light sensitive paper. The maximum penetration was between three and four seconds of two-way time in relatively unconsolidated sediments. The operation of this equipment was somewhat spasmodic. This was mainly caused by failures of the energy source. Compressor breakdowns were experienced but the principal cause of trouble was failure of the high pressure air lines in the vicinity of the airgun where they underwent considerable stress in the water. On Line 31/70 the failure of the pressure relief valve on the compressor finally curtailed profiling. Fortunately this occurred near the end of the cruise.

In 1971, a commercially marketed Bolt airgun was used. This was fitted with a 12 cubic inch chamber and air at a pressure of about 2,000 lb/in$^2$ was supplied by the same compressor as in 1970. A Géoméchanique array was again used but triggering and recording was carried out using the same E.G. & G. Type 254 system as was used with the sparker source. The signal was not recorded on magnetic tape therefore all processing had to be carried out concurrently. A band-pass of about 20-100 Hertz provided the best penetration and resolution. Recording was on electro-chemical sensistive recording paper as it was when the sparker source was used. A penetration of about three seconds two-way time was the maximum recorded. Little trouble was experienced with this system. The only problems of any importance were the failure of the drive belts from the diesel engine to the compressor involving a visit to Stornoway for replacements and trouble from dirt in the diesel engine fuel.

### 2.6.2. Processing and display of data.

The data from the two cruises was in two distinct forms. All the sparker and the 1971 air gun data was recorded only on the paper chart recorder therefore no further processing of the original signal was possible. Two methods can be used to display data available in this form. The first involves producing photographs of important sections of the original records. This method has been used to show particular structures and the relationships between various sedimentary layers. The vertical exaggeration of the records is unchanged on the photographs therefore only short sections can be covered.

The second method involves recognising the important reflectors, digitising the records and then reproducing them using different horizontal and vertical scales. This method allows long profiles to be condensed into short presentable sections and often elucidates the broad relationships between various structures and reflecting horizons. The method is somewhat subjective in that the reflectors must first be recognised as such and multiple reflections must be eliminated. The digitising and reproduction of the records can be done manually or using a digitising table and the on-line Calcomp computer plotter. The profiles from this survey have all been reproduced manually since the numerous changes in scale, the number of breaks in the records and other small imperfections would have made a more automated system cumbersome. All lines on the original records, no matter how short, have been reproduced excepting those which are obvious multiples.

The airgun data from 1970 was all recorded on magnetic tape. A system is being designed which should be capable of processing the data to eliminate multiple reflections and increase the signal to noise ratio. This system was not available for the present work so the data was replayed on the Geospace variable-area recorder in a similar manner to that used on board the ship. The horizontal scale was halved to 0.42 cm/minute which made the reflectors more easily recognisable than they were on the original records. Since the reduced horizontal scale was not small enough to make the records presentable they were digitised and reproduced in a similar manner to the other type of records.

### 2.6.3. Wide angle reflection work.

On the 1970 cruise, wide angle reflection work was carried out using the air gun and the recording equipment. Disposable sonobuoys of a type manufactured by Ultra Electronics were used as receivers. The signals were transmitted to the ship using a V.H.F. wavelength and were recorded and displayed using the same equipment as for the profiling. The results were interpreted by A.G. McKay (1972) (Appendix C) using a computer program written by Le Pichon, Ewing and Houtz (1968) and adapted by R. Whitmarsh (N.I.O., England).

# CHAPTER 3.

## Methods of Interpretation

### 3.1. Preparation of data

Before interpretation can be carried out, the data must be reduced and stored in useable form. Values of latitude, longitude, depth, gravity and magnetic field were interpolated at half kilometre intervals and stored in a computer card image format on magnetic tape for use on the NUMAC IBM 360/67 computer. The latitude, longitude, gravity and depth were interpolated using a program called SPLINE. The program fitted a cubic curve to a specific number of successive points and then interpolated between the middle points. Since no short wavelength variations of these readings were expected, this interpolation should give accurate values. The magnetic observations were digitised at short enough intervals to record all the short wavelength variations (3 points/wavelength) and therefore linear interpolation between adjacent points was used. The stored data was arranged into blocks, each block containing one Line of data. Data could be selected and read off the tape at any time thereby making the handling of data relatively simple. All the interpretation was carried out using data in this form. The spacing of the data points was varied by using the data from card images at various intervals from the data blocks.

### 3.2. Basic methods

The gravity and magnetic interpretational methods are of two types. The basic methods involve fitting the calculated anomaly of a model to an observed anomaly along a profile. Either a two or three dimensional model can be used depending on the structure being investigated.

Before this type of interpretation can be carried out certain parameters, such as the density or magnetisation of the body, must be estimated or assumed. Methods of estimating these parameters are called here 'Control methods'. These do not produce a model of an actual structure but provide estimates of key parameters such as the depth to the top surface.

The basic methods are now described. Although they are divided into two, gravity and magnetics, the information gained from each method is used to control the other.

### 3.2.1. Gravity fitting

The profiles were planned to lie perpendicular to the dominant strike of the obvious structures. Two-dimensional interpretational methods were used except in a few cases where it was clear that the structures were not two-dimensional. In these cases three-dimensional interpretation was used.

The gravity anomaly caused by a model body is calculated and compared to an observed anomaly. The basis of this calculation is that used by the program GRAVN (Bott 1969a). The gravity anomaly at a point caused by a body is calculated by adding and subtracting the effects of a series of semi-infinite horizontal slabs, each one having a sloping end defined by two of the body points. The anomaly caused by any polygonal body can be calculated by taking a slab for each pair of adjacent body points.

A program GRAVZ has been written (Appendix D) which computes the gravity anomaly of a specified model and compares it to the observed anomaly. In the present work, variations in structure from an assumed structure at one point on a profile are considered therefore the value of a uniform regional field is irrelevant to the calculations. Only a regional field with a gradient across the area has any effect on the interpretation. Perturbations in satellite orbits have been used to calculate both the Earth's geoid, described using spherical harmonic analysis to the eighth degree, and the long wavelength deviations of the Earth's gravity field (King Hele 1967). A gravity high of 19 mgal is associated with the North Atlantic (Moberly and Khan 1969) but the change between Rockall and Ireland, the direction of maximum gradient, is no more than -3 mgal. Since a change in the depth of the Moho of 1 km causes a change in gravity of about 16 mgal (Bott and Watts 1971), a regional gradient of 3 mgal in 300 km is clearly negligible.

The program GRAVZ assumes a constant regional which equalises the value of the computed and observed profiles measured at the first station point. GRAVZ reads the model as a series of layers and of individual bodies of particular densities. The observed values of the free-air gravity anomaly, the bathymetry values and the distances along the profile of the station points are read from the standard data bank. The gravitational effect of the sea water layer is calculated before the density, body point spacing and number of body points of the next layer, usually a sedimentary layer, are read. The spacing of the body points for each layer must be constant but may be changed from layer to layer. Only the body points for the base of each layer are required as it is assumed that the top of the layer is the same as the bottom of the previous layer. All layers are automatically extended to infinity at either end of the profile. If a complete model is being considered the lowest layer is usually the mantle and is given a horizontal base at any arbitrary depth. Alternatively, a Bouguer anomaly may be calculated by only considering the upper layers. After the layers have been considered, it is possible to add on the effect of any individual bodies to the calculated gravity profile by feeding in the positions of the body points and the density of the body. When all the data has been read in, the program calculates the gravity anomaly and subtracts this from the observed anomaly. The output includes all the input data, for checking, and the differences between the anomalies. The divergence of the model from hydrostatic equilibrium relative to one end is also calculated at each station point.

Originally, an optimisation procedure was included in the program. This repeated the process for slightly different body points until the value of the sum of the squares of the differences between the observed and computed anomaly values was a minimum. This was found to be unmanageable since many values could be varied and geologically unreasonable models were often produced. Reasonable models were found with little trouble by running the program several times and altering the body points manually. The program and the data were stored in the computer and the program was run using a direct link to the computer through an IBM communications typewriter terminal. Alterations to the data were also carried out after each run through the terminal. Up to about ten different models could therefore be tried in one half hour period depending on the lengths of the profiles and the complexity of the models.

The gravity anomalies over three-dimensional models were calculated using the computer program GREND (Bott and Tuson - in press). This requires a division of the model into a series of polygonal prisms with their horizontal axes perpendicular to the plane of the profile as shown in Fig.38 . The anomaly caused by the model is first calculated assuming that the prisms are two-dimensional. The value of the anomaly caused by each prism at each field point is then multiplied by an end-correction factor calculated using the method described by Nettleton (1940). The accuracy of the computed anomaly can be made as good as is required by varying the size and number of the prisms. The computed anomaly is compared to the observed anomaly and the model is altered until a reasonable fit is obtained.

### 3.2.2. Magnetic fitting

Only two-dimensional bodies, uniform and infinite in the third dimension, have been considered in the magnetics interpretation. The anomaly caused by a model is calculated using the basis of the program MAGN (Bott 1969b) which is similar to GRAVN (Section 3.2.1.). The magnetisation contrast and direction are required in place of the density contrast. The calculated anomaly is compared to the observed anomaly. The model is then changed slightly and the procedure is repeated until a reasonable fit is obtained. This process has been carried out using a non-linear optimisation program MINUIT (CERN 1969) and a specially written subprogram OMAGY. By varying the body point parameters and the magnetisation parameters of the model, MINUIT minimises the value of the sum of the squares of the differences at the station points between the observed and computed magnetic profiles. The subprogram OMAGY calculates this value for each set of parameters passed to it by MINUIT. Any number of closed bodies may be used in the model and each body may have any magnetisation vector. It is often desirable to extend a body to infinity. This is achieved by extending it to a distant point (± 1000 km). The resulting loss in accuracy is negligible. Since many minima of the function are likely to exist, geologically reasonable limits are applied to some or all of the parameters. This facility is catered for by MINUIT.

## 3.3. Control methods

### 3.3.1. Gravity-magnetic transforms

The magnetic and gravity profiles over a body of arbitrary shape, which satisfies the Poisson condition, are related. A magnetic profile over a body can be transformed to a gravity or pseudogravity profile for a defined magnetisation vector of the body. By varying the magnetisation vector, and the magnetisation to density ratio, the pseudogravity anomaly can be fitted to the observed gravity anomaly. Estimates of the true magnetisation vector and magnetisation to density ratio can thus be made. Provided that the Poisson vector ($\underline{P} = \frac{\underline{m}}{\rho}$) is constant at every point in a body of arbitrary shape, the magnetic potential, V, and the gravitational potential, U, at an external point are related by Poisson's equation:

$$V = -\frac{\underline{m} \cdot \nabla U}{G\rho}$$

where $\underline{m}$ is the magnetisation of the body.

p is the density of the body.

and G is the gravitational constant.

For two-dimensional bodies:

$$a = \frac{m\,F}{G\,p}\left(\frac{\partial g}{\partial x}\sin\beta - \frac{\partial g}{\partial z}\cos\beta\right) \qquad \text{(Bott 1969c).}$$

where g is the gravity anomaly.

a is the magnetic anomaly component.

the z-axis is positive vertically downwards.

the x-axis is horizontal and perpendicular to the strike of the body.

$F = (\sin^2 Im + \cos^2 Im \cos^2 \alpha_m)^{\frac{1}{2}} (\sin^2 Ie + \cos^2 Ie \cos^2 \alpha_e)^{\frac{1}{2}}$

$\beta = \mu + \sigma$

$\mu = \arctan(\tan Im/\cos \alpha\, m)$

$\sigma = \arctan(\tan Ie/\cos \alpha\, e)$

$I_m$ = dip of direction of magnetisation

$\alpha m$ = azimuth of direction of magnetisation

$I_e$ = direction of the magnetic anomaly component.

$\alpha e$ = azimuth of the magnetic anomaly component.

(azimuth is measured from the positive x-axis).

If it is assumed that the ratio $\frac{m}{\rho}$ is constant throughout a body, it is possible to calculate a gravity anomaly from a magnetic anomaly for assumed values of the ratio . Values for Im, $\alpha$m, Ie and $\alpha$e are either known or assumed. The resulting gravity anomaly is known as a pseudogravity anomaly. Bott and Ingles (1972) have developed a method of carrying out this process using the linear inverse method. A layer, made up of uniform blocks, is calculated which is equivalent to the magnetic source body in that the magnetic anomalies of the two are approximately the same. The magnetisation of each block is constant but varies from block to block. The I.B.M. scientific subroutine LLSQ is then used to calculate the optimum value of $\frac{m}{p}$ which gives the best fit of the calculated gravity anomaly caused by the blocks to the observed gravity anomaly.

The program TRMG (Ingles 1972), written in PL/1 for use on the NUMAC IBM 360/67 computer, has been used in the present work. Slight modifications were made to suit the form of the data and to enable it to be read in from either north to south or from south to north. The values of the dip and azimuth of the magnetisation vector in the body were varied until the highest correlation ratio between the observed and calculated gravity anomalies was obtained. If this ratio was high, it was deduced that the gravity and magnetic anomalies were strongly related and the values of dip, azimuth and $\frac{m}{p}$ were noted. If the correlation ratio was low the results were ignored.

### 3.3.2. Magnetic power spectrum analysis

The depth to a magnetic basement can be estimated by analysing the power spectrum of a magnetic anomaly profile over it. A profile over a shallow basement contains anomalies of shorter wavelength than a profile over a deep basement. Assuming that a magnetic basement may be approximated by a single uncorrelated distribution of infinitely long, magnetic line sources, a plot of the natural logarithm of the normalised power of the magnetic anomaly against the wavenumber is a straight line. The line passes through the origin and is of slope -2d where d is the depth to the basement (Treitel et al. 1971). The prime advantage of the method is that knowledge of the magnetisation vector of the body or the direction of the Earth's field is unnecessary.

The power spectrum of a waveform can be calculated by taking the cosine transform of the autocorrelation function of that waveform (Blackman and Tukey 1958). Since a magnetic record is always of finite length, inaccuracies can occur in the calculation of the autocorrelation function. The function is therefore multiplied by a suitable even function of the lag used to calculate the autocorrelation function. This is known as a lag window. Although the calculated autocorrelation function may then be a poor estimate of the true function its transform is usually a reasonable estimate of smoothed values of the true power spectrum. The use of a lag window introduces other problems to the method. If there is a large peak in the power spectrum, it may be 'reflected' at higher frequencies by the side lobes of the lag window therefore prewhitening must be applied to the data. A flatter power spectrum is therefore calculated which is later transformed to give the true spectrum.

Any regional trend or constant term in the magnetic profile affects the shape of the power spectrum. The regional values at the station points must therefore be subtracted before the autocorrelation function is calculated. The power at zero frequency is affected by the magnitude of a constant term and will therefore be changed if the term is not present. To compensate for this, the zero frequency term is multiplied by a calculated factor (Blackman and Tukey 1958). The resulting value is, however, still likely to be inaccurate and it is therefore usually ignored.

A computer program POW2 (Lee 1972), written for use on the NUMAC IBM 360/67 computer, was used in the present work to calculate the power spectra. Lee has found through experience that the use of prewhitening and a Hanning lag window gives the most accurate estimates of basement depths. The maximum lag used to calculate the autocorrelation function was that recommended by Lee. The procedure was usually carried out on several separate and overlapping sections of a profile and the results from each were compared to give an estimate of the accuracy.

### 3.3.3. Use of reflection profiles

Reflection profiles can be used both qualitatively and quantitatively. Their qualitative use involves the recognition of different structures in the various rocks and sediments underlying the seabed. In the present area, the distinction between acoustically opaque or basement rocks and the overlying sediments is fairly distinct. On all the banks and on the continental shelf, the basement rock can be recognised and in many cases the surface of it can be traced beneath the sediments. Unfortunately, the power of the air gun was not sufficient to trace the basement over the whole area. The sedimentary reflecting horizons, which are common in the area, can be mistaken for the basement at depths approaching the limit of penetration as has been pointed out in the Hatton-Rockall Basin (Roberts et al. 1970).

The quantitative use of seismic reflection records depends, initially, on the qualitative interpretation of the reflecting horizons being carried out satisfactorily and, secondly, on the values of sediment velocities being known with some accuracy. The two-way time for the reflection from any position on a reflecting horizon can be measured directly from the records. Two corrections should be applied to this time. Allowance should be made for the pressure wave not having travelled vertically since the source and the receiver were not in the same position. In the case of the Géomécanique array, the distance between the two was approximately half a kilometre. Most of the quantitative work has been carried out in water of at least half a kilometre depth and on reflecting horizons of greater than one kilometre depth therefore the maximum correction should be of the order of one hundred metres. Over most of the profiles the correction would be much less. Since the velocities of the deeper sediments were not known to an accuracy of greater than about 0.2 km/s, the accuracy of any depth determination through sediments 1 km thick are unlikely to have an accuracy of greater than 200 m therefore the wavepath correction can be discarded.

The other correction which could be applied is for the depth of the sparker or airgun and the hydrophones beneath the water. This correction is a constant one of between 10 and 15 m. The correction has not been applied since it is again very small compared to other possible errors. It will to some extent cancel out the effect of the previous error. The correction is irrelevant when considering the depth of reflectors beneath the seabed.

The calculation of the depth of a reflecting horizon or the basement was carried out manually assuming an average velocity for the sediments. The velocities used were calculated from previously published results and from the wide-angle reflection results gained from the 1970 cruise.

The reflection profiles have been used to determine the depth to the basement, where it is seen, for use as a control in the other interpretative methods. They have also been used to determine the type and attitude of bedding or layering in the sediments and to trace reflecting horizons lying in the sediments.

# CHAPTER 4

## The Rockall Trough, adjoining margins and the outer banks

### 4.1. Introduction

The Rockall Trough separates Rockall Plateau, described as a microcontinent by Scrutton and Roberts (1971), to the northwest from the British continental shelf to the southeast (Fig.2). To the southwest, the Trough opens into the eastern North Atlantic basin, whereas, to the northeast, the bathymetric barrier formed by Faeroe Bank and the Wyville-Thomson Rise separates the Trough from the Faeroe-Shetland channel and the Norwegian Sea. To the north of the Trough lie George Bligh, Lousy and Bill Bailey's Banks which rise to a depth of 100 to 300 fathoms. The water depth in the Trough decreases from about 2000 fathoms at the southwestern end to about 500 fathoms at the northeastern end. In the centre of the northern part of Rockall Trough, Rosemary Bank and the Anton Dohrn seamount rise to depths of 300 to 400 fathoms.

### 4.2. The sediments

### 4.2.1 Thicknesses

The thickness of the sediment in the south of the Trough, at $55^{\circ}$N, has been estimated by refraction methods to be about 5 km (Ewing and Ewing 1959 - Line E 10) (Fig.4). The sediments are underlain by a layer with a P-wave velocity of 6.96 km/s, although an alternative interpretation indicated about 4.5 km of sediment underlain by a layer of P-wave velocity 5.55 km/s. (Fig.4). A seismic refraction profile from slightly further north (Scrutton 1971 - Line C) indicates that about 5 km of sediment is present underlain by a layer of P-wave velocity 4.72 km/s. In the northern part of the Trough, at $58^{\circ}$ 15' N, about 2.6 km of sediment are underlain by a layer of P-wave velocity

4.97 km/s (Ewing and Ewing 1959 Line E11). All the refraction lines were unreversed therefore if dipping layers are present, the velocities and thickness estimates may be in error. The overall smoothness of the sediments in the Trough shown by reflection profiles (Scrutton and Roberts 1971, Jones et al. 1970) makes this appear unlikely.

The apparent velocities of 4.72, 4.97 and 5.55 km/s all lie within a range representative of both consolidated sediments and of oceanic layer 2 material (Bott 1971). In order to investigate the nature of the layer underlying the sediments, power spectral analysis of the magnetic profile on Line 3/970 was carried out. This line passes close to the position of refraction line E 11. Since the depth to the magnetic basement was expected to be several kilometres, lengths of about 150 km of the profile were used for analysis. The results from three lengths of the line were 5.5, 4.4 and 5.0 km. The scatter of values is unlikely to be caused by real lateral variations in depth since the lengths of line used overlapped considerably. A magnetic equivalent layer 5 km thick was computed at a depth of 5 km beneath Line 3/970. The magnetisations of the blocks making up the layer varied from about 0.001 to 0.003 emu/cm$^3$. Since the magnetic basement is presumably only overlain by relatively non-magnetic sediments, these results indicate that a thickness of sediment of about 3 km is present allowing for the water depth of 2km. This is in good agreement with the results of refraction line E 11 and indicates that the 4.97 km/s layer is the magnetic basement. It is reasonable to assume that the 4.72 km/s layer found by Scrutton and probably the 5.55 km/s layer on line E 10 are also magnetic basement. The scatter of these velocities, if they are representative of the same layer, may be due to the refraction lines being unreversed and, in some cases, being carried out in bad weather.

Old Red Sandstone and Torridonian Sandstone are the only sedimentary rocks in the region with velocities similar to those measured. Old Red Sandstone in Brecknockshire has velocities between 4.15 and 4.64 km/s (Day et al. 1956) whereas measurements of the velocities of the Middle Old Red Sandstone in the Orkneys have yielded 4.9 to 5.8 km/s (McQuillin 1968). The Old Red Sandstone in the Orkneys is relatively non-magnetic (Flinn 1969) and it would therefore be unlikely to form a magnetic basement. Torridonian Sandstone, which is slightly denser than Old Red Sandstone (Tuson 1959), probably has a velocity near the top of, or above, Class 3 (3.65 to 4.85 km/s) of Day et al. (1956) and Hill and King (1953), defined from their studies in the English Channel and its approaches. Material with a well-determined velocity of 4.7 km/s, lying in Basin 'E' on the continental shelf west of the Shetlands (Watts 1971), may be Torridonian Sandstone (Browitt 1971). This velocity agrees well with that measured in the Rockall Trough but Torridonian Sandstone is relatively non-magnetic (Powell 1970) and is unlikely to form the magnetic basement. Lewisian material forms the magnetic basement over large areas in northwest Scotland (Powell 1970) but its velocity, calculated from its density and from refraction experiments, lies between 5.95 and 6.4 km/s which is probably too high for the material in the Trough. It is unlikely that continental material underlies the sediments in the Trough.

The velocity of an oceanic layer 2, which probably consists of basaltic lava or intrusive rocks of similar composition, lies between 4.0 and 6.0 km/s and it has been shown that highly magnetic rocks form a substantial part of the layer (Bott 1971). The magnetisation of oceanic layer 2 lies between about 0.001 and 0.01 emu/cm$^3$ (Bott 1971). The calculated values for the basement are therefore possible values for a layer of that type. The geophysical data is consistent with a layer of similar properties to an oceanic layer 2 underlying the sediments.

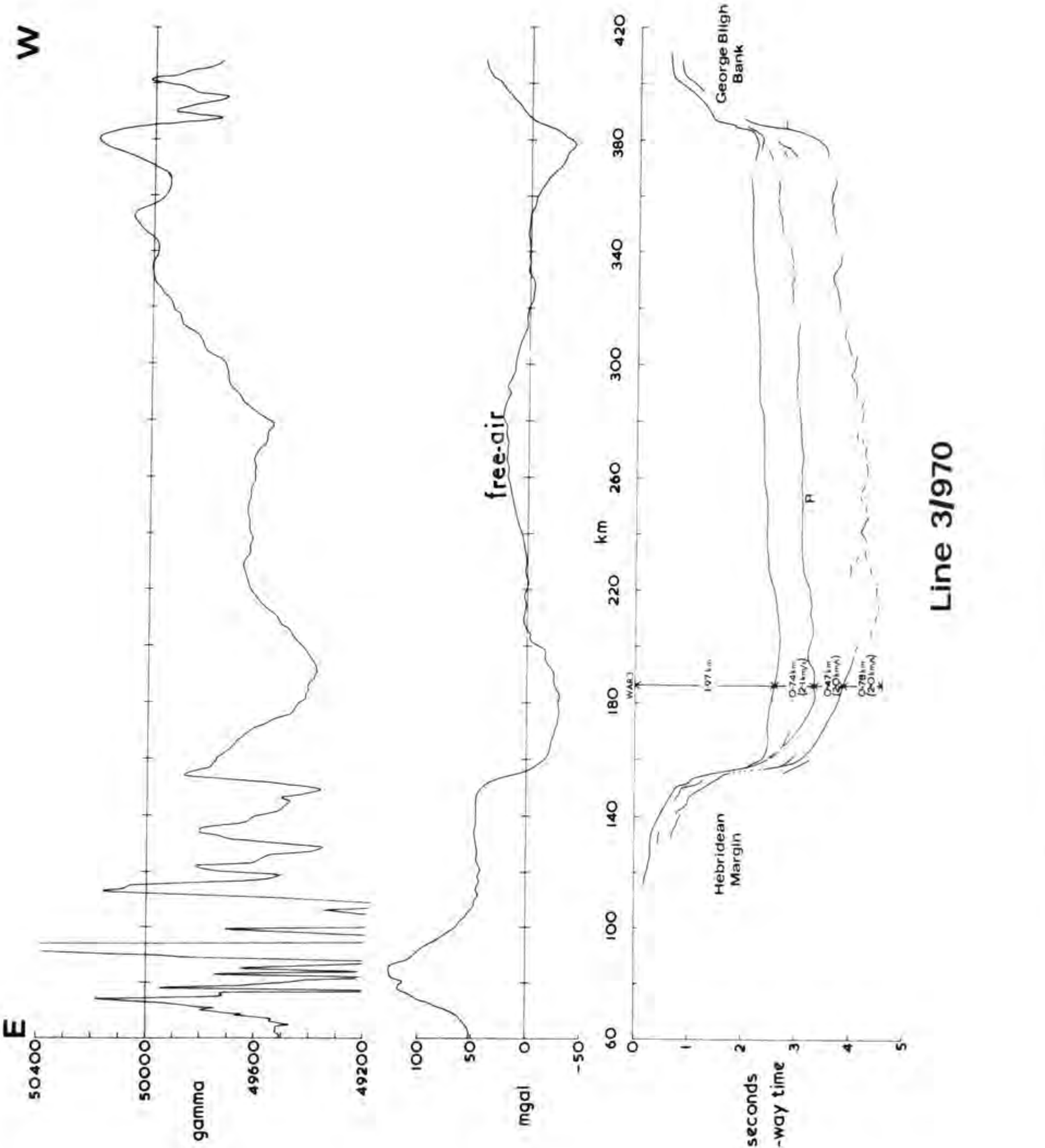


Figure 7. Profiles on Line 3/970.

This substantiates the theory that Rockall Trough was formed by ocean floor spreading (Vine 1966) rather than by continental subsidence.

The depth of the basement in the Rockall Trough appears to decrease from about 7 km to 5 km beneath sea level between 55°N and 58°N. A deep irregular reflector across the southern part of the trough (Scrutton and Roberts 1971 - reflector '5') has been correlated with the top of the basement layer. The reflection profile on Line 3/970 (Fig.7) shows a reflecting horizon at a depth of about 4.5 s two-way time. It is somewhat intermittent and slightly irregular but it does not appear to be as irregular as Scrutton and Roberts' reflector '5'. On Line 31/70 (Fig.8) the reflector is smoother and more continuous and looks less like a basement reflection although it does appear to be continuous with the basement on Rosemary Bank. On Lines 6/970 and 7/970 (Fig.9) the deepest reflector is at a depth of about 4 s which may indicate that the reflector depth is decreasing towards the north. A wide angle reflection station on Line 3/970, WAR3 (Fig.7, Appendix C), gave results which may be unreliable. The top layer has a velocity of 2.1 km/s whilst the lower two layers have estimated velocities of only 2.0 km/s. The velocity of 2.0 km/s agrees well with Ewing and Ewing's unreversed velocity of 2.08 km/s but neither of these results are well-determined. The depth of 2 km beneath the sea bed of the lowest reflector, as calculated from the wide-angle reflection results, is likely to be a minimum estimate since the velocities measured in the sediments in the southern part of the Trough are higher than those used for this estimate. It is therefore possible that the lowest reflector on the reflection profiles is the surface of the basement layer. It could however be a reflecting horizon slightly above the basement.

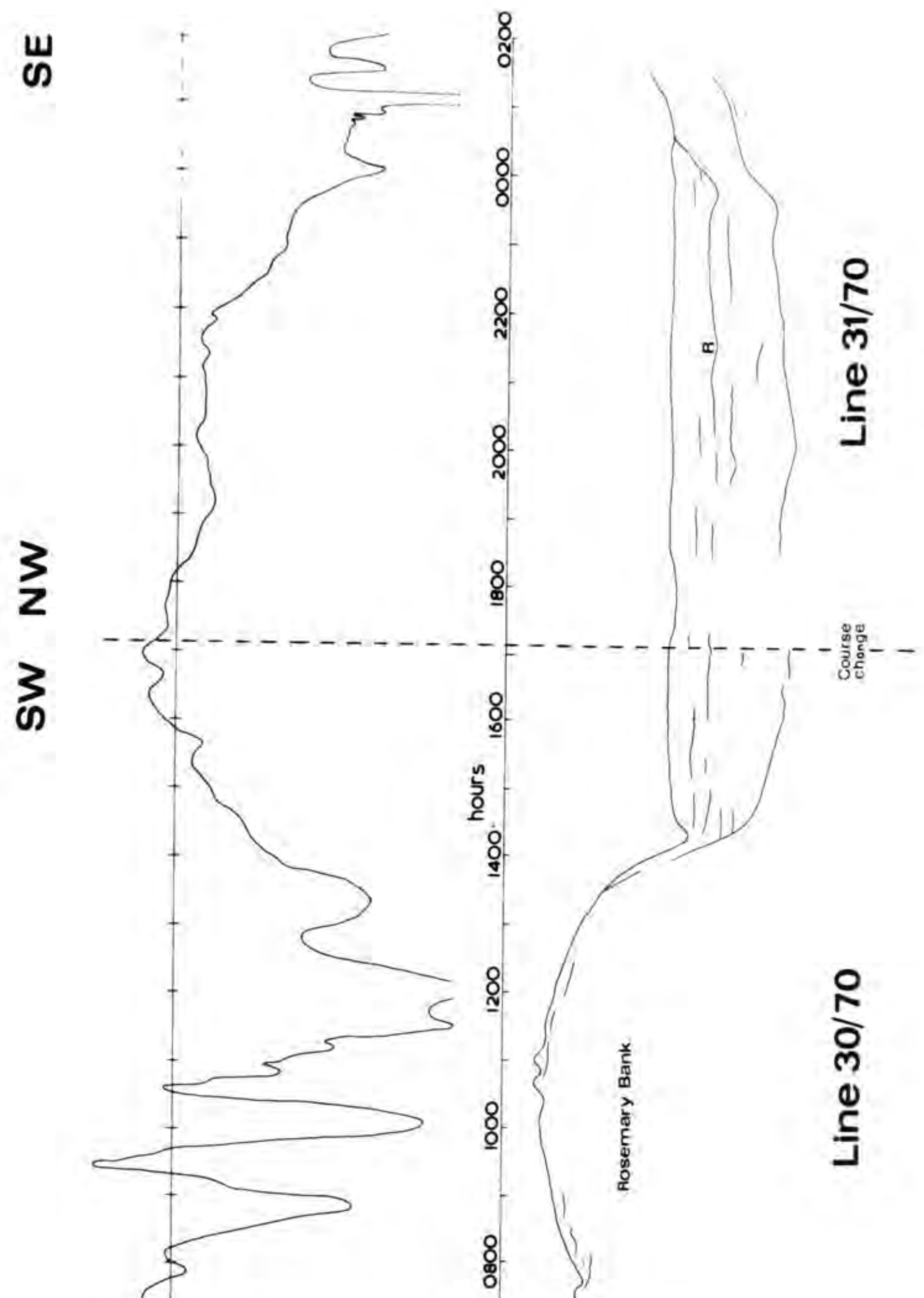


Figure 8. Profiles on part of Line 30/70 and on Line 31/70.

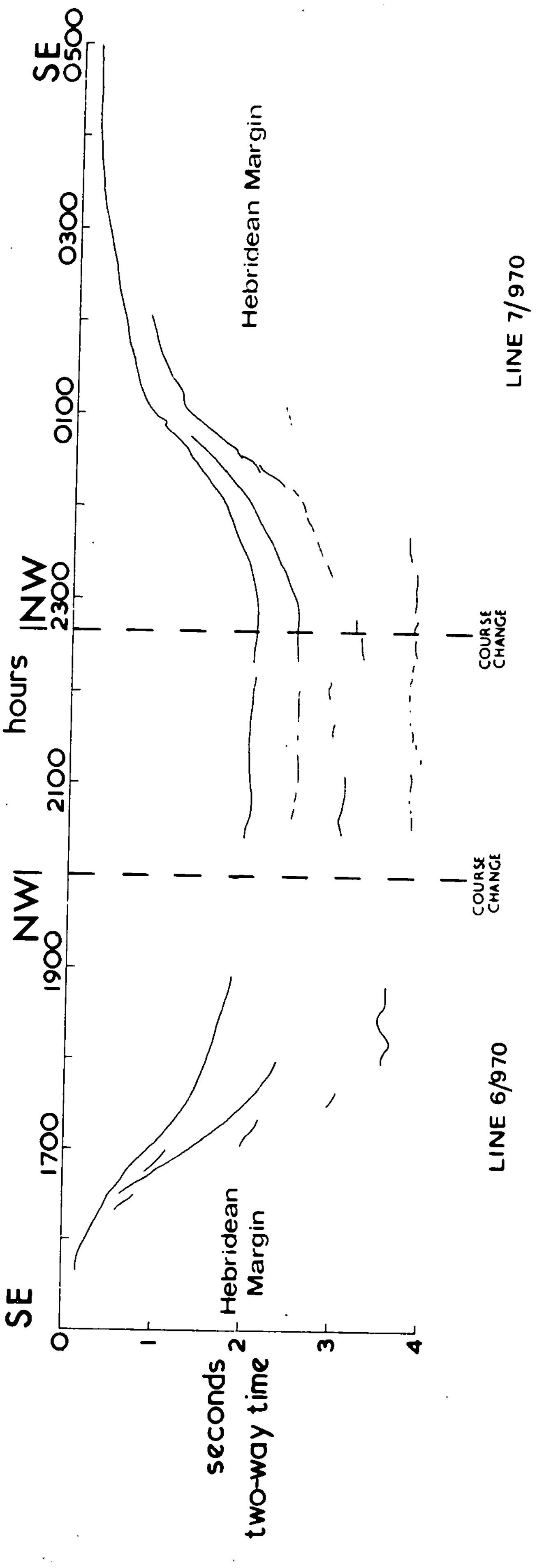


Figure 9. Profiles on Lines 6/970 and 7/970.

On Line 4/970, between George Bligh and Bill Bailey's Banks (Fig.10), a strongly reflecting horizon, which can be traced from the basement outcropping on the Banks, is seen on most of the profile. The significance of this is discussed in Section 4.4.1. Line 5/970 passes along the southern side of the Wyville-Thomson Rise. The eastern end of the Line shows a sedimentation pattern typical of the Trough with the basement at a depth of 2 to 3 km below the seabed (WAR5 - Appendix C, Fig.11) but the remainder is clearly affected by the Rise and is discussed in Chapter 5.

### 4.2.2. <u>The reflecting horizons and the sediment ages</u>

A strongly reflecting horizon, composed of many small cuspate reflectors and at a depth of between 0.5 and 0.75 seconds two-way time, has been recognised in many parts of the Rockall Trough (Le Pichon et al. 1970, Scrutton and Roberts 1971, Jones et al. 1970). It is usually known as reflector 'R' and is underlain by relatively transparent sediments. Jones (personal communication) has dated reflector 'R' as Lower-Middle Oligocene by tracing it into the main basin of the Atlantic and across to the position where it wedges out against the oceanic layer 2. This position has been dated using the magnetic reversal time scale recorded by the magnetic lineations of the ocean floor (Heirtzler et al. 1968). D.G. Roberts (personal communication) dated the reflector by correlating it with a reflector in the Hatton-Rockall Basin which has been dated at 45 m yr in a Deep Sea Drilling Project borehole.

Reflector 'R' can be recognised on most of the reflection profiles in the Rockall Trough. Line 3/970 (Fig.7) crossed Line C of Jones et al. (1970) on which they have recognised reflector 'R'. The identity of the reflector on Line 3/970 is therefore established. The reflector is identifiable on Line 4/970 (Fig. 10) by reference to the adjacent Line 3/970. D.G. Roberts (personal communication) has

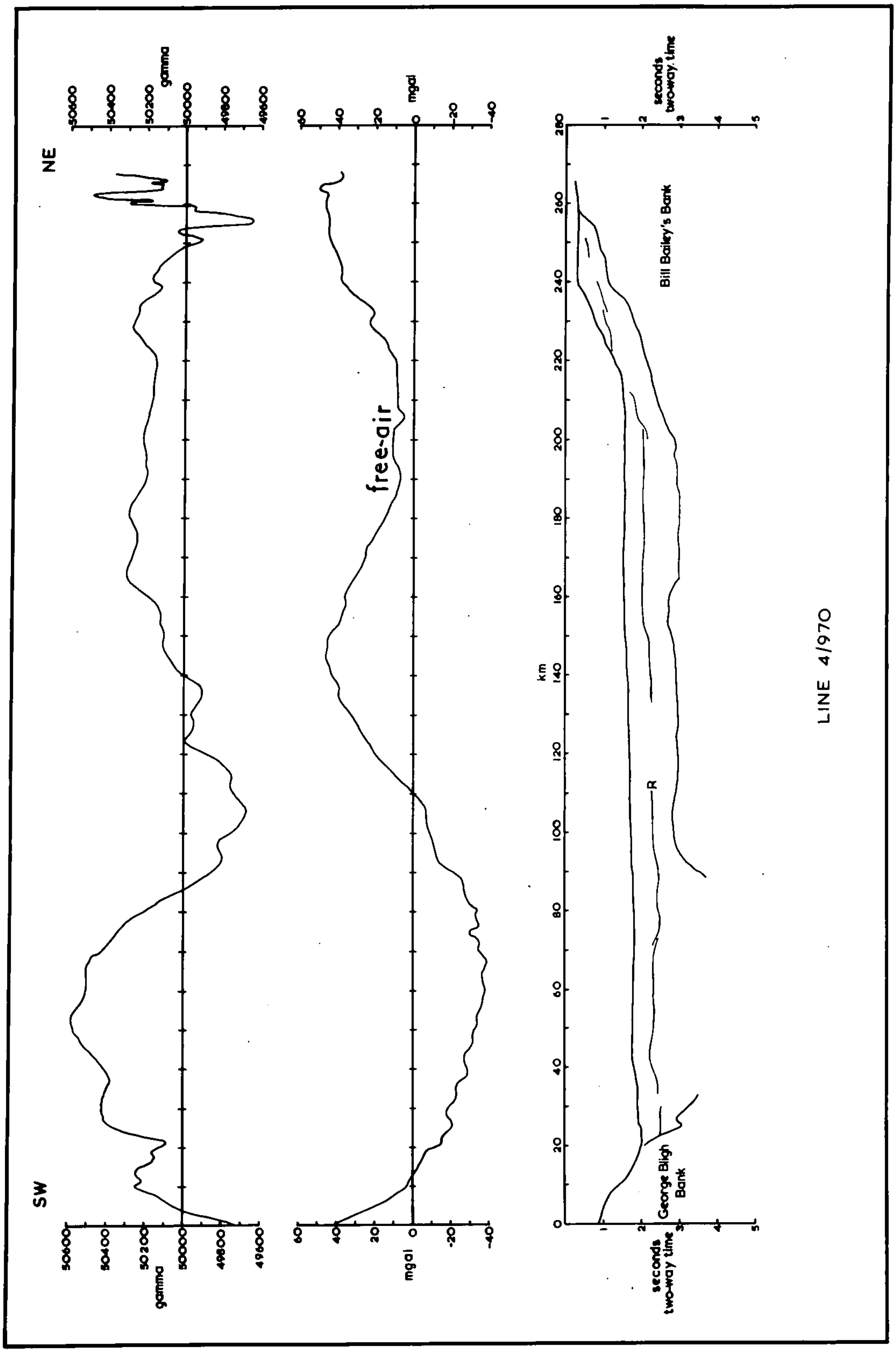


Figure 10. Profiles on Line 4/970.

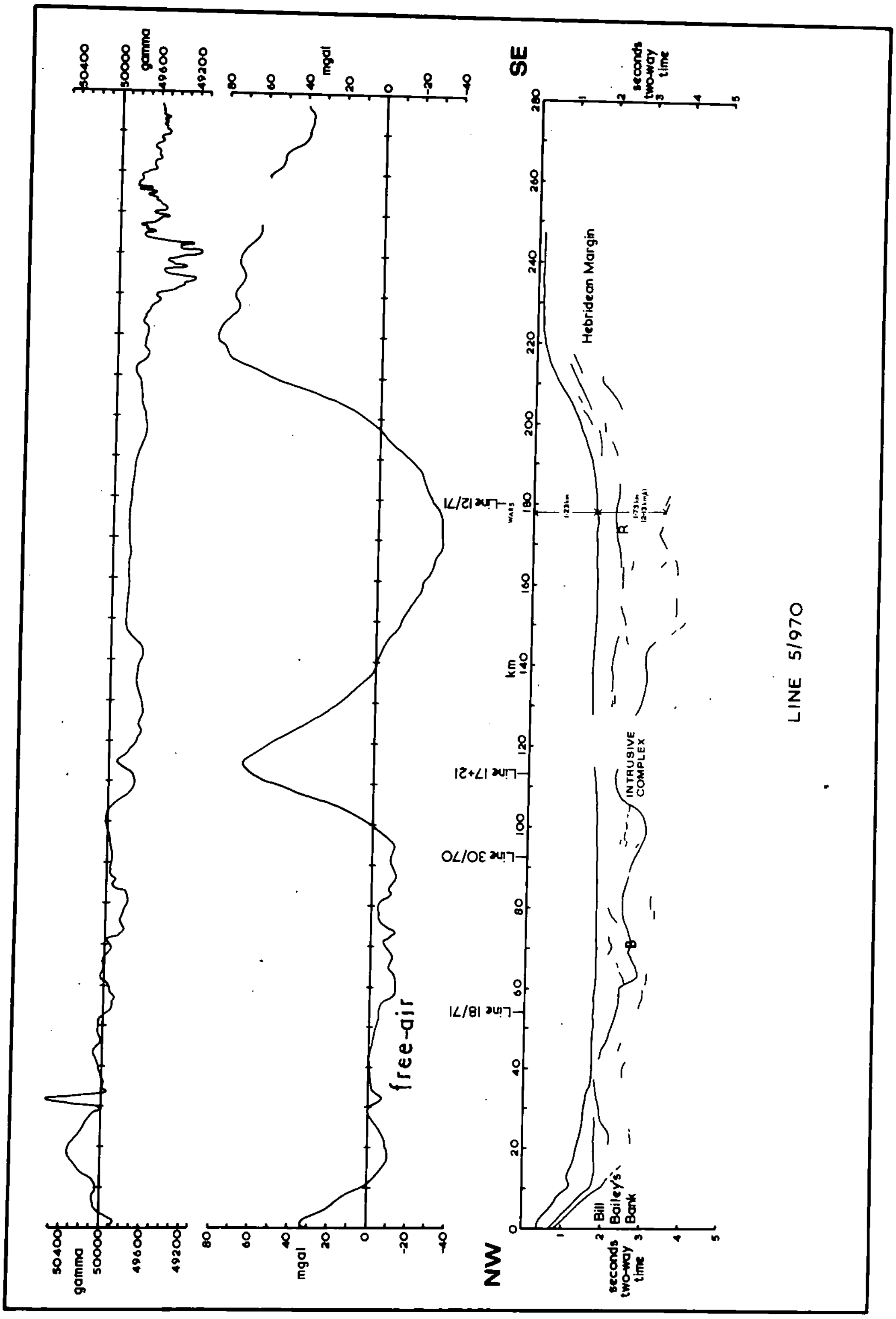


Figure 11. Profiles on Line 5/970.

confirmed that reflector 'R' lies at a depth of about 0.5 seconds in this area. Reflector 'R' has been recognised on Lines 31/70, 24/71, 7/970, 6/970 and 5/970 (Figs. 8, 12, 9 & 11) by correlation using the depth of the reflector. The depth of the reflector on all previous profiles in the Rockall Trough is between about 0.5 and 0.75 seconds therefore it is reasonable to assume that a prominent reflector elsewhere in an undisturbed part of the Trough and at the correct depth is 'R'. The consistency of the depth of the reflector is confirmed by the present profiles.

At the Hebridean continental margin, reflector 'R' rises towards the surface. On profiles 31/70, 24/71 and perhaps 3/970 (Figs. 8, 12 & 7), all of which cross the margin where it changes from a north-south to a northeast-southwest trend, the reflector emerges at the seabed. This is most clearly seen on Line 31/70 where there is also a dip in the reflector close to the margin. Further along the margin to the northeast on Lines 5/970, 6/970 and 7/970 (Figs. 11 & 9), reflector 'R' slopes up and becomes lost in the sedimentary layers which drape the margin. A similar situation is present to the south of the corner in the margin (Jones et al. 1970 - Profile C). There has therefore either been less sediment deposited over the corner of the margin or it has been deposited and eroded away. The dip in the reflectors on Line 31/70 (Fig.8) suggests that currents scoured a trough round the foot of the margin in the past and the presence of a trough about 30 m deep in the present seabed suggests that they still do. A similar, but more pronounced effect is seen round the base of Rosemary Bank (Line 30/70, Fig.8).

The sediments lying on the margin can be most clearly seen on the sparker profiles from Lines 24/71 and 14/71 (Figs. 12 & 13). Two unconformities can be seen on Line 24/71. The lower one, which may also be present on Line 14/71 slightly below the seabed, lies at a depth of about 1300 m whilst the upper unconformity is at about 680 m

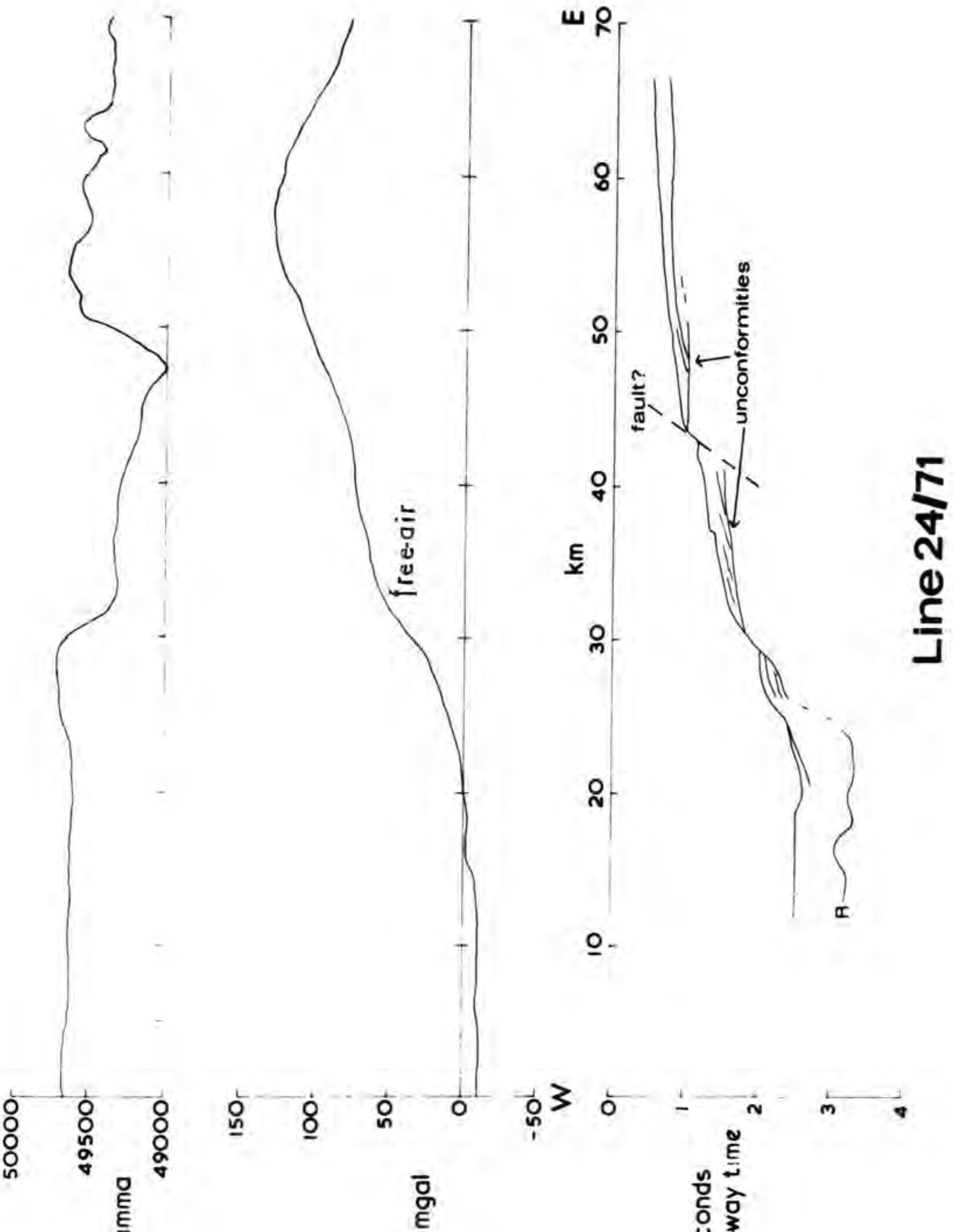


Figure 12. Profiles on Line 24/71.

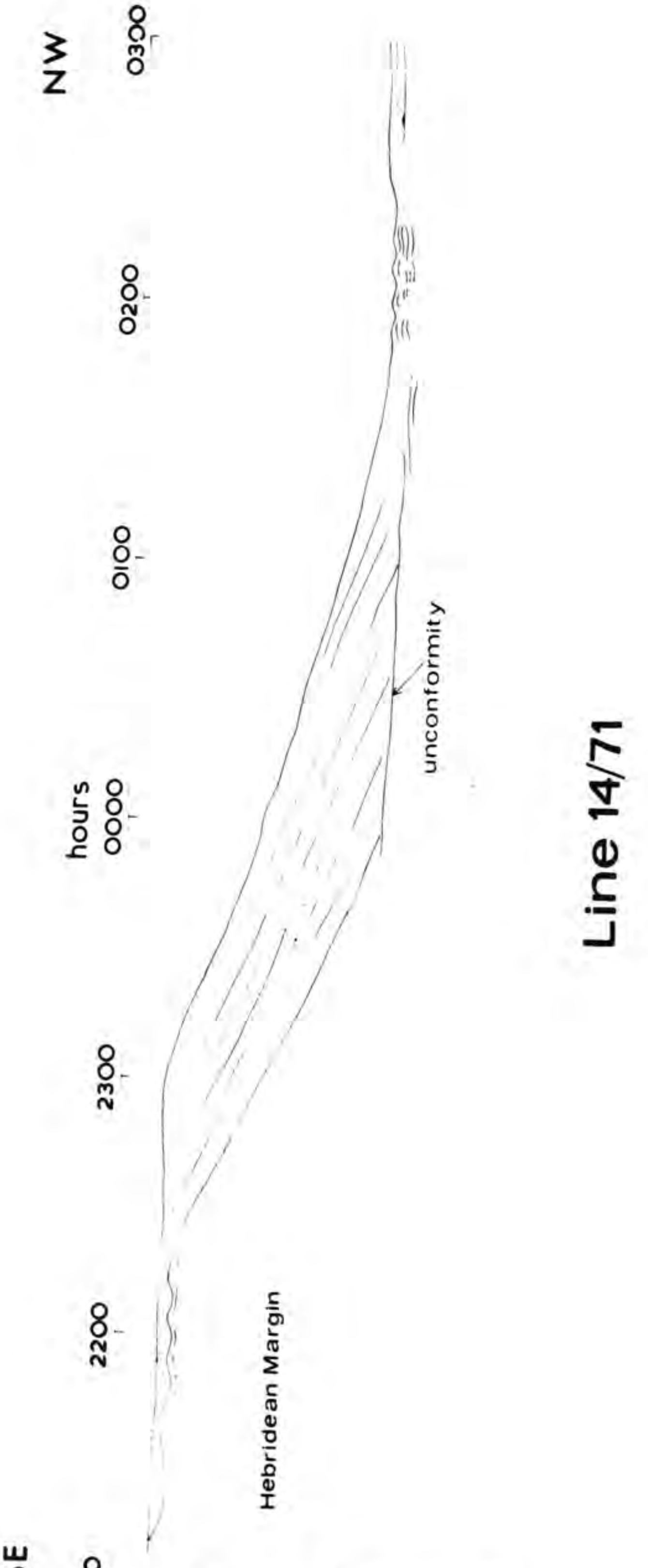


Figure 13. Profiles on Line 14/71.

depth. The lower unconformity is almost horizontal and is overlain by gently seaward-dipping sediments. The sediments show fairly continuous bedding which indicates a post-Cretaceous age (Stride et al. 1969) and have a thickness which decreases from about 700 m on Line 14/71 to about 300 m on Line 24/71. The thickness of similar sediments on the eastern margin of the Faeroe-Shetland channel (about 1200 m) is such that the sediments are unlikely to be entirely Quaternary in age and are probably also Tertiary (Stride et al. 1969). Profiles 24/71 and 31/70 show that the lower unconformity is probably younger than or contemporaneous with reflector 'R'. The sediments overlying it may therefore be of Oligocene or later age. The material underlying the unconformity shows no bedding on the present profiles. Stride et al. (1969) recognised 'a sedimentary series with rather ill-defined, discontinuous bedding with a low westerly (apparent) dip' beneath the well-bedded series. They considered it to be Palaeozoic in aspect. Gravity and magnetic evidence on Line 24/71 and magnetic evidence on Line 31/70 (Figs. 12 & 8) indicates that an intrusive complex lies beneath the continental slope (Section 6.3.2.). The lack of bedding beneath the lower unconformity may be caused by the presence of igneous rock. If intrusive material had risen in the crust beneath, it may have caused both the exposure of reflector 'R' and the formation of the unconformity. The unconformity would therefore be younger than the intrusion, whilst reflector 'R' would probably be older.

The upper unconformity may be a continuation of the lower one lying to the eastern side of a normal fault. The bedding of the sediments lying above it is similar to that above the lower unconformity but indistinct bedding is present beneath it.

The relationship between reflector 'R' and the sediments draping George Bligh and Bill Bailey's Banks is quite different from that found at the continental margin. The beds containing reflector 'R' overlap onto the sediments which are draped over the Banks (Figs. 7 & 10). The boundary between the horizontal sediments and the prograded sediments is distinct thereby indicating that little or no sediment has been deposited over the sides of the Banks, as distinct from the general sedimentation on the ocean floor, since well before reflector 'R' or Lower Oligocene times. This relationship is also found on Rosemary Bank and on the Wyville-Thomson Rise. The difference between the Hebridean margin and the margins of the Banks is also shown on the reflection profiles of Scrutton and Roberts (1971), Jones et al. (1970) and Le Pichon et al. (1970). The relationship on the Hebridean continental margin implies that an almost continuous supply of sediment was available from the land areas until well after Lower Oligocene times. This situation has presumably changed relatively recently since there is unlikely to be any flow of sediment over the shelf and there is no sizeable provenance for any sediment at present. Around the Banks, the supply of sediment presumably only lasted until some time before the Lower Oligocene except perhaps for a small supply during Flandrian times when the sealevel was low. The lack of sediment supply could be caused by not only the relatively small size of the Banks but also by the Banks sinking rather more than the continental margin. The relatively rapid sinking of the basement in the Hatton-Rockall Basin during the Late Palaeocene (D.S.D.P. Scientific Staff) may have been contemporaneous with a similar sinking of the Banks.

### 4.2.3. <u>Rosemary Bank</u>

Little sediment can be seen draping the sides of Rosemary Bank on Line 30/70 (Fig.8) and, since there is no flat wave-cut platform on its top, it seems unlikely that the Bank has undergone much if any subaerial erosion. Reflector 'R' wedges out horizontally against the Bank as do other reflecting horizons at least 0.5 second (over 0.5 km) beneath 'R'. This implies that the Bank, which Scrutton (1971) has interpreted as an old volcano, was formed a considerable time before the Lower Oligocene and could be as old as the basement. Scrutton's hypothesis, based on the analysis of dredged samples, that the volcano is not part of the Tertiary igneous province but was formed simultaneously with the opening of the Rockall Trough by ocean floor spreading, is supported by this evidence.

## 4.3. The crustal structure beneath the Rockall Trough and its margins

### 4.3.1. Seismic control

The seismic refraction results available from the Rockall Trough are summarised in Fig.4. No definite arrivals have been received from the Moho but Line E 10 (Ewing and Ewing 1959) can be interpreted to show a layer of velocity 8.0 km/s at a depth of about 14 km. Several reasons for the lack of refracted arrivals from any great depth have been proposed in the light of similar experience elsewhere. A high velocity layer, possibly composed of limestone or salt, or a layer with high attenuation properties may be present (Scrutton 1971). The former is used to explain similar problems in the Eastern Mediterranean experienced by German scientists but in that case the presence of a salt layer has been confirmed by the Deep Sea Drilling Project. The seismic refraction data from the Trough can therefore only be used to determine the sediment thickness.

Gravity profiles across the margins of the Trough have been used in conjunction with seismic information from the Hebridean shelf and Rockall Bank to investigate changes in the crustal thickness.

A seismic refraction experiment on Rockall Bank found a continental type of crust with a thickness of approximately 31 km (Scrutton 1970). A variable shallow structure is underlain by an upper crust of velocity 6.36 km/s and a lower crust with a less well-determined velocity of 7.02 km/s. Inaccuracies in this velocity could cause errors in the estimated depth to the Moho. Agger and Carpenter (1964) used data from the Eskdalemuir station to calculate a Moho depth of 25 to 30 km in that area whilst Blundell and Parks (1969) calculated the depth to be about 29 km beneath the Irish Sea. Preliminary results from the 1972 North Atlantic Seismic Project indicate that the depth to the Moho beneath the shelf off northwest Scotland is between 25 and 26 km (Smith - personal communication). This result has been used in the following work.

### 4.3.2. Seismic reflection control

A minimum thickness of sediment in the Trough was determined from the reflection profiles. At the margins of the Trough, the position of the break in slope of the basement and the approximate thickness of sediment draped over the continental slope could also be determined. This was useful, particularly on Line 3/970, for reducing the ambiguity in the magnetic and gravity interpretations.

### 4.3.3. Magnetic profile interpretation

The magnetic profile at the western end of Line 3/970 was used quantitatively to determine the basement shape. The effect of magnetic igneous material masked the effect of the change in basement depth on the profiles over other parts of the margins. Even on the short section used the fit obtained was rather poor (Fig.14) because of large variations in the anomaly over the Bank. The magnetic susceptibility of rock ranges from less than $10^{-5}$ to about $10^{-2}$ emu/cm$^3$ (Nagata 1961) depending on the proportion of magnetic minerals in the rock. Mafic igneous extrusive rocks usually have susceptibilities of 0.001 to 0.004 emu/cm$^3$ whereas metamorphic rocks have somewhat lower values (Clark 1966). Igneous rocks, particularly oceanic basalts, often have a high remanent magnetisation. Values range from 0.005 to 0.3 emu/cm$^3$ (Cox and Doell 1962, Ade-Hall 1964, Matthews 1961). Since there may be a change in the nature of the basement across the margin of George Bligh Bank and the nature of the basement in either the Trough or on the Bank is not known, the magnetisation contrast used in the model may not be accurate. The value of 0.002 emu/cm$^3$ provided the best fit of the calculated anomaly to the observed anomaly assuming that the basement has a magnetisation vector lying in the same direction as the Earth's field. The depth of the basement at either end of the structure was fixed and the shape of the basement over the edge of the Bank was modelled. This shape was used as a basis for the gravity fitting although slight modifications were made to improve the fit of the gravity anomalies.

The relative wavelengths of the magnetic anomalies were used qualitatively over the Hebridean margin to estimate where the break in slope of the basement lies beneath the sediments.

### 4.3.4. Gravity interpretation

The gravity models for Lines 3/970, 14/71 and 5/970 are shown in Figs. 14, 15 & 16. The thickness of the sediments and the shapes of the margins agree well with the magnetic and reflection information. The dense bodies at the eastern ends of profiles 3/970 and 14/71 represent intrusive complexes which are discussed in Chapter 6.

The sediments were assumed to have a density of 2.1 g/cm$^3$ above a depth of about 1 km and a density of 2.25 g/cm$^3$ below this depth. These densities are based on the experimentally determined velocities in the sediments and their density equivalents (Nafe and Drake 1963). Reflector 'R' lies approximately on the boundary between sediments with a velocity of 1.71 to 2.0 km/s and sediments with a velocity of 2.1 to 3.2 km/s (Fig.4, Jones et al. 1970). Results from the wide-angle reflection experiments on the 1970 cruise indicate that the velocity above 'R' is 1.8 to 2.0 km/s (Appendix C). Since the reflector is at a depth of about 0.75 second of two-way time, a layer of 1 km thick of density 2.1 g/cm$^3$ is a reasonable approximation to the sediments overlying the reflector. The density of 2.25 g/cm$^3$ for the sediments beneath 'R' is equivalent to a velocity of 2.9 to

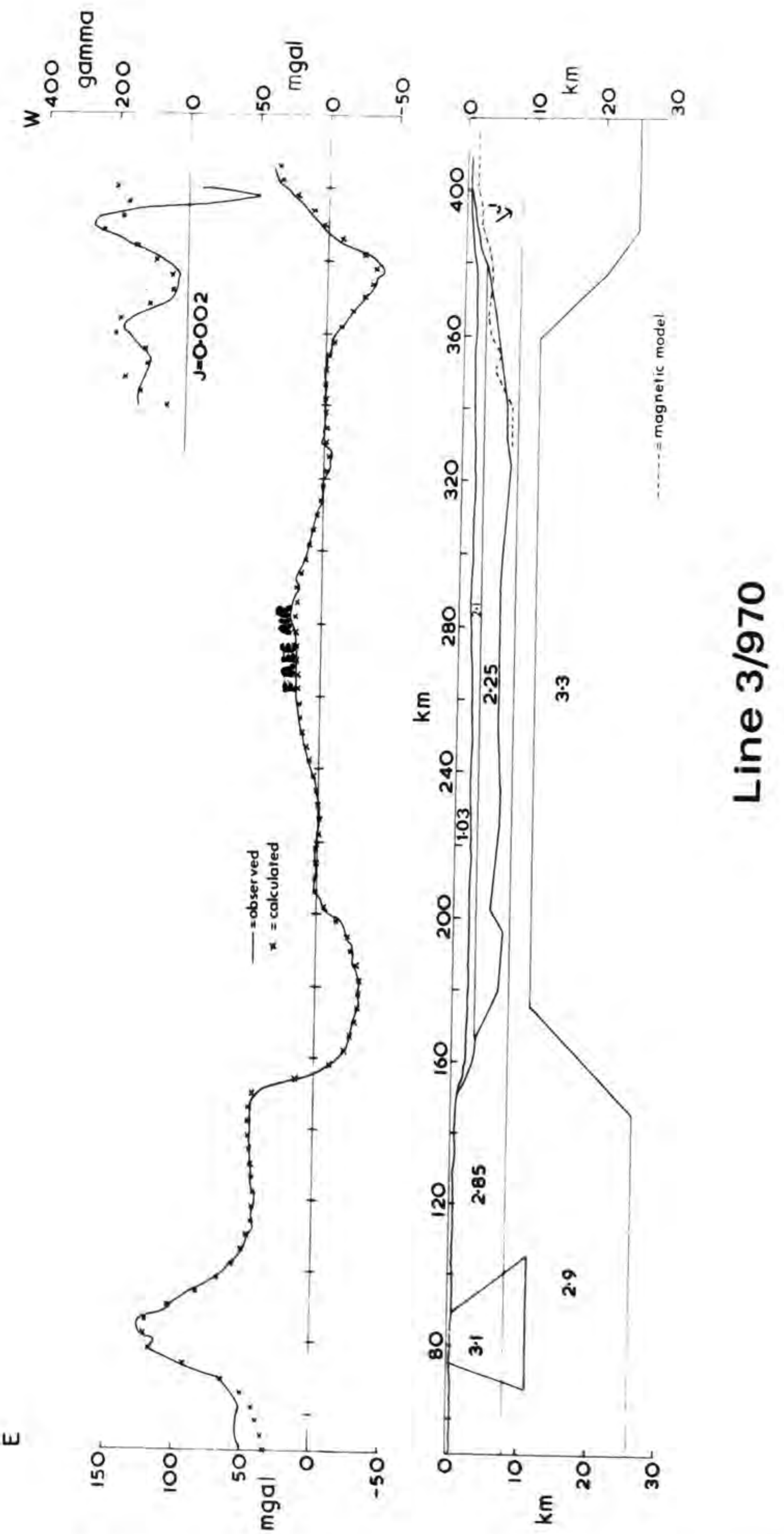


Figure 14. Gravity and magnetic interpretations on Line 3/970.

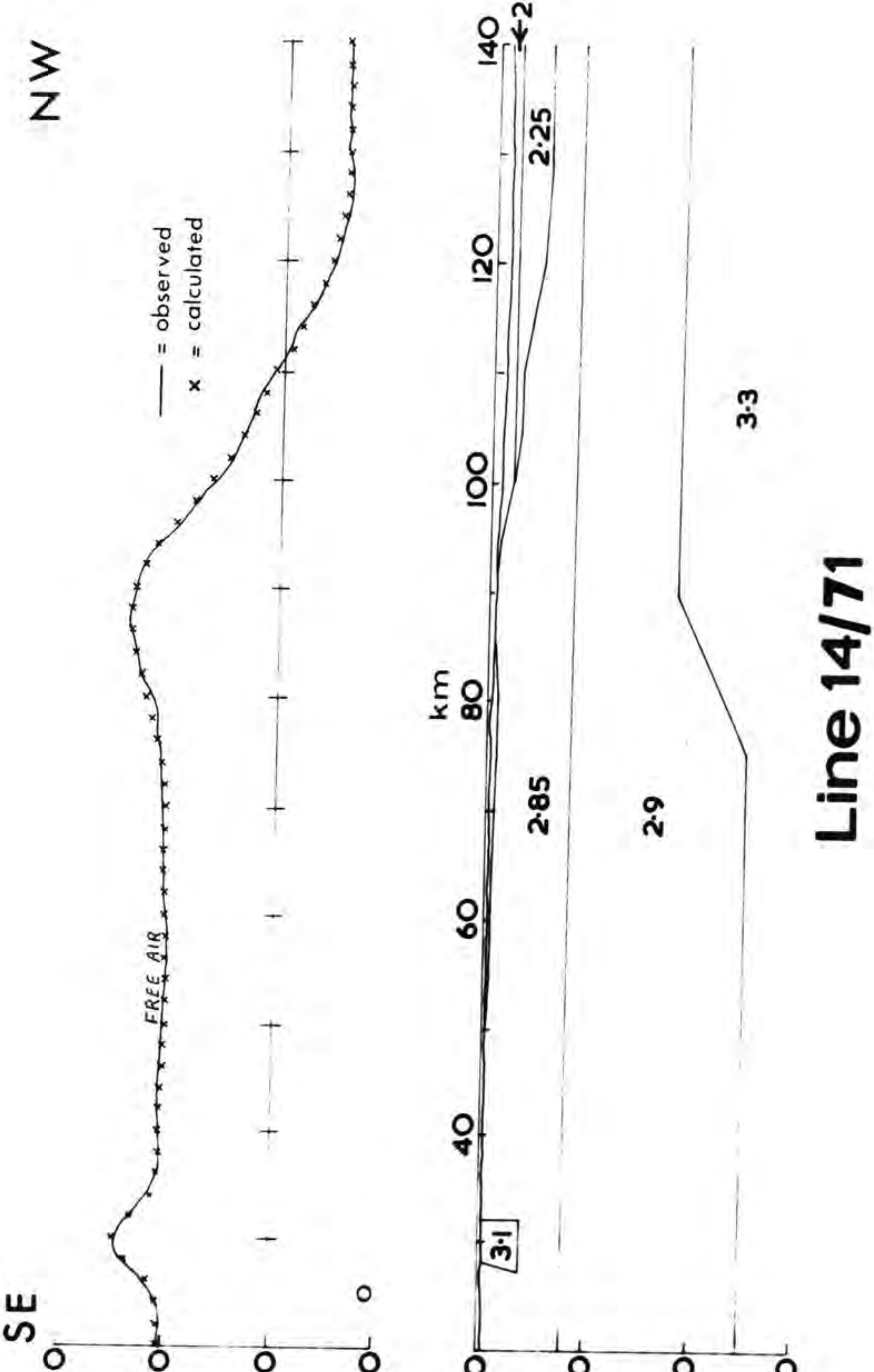


Figure 15. Gravity interpretation on Line 14/71.

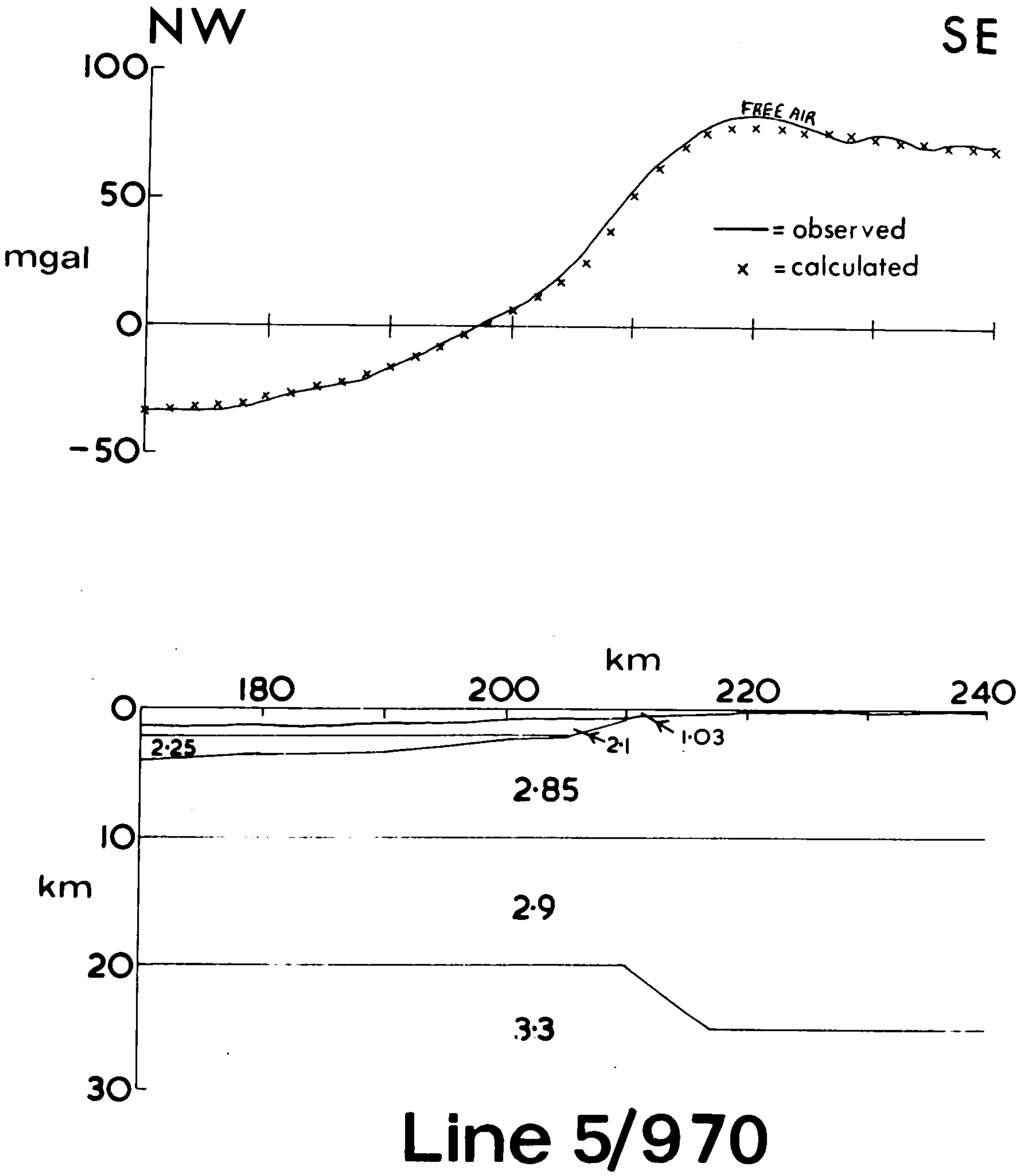


Figure 16. Gravity interpretation on part of Line 5/970.

3.0 km/s which is a reasonable average of the measured velocities.

Woollard (1966) found the average density of many samples of basement rock from North America to be 2.742 g/cm$^3$ and estimated that the mean density of the continental crust was in the range 2.87 to 3.00 g/cm$^3$. Bott et al. (1972) measured the densities of a few samples of Lewisian rock to be 2.69 to 2.76 g/cm$^3$ but they estimated that the true densities were somewhat higher (Section 6.3.1). In the present work, densities of 2.85 g/cm$^3$ above 8 km and 2.9 g/cm$^3$ below 8 km are used for the continental crust. These estimates may be slightly high near the surface but are probably reasonable at depth. The same densities are used for the crust beneath the Trough. If this crust is oceanic, the densities are still reasonable estimates. No matter whether Layer 3 of an oceanic crust is composed of partially serpentinised peridotite (Hess 1965) or amphibolite (Cann 1968), the density would be unlikely to be greater than 3.0 g/cm$^3$ or less than 2.85 g/cm$^3$. The assumed density contrast at the Moho of 0.4 g/cm$^3$ is based on Woollard's (1966) estimate calculated by considering variations in crustal thickness of regions in isostatic equilibrium. Any small inaccuracies in the estimates of these densities or variations between the density beneath the shelf and that beneath the Trough will produce relatively small inaccuracies in the calculated depth to the Moho. The basic model will not be greatly affected.

The interpretation on Line 3/970 (Fig.14) shows the Moho at a depth of 11 km. This increases to 18 km on Line 14/71 and 20 km on Line 5/970 (Figs. 15 & 16). There is therefore an increase in the Moho depth towards the northern end of the Rockall Trough. The difference between the interpretations on Lines 14/71 and 5/970, which are about 30 km apart, illustrates the possible range in the depth to the Moho in the interpretations caused by the uncertainty in the thickness of the sediments. The slope of the Moho beneath the margin is considerably less beneath the two northerly profiles. The basement depth in the centre of the Rockall Trough is approximately 1 km less than it is towards the sides on Line 3/970. This rise could be replaced in the model by a similar but greater rise in the Moho. This is unlikely since the crustal thickness would be unreasonably small.

A sediment-filled basin lying on the continental margin is present on the interpretation of Line 14/71. The density used for the sediments is 2.1 g/cm$^3$ which represents relatively unconsolidated sediment. If the sediments were of a lower density the maximum thickness of 0.8 km would be less. There may only be a depression in the basement, filled with sediment, rather than a major basin. Watts (1971) tentatively suggested the presence of a major sedimentary thickness on the continental margin a short distance to the north of this Line.

### 4.3.5 Conclusions

The crustal structure beneath the Rockall Trough, at about 58$^{\circ}$N, resembles that of a typical oceanic area overlain by a large thickness of sediment. The evidence suggests that the sediment thickness decreases towards the north from about 5 km to about 3 km and that the Moho depth increases from 11 km to about 19 km. There is evidence that a rise in the basement of about 1 km may be present in the middle of the Trough. This could represent the remains of a ridge system along the centre of the Trough.

### 4.4. The Banks

Reconnaissance gravity and magnetic profiles have been collected over George Bligh, Bill Bailey's and Faeroe Banks. The gravity profiles over George Bligh and Bill Bailey's Banks give an indication of the crustal thicknesses whilst the magnetic profiles indicate the nature of the upper basement material.

### 4.4.1. Crustal thicknesses

Line 3/970 (Fig.14) includes, at its western end, George Bligh Bank. The interpretation shows considerable crustal thickening beneath the Bank to a maximum of about 25 km. This is approximately equal to the thickness beneath the Hebridean continental shelf but it is 6 km less than the thickness measured by Scrutton (1970) beneath the Rockall Plateau. A crust of continental thickness is therefore indicated beneath the Bank but subsidence may have caused thinning of the crust from an initially greater thickness. The rise in the basement from the Trough onto the Bank occurs more gradually than it does at the margin of the Hebridean shelf. A similar situation was found by Scrutton (1971) at the edge of the Rockall Plateau although it was more pronounced in that area. Scrutton correlated the rise with the 'Jean Charcot' fracture zone which is recognised on seismic reflection profiles. He suggested that the eastern edge of the zone may represent the true oceanic-continental crustal boundary. There is no indication of a similar zone on the reflection profile from Line 3/970 but it may be obscured beneath the sediments.

Fig.17 shows the magnetic and gravity profiles along Line 4/970 together with a 2D model section. Difficulty was experienced in interpreting this line since several unusual features are present. A reverse correlation between the gravity and magnetic profiles can be clearly seen although the magnetic profile is displaced slightly to the southwest. This correlation was investigated using the magnetic to gravity transform method. The results are shown in Fig.18. The correlation ratio (C.R.) is good but the value of T, (m/p), is remarkably large. The angle of magnetisation indicates that the magnetic material is reversely magnetised with respect to the present Earth's field.

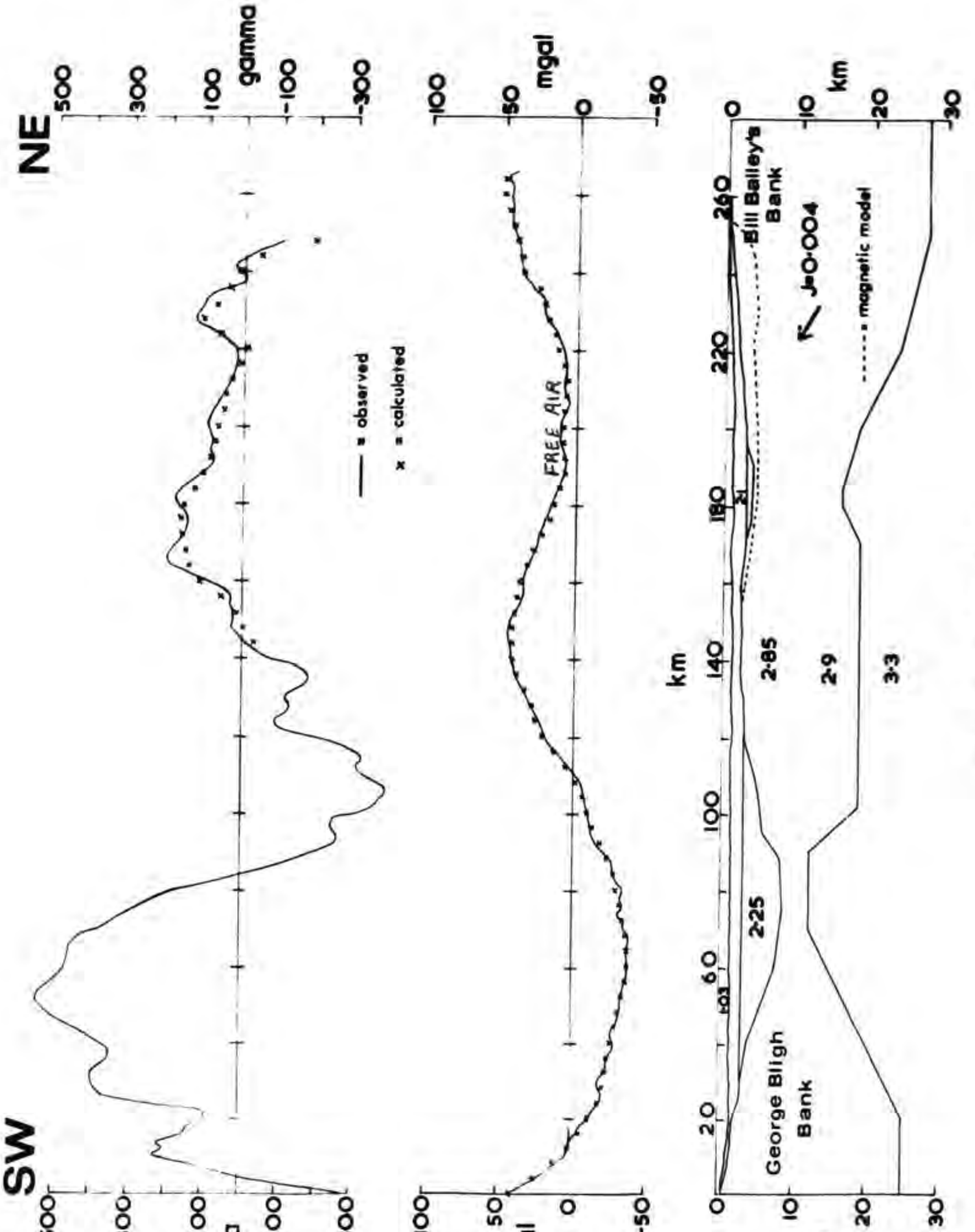


Figure 17. Gravity and magnetic interpretations on Line 4/970.

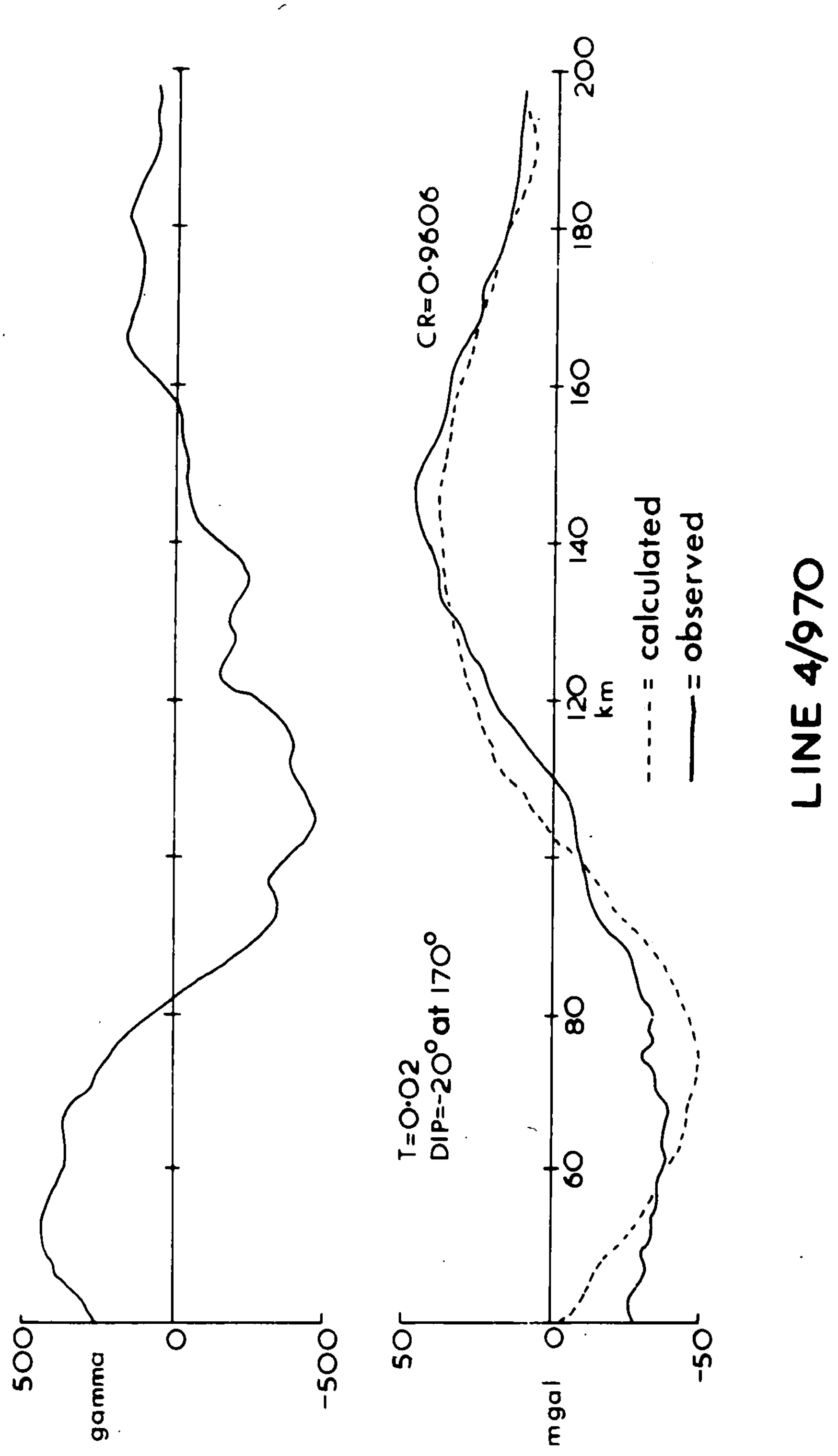


Figure 18. Magnetic-gravity transform results on Line 4/970.

A magnetic interpretation was carried out for the whole profile using a value for J of 0.004 emu which is probably more reasonable than that suggested by the value of T. The interpretation of the northeast end of the profile is shown by Fig.17. It is not in agreement with the reflection profile results or with any possible gravity interpretation. No sensible interpretation of the southwest end of the profile could be obtained. An impossibly deep basin was required to explain the anomaly. The gravity interpretation was calculated using the information available from the seismic reflection profile and assuming that the bottom reflector in the central part of the profile is the basement. The difficulties in the interpretation have been explained by the information (D.G. Roberts - personal communication) that a large vertical fault runs approximately parallel to the line of the profile. The fault separates a basement block to the northwest, which appears to connect the two Banks, from the basin of the Rockall Trough to the southeast. The basic assumption in the interpretative methods that the structures are two-dimensional is therefore incorrect on this Line and the interpretation has little meaning. The thickness of the crust beneath the two Banks, at either end of the profile, may however be relevant since on the Banks the two-dimensional assumption may be more nearly correct. The thickness of the crust beneath Bill Bailey's Bank is similar to that beneath George Bligh Bank. Both Banks may therefore be underlain by crust of continental thickness.

Gravity profiles onto Faeroe Bank are available from Lines 19/71 and 20/71 (Fig.19). Since the crustal structure in the Faeroe channel and under the Wyville-Thomson Rise is not known, no attempt has been made to model the margin of the Bank. The free-air anomaly on the Bank is about 55 mgal which is approximately equal to that on

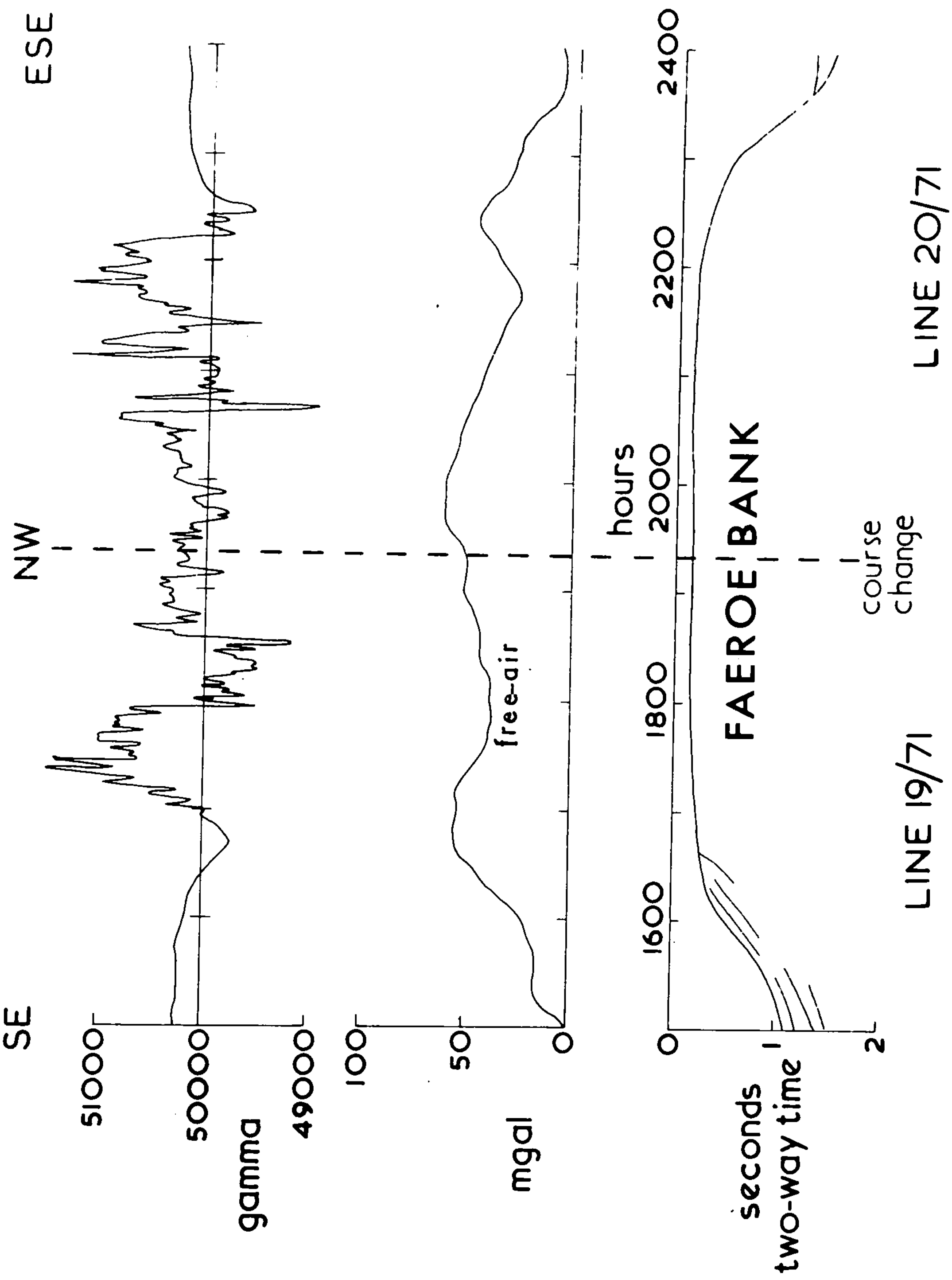


Figure 19. Profiles on Lines 19/71 and 20/71.

the other Banks and on the continental shelf. It is therefore probable that crustal thickening also occurs beneath Faeroe Bank.

### 4.4.2. The upper crustal structure

The magnetic profiles over the three Banks are shown in Figs. 19 & 20. The profiles over George Bligh and Bill Bailey's Banks have anomalies of about 500 gamma amplitude and of similar wavelengths (5 - 10 km). The profile over Faeroe Bank can be divided into two parts. The middle portion, which comes from the centre of the Bank, contains similar anomalies to those over the other Banks but superimposed on these are short wavelength (0.5 - 1.0 km) anomalies with amplitudes of 100 to 200 gamma. Dobinson (1970) suggested that basic lava flows and dykes cause these anomalies. The lack of the short-wavelength anomalies over George Bligh and Bill Bailey's Banks cannot be explained by attenuation of short wavelength anomalies because of the depth of the Banks since Bill Bailey's Bank is at almost the same depth as Faeroe Bank. The two courses on each Bank were approximately orthogonal therefore it is unlikely that short wavelength anomalies are not seen because the course directions were parallel to linear anomalies. The profiles are similar to those over the northern and southern parts of Rockall Bank (Roberts and Jones - in preparation). Profiles over the northern part of Rockall Bank show the short wavelength anomalies found over Faeroe Bank whereas profiles over the southern part are lacking in short wavelength anomalies. Roberts and Jones suggested that this may be caused by the presence of basic igneous rocks in the north and their absence in the south. It is probable that little or no magnetic igneous rock is present on Bill Bailey's and George Bligh Banks. Dangeard (1928) dredged basalt from Bill Bailey's Bank. The basalt may have been an erratic or, alternatively, it may compose only a small part of the Bank. Apart from the presence and absence of lavas, the three Banks may all be composed of similar material.

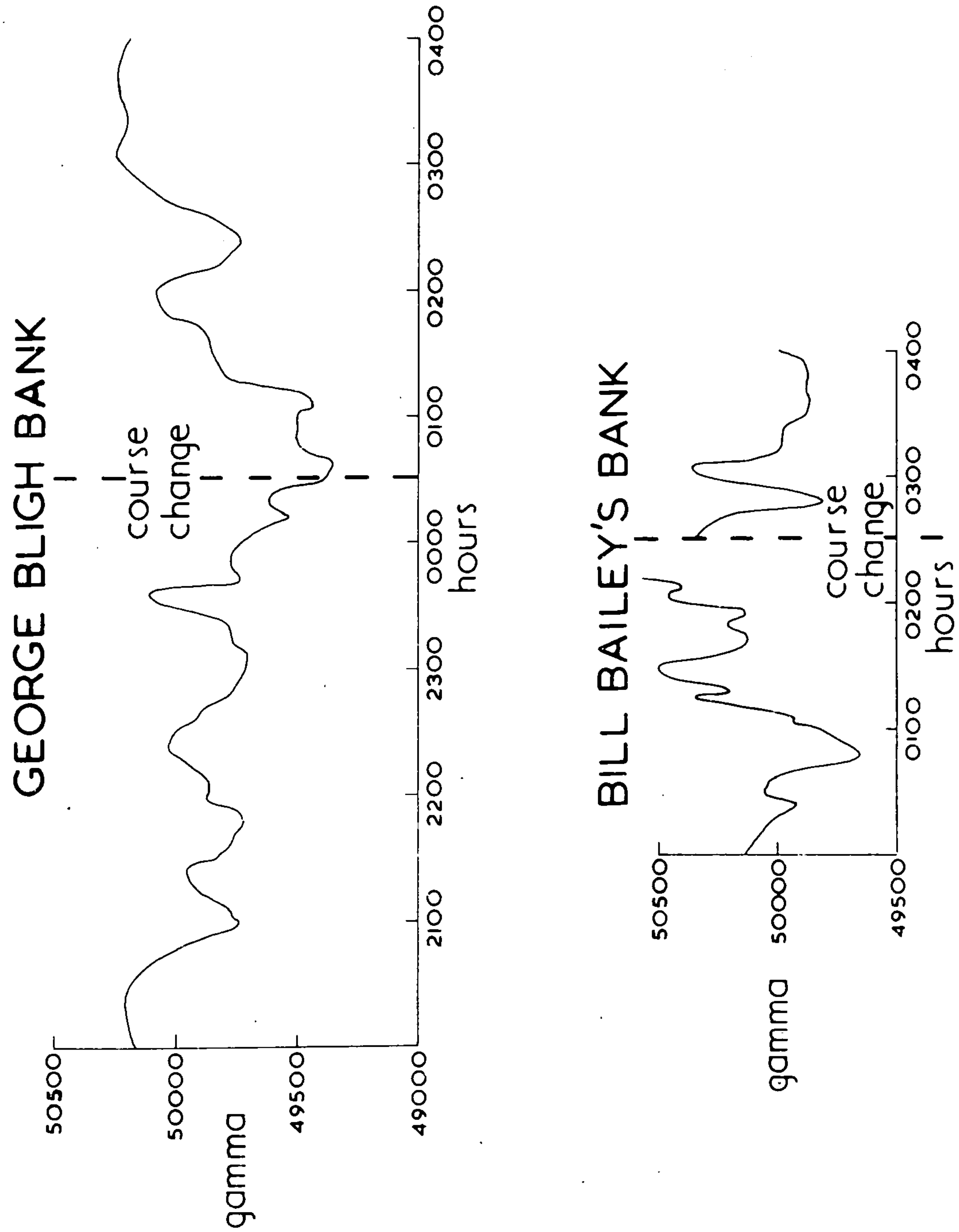


Figure 20. Magnetic profiles over George Bligh and Bill Bailey's Banks.

The two Lines on Faeroe Bank, Lines 19/71 and 20/71, both crossed a broad positive magnetic anomaly which trends in an east-west direction (Dobinson 1970). Dobinson calculated that the source has a width of 10 to 15 km, extends to a depth of at least 4 km, and has a relatively large magnetisation contrast with its surroundings. He considered a granite, on account of the magnetisation contrast, and a lava sheet, on account of the high-amplitude, relatively long wavelength magnetic anomaly, to be unlikely sources. A gravity low of about 15 mgal is associated with the anomaly. The gravity profile on Line 19/71 has been interpreted (Fig.21) assuming a density contrast of -0.16 g/cm$^3$. The body is similar in size to Dobinson's model although an alteration in the density contrast could cause a change in the size of the model. Any regional effects, as could be caused by changes in the Moho depth, would also affect the shape of the model body. Assuming that the top of the body is at the surface of the basement and that Dobinson's suggested minimum depth of 4 km is correct, the density contrast must be -0.16 g/cm$^3$ or less. -0.16 g/cm$^3$ is a typical value for a granite lying in crustal material (Bott 1971). Granites are found associated with the intrusive centres at Arran, Skye and Mull but they have little effect on the overall gravity 'highs' (Bott & Tuson - in press). The density of the basalts on the Faeroe Islands varies from 2.82 to 2.9 g/cm$^3$ (Saxov and Abrahamsen 1966) therefore the maximum contrast between two basalt sequences is unlikely to be greater than 0.1 g/cm$^3$. This density contrast could explain the anomaly but the body would have to extend to a depth of 6 to 7 km. No instances of basalts causing a gravity low has been reported from elsewhere in the Tertiary igneous province.

### 4.4.3. Conclusions

Although seismic refraction results are needed to determine whether the Banks are composed of continental crust, the gravity

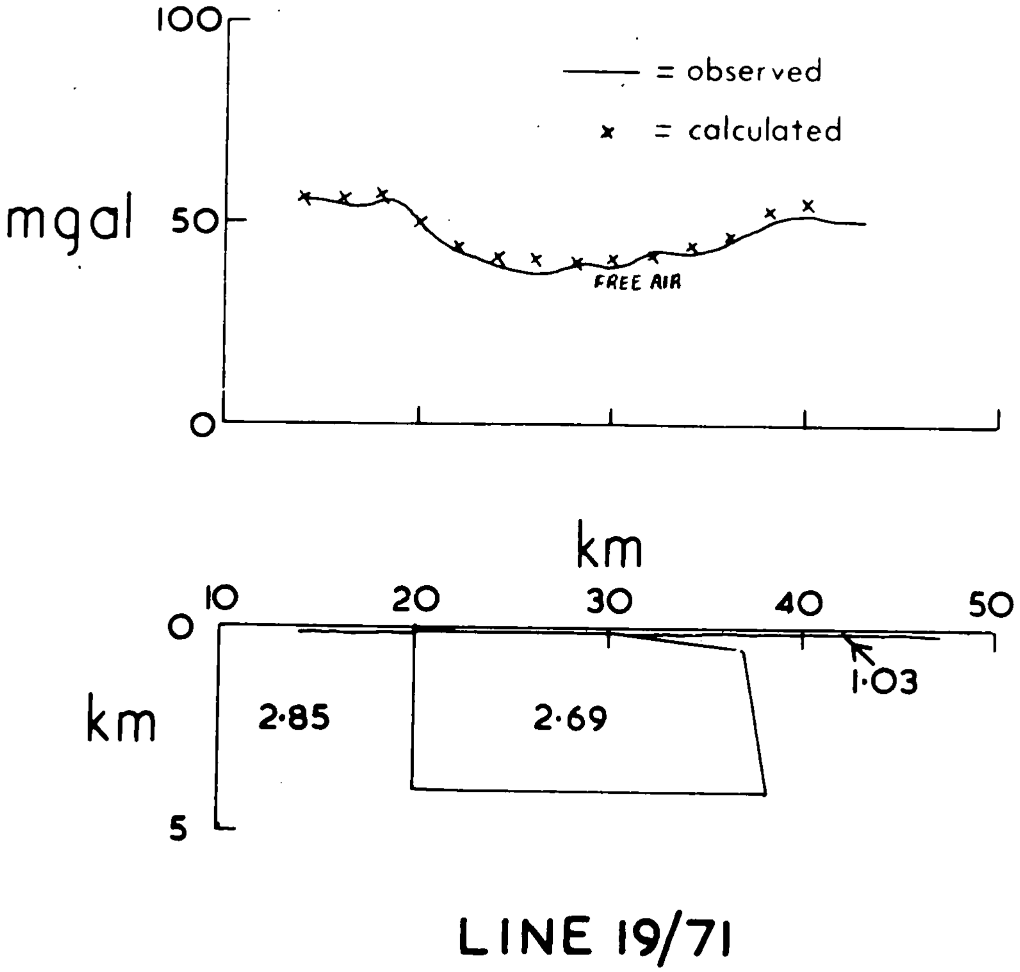


Figure 21. Gravity interpretation on Line 19/71.

evidence suggests that they are underlain by a typical continental crustal thickness. George Bligh Bank is similar to Rockall Bank in that the basement deepens relatively gradually on its eastern side. There is no evidence to suggest that intrusive complexes are present on the Banks. Faeroe Bank is probably covered by basic lavas. A gravity low and an east-west trending magnetic anomaly may indicate the presence of either a granite or a considerable thickness of lavas on the eastern flank of Faeroe Bank.

## 4.5. Summary

Gravity evidence combined with available refraction lines indicates that Rockall Trough has a crustal structure resembling that of an oceanic area. In the central region of the Trough, the Moho appears to be at a depth of about 11 km and is overlain by a crustal layer about 5 km thick. The upper part of this layer is probably composed of basaltic material. At the northern end of the Trough, gravity and reflection profiles suggest that the surface of the basement rises and the Moho depth increases. Close to the Wyville-Thomson Rise, the crustal thickness is estimated to be about 14 km. To the east, the Trough is flanked by the Scottish continental crust. Rockall Plateau flanks much of the western side of the Trough. This is probably a microcontinent. The northwest part of the Trough is flanked by George Bligh, Lousy and Bill Bailey's Banks. Gravity interpretation indicates that George Bligh and Bill Bailey's Banks have continental thicknesses and they may also be continental fragments. Lousy Bank has not been investigated but it may be similar to the other Banks. A basement ridge may connect George Bligh and Bill Bailey's Banks and perhaps also Lousy Bank. Sedimentary evidence from reflection profiles suggests that the Banks originally formed subaerial features but sank to a lower level prior to Lower Oligocene times. The Hebridean continental shelf appears to have become submerged considerably later. The whole of Rockall Trough has been an area of deposition since well before Lower Oligocene times. Previous to that period the overall rate of sedimentation in the north of the Trough was considerably less than in the south. Since the Lower-Middle Oligocene, the sedimentation has been affected by deep-sea currents but the rate of deposition has been approximately the same throughout the Trough.

Rosemary Bank and the Anton Dohrn Seamount appear to be ancient volcanoes. The sedimentary evidence suggests that Rosemary Bank is almost as old as the basement in the Trough.

# CHAPTER 5

# The Wyville-Thomson Rise

## 5.1. Introduction

The Wyville-Thomson Rise lies between the southeast corner of Faeroe Bank and the Scottish continental shelf (Fig.2). It forms a continuous bathymetric barrier between 300 and 400 fathoms deep between the northeast end of the Rockall Trough and the southwest end of the Faeroe-Shetland channel. The Rise creates a barrier for the southward flowing deep-sea currents.

Lines 12/71, 15/71, 17+21, 30/70 and 18/71 all cross the Rise perpendicularly. The respective profiles are shown in Figs. 22, 23, 24, 25 and 26. The reflection profiles show that the Rise is made up of two major basement ridges masked by sediments. The northeasterly ridge is seen on all the profiles and it is clear from the detailed bathymetric map (Deutches Hydrographischen Institut 1972) that it is continuous from Faeroe Bank to the continental shelf. The southwesterly ridge is seen distinctly on Lines 30/70 and 17+21 (Figs. 25 & 24) but, on Line 18/71 (Fig.26), two smaller features are seen in its place. On Line 15/71 (Fig.23) where there was little penetration of the sediments by the seismic energy source, the southwesterly ridge is not seen but it has a small gravimetric expression. On Line 12/71 (Fig.22) there is no evidence of a southwesterly ridge. The profiles also show that the basement ridge forming a southeasterly extension to the Faeroe Plateau (Fig.2) can be traced to within 40 km of the Scottish continental margin.

## 5.2. The sediments

### 5.2.1. Thicknesses

To the southwest of the Rise, the sediments in the Rockall Trough are probably between 2 and 3 km thick (Section 4.2.1.). On Line 30/70,

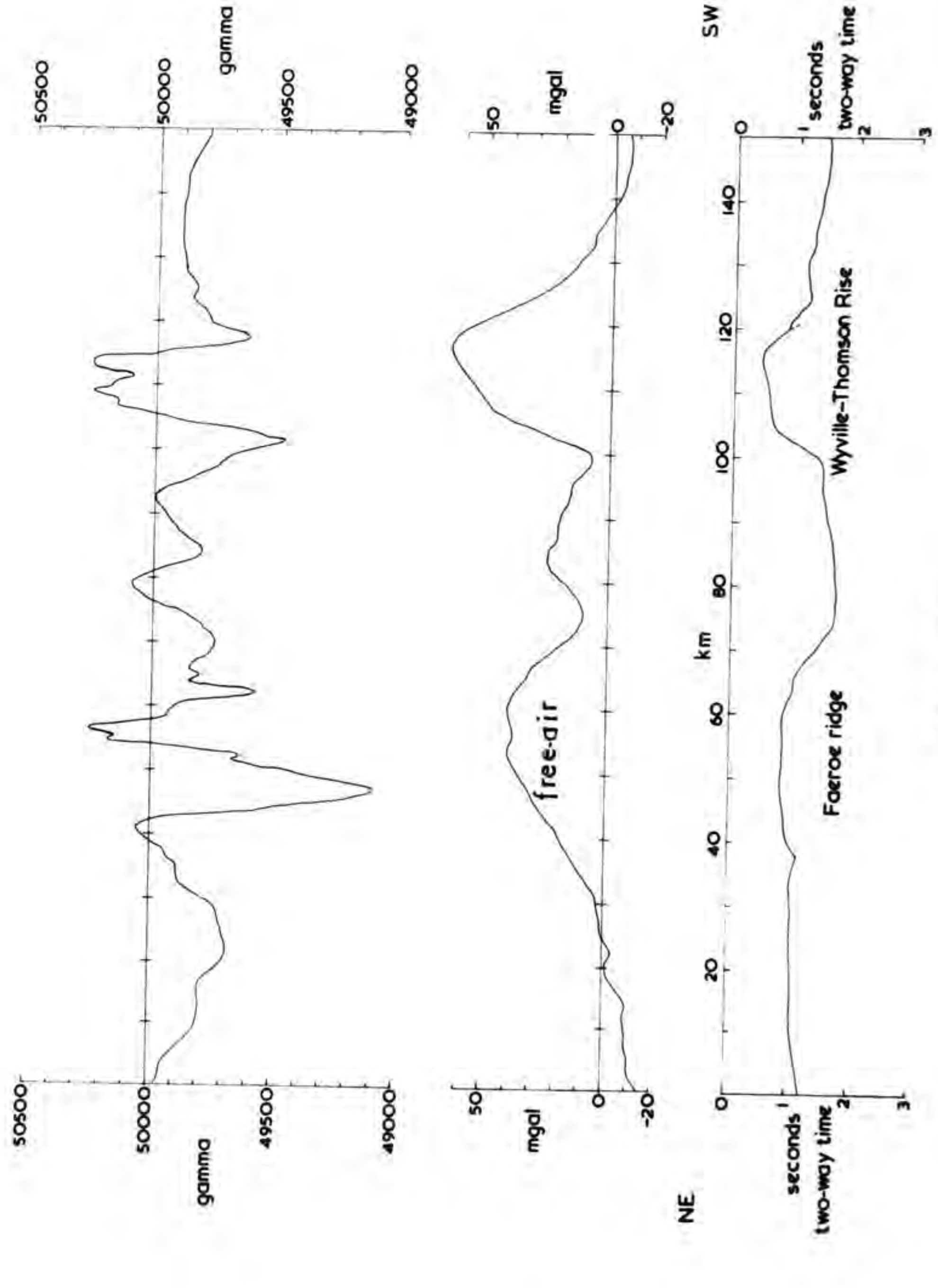


Figure 22. Profiles on Line 12/71.

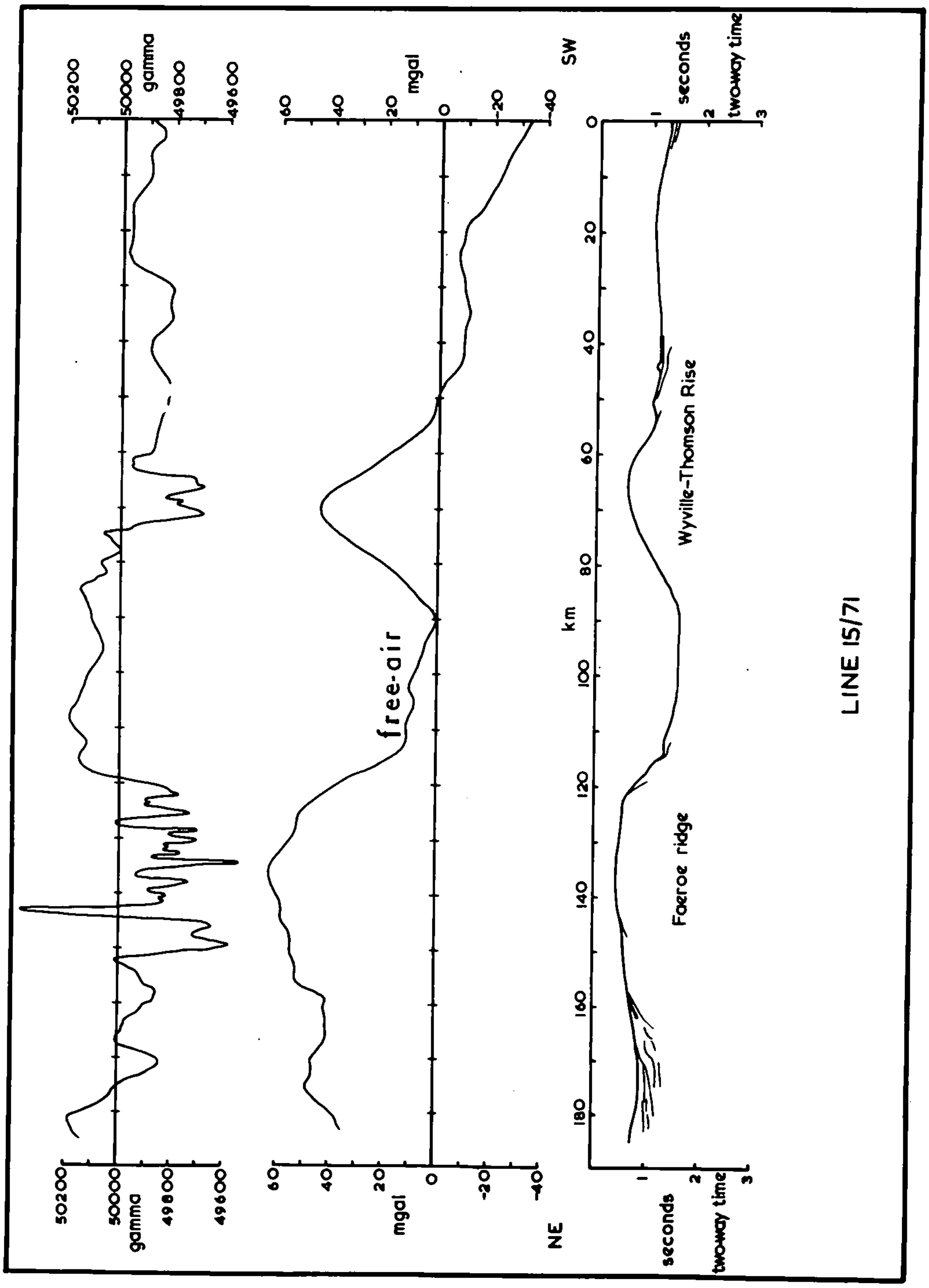


Figure 23. Profiles on Line 15/71.

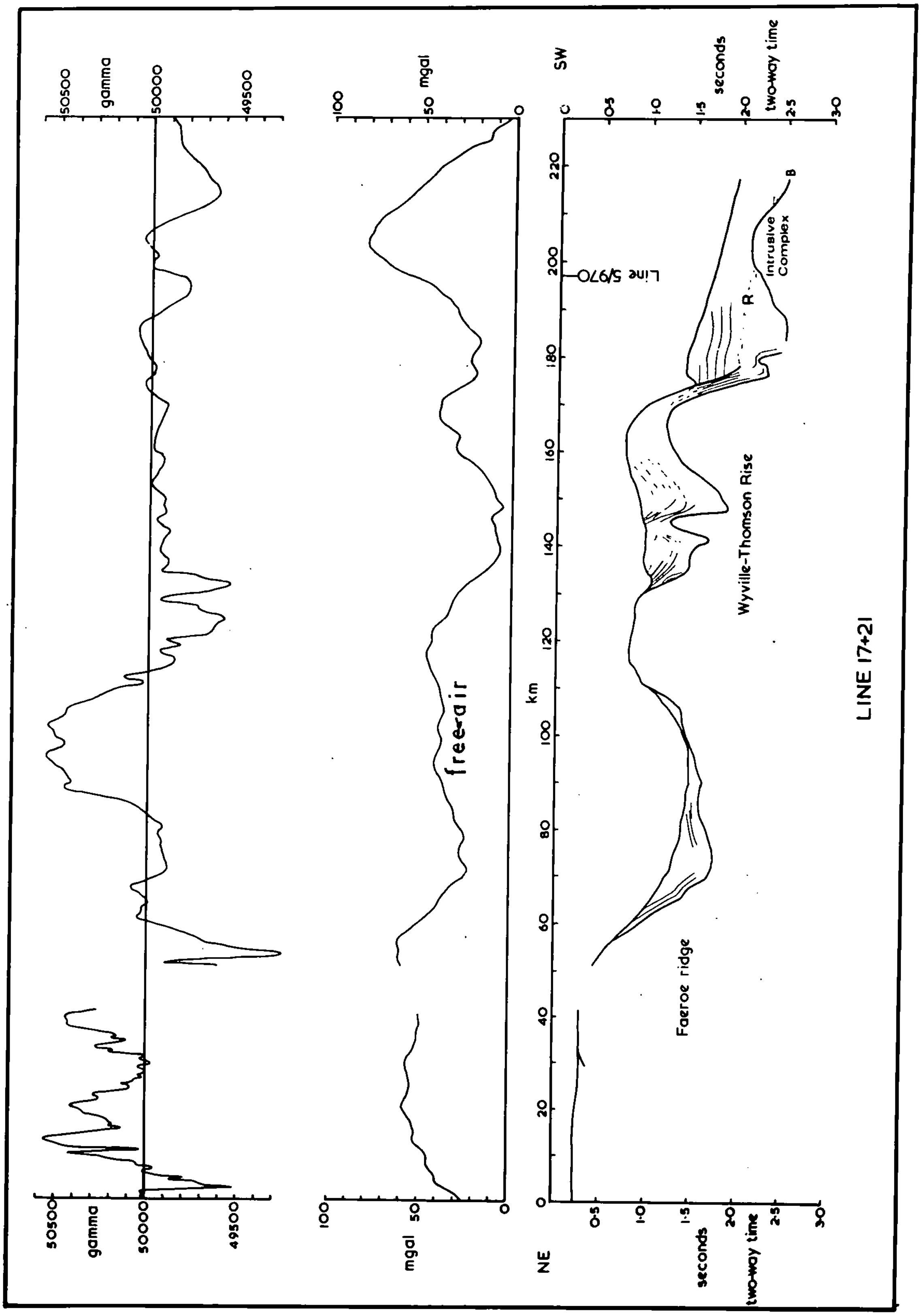


Figure 24. Profiles on Line 17+21.

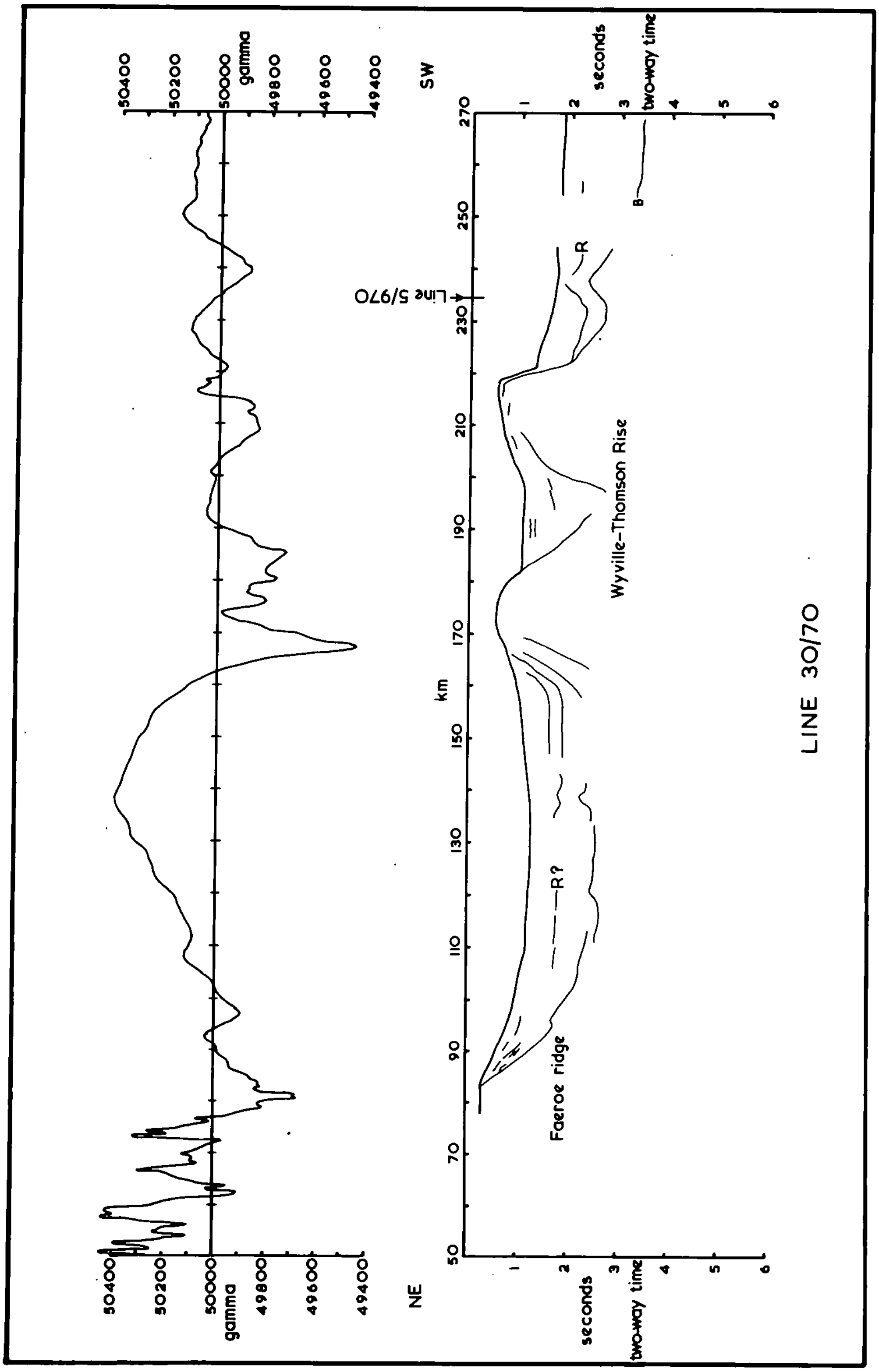


Figure 25. Profiles on Line 30/70.

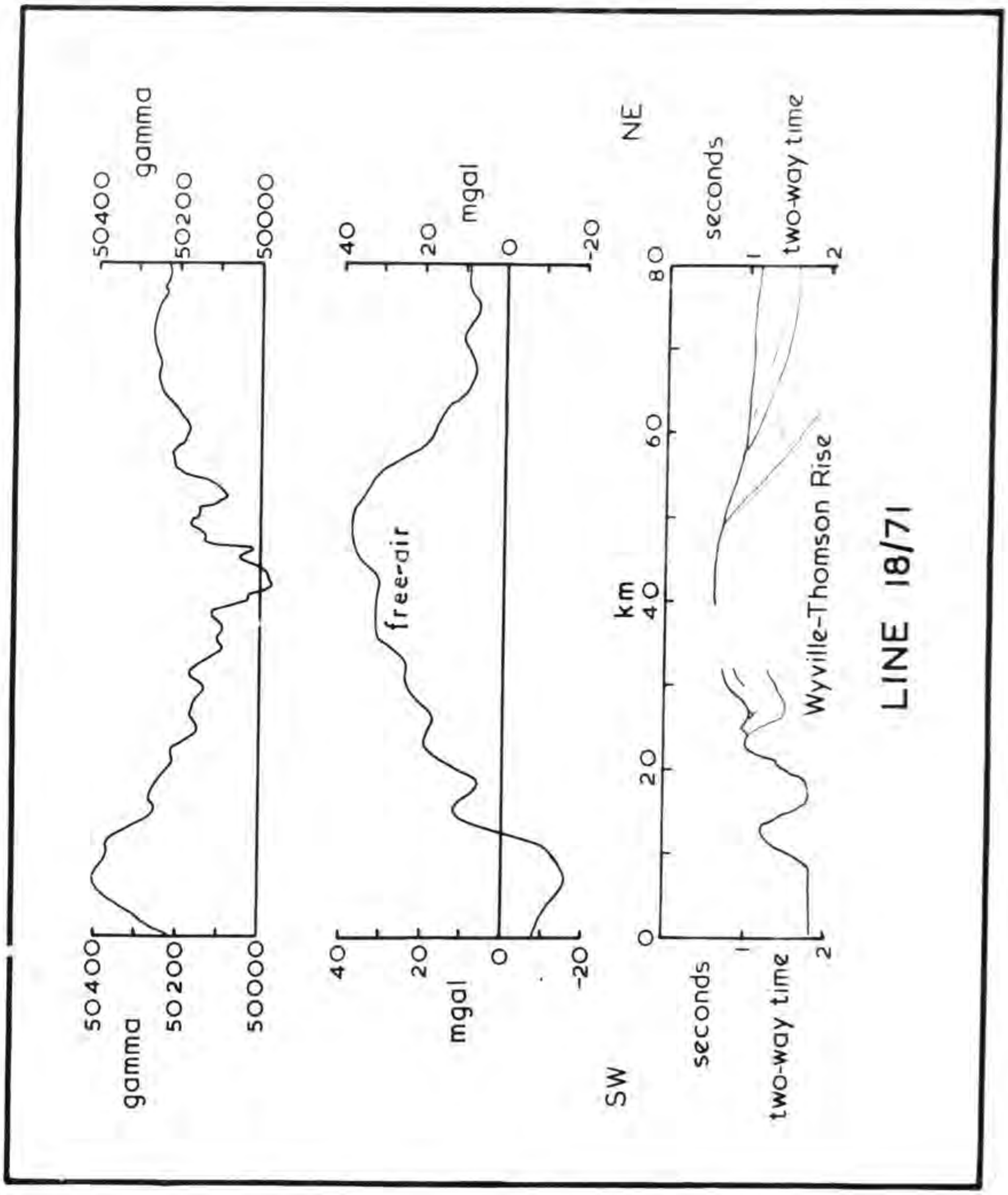


Figure 26. Profiles on Line 18/71.

between Rosemary Bank and the Rise, a reflector rises towards the north from a maximum depth of 2 seconds two-way time beneath the seabed. It can be seen, marked 'B', at a depth of 1.6 seconds at the southwest end of Fig.25. Assuming an average sediment velocity of 2.1 km/s, it is at a depth of between 1.6 and 2.1 km. Although the reflector can not be traced to either Rosemary Bank or to the Rise, its depth is similar to that estimated for the basement and it may be a basement reflection. The seismic reflection profile on Line 5/970 (Fig.11), which passed along the southwest side of the Rise, shows that the termination of the south-westerly basement ridge at a distance of about 50 km from the continental shelf allows the normal Rockall Trough sedimentation pattern to extend into an embayment on the southwest flank of the Rise. The area of normal sedimentation shows clearly on the bathymetric map as a smooth, deep region (Fig.2). The wide-angle reflection station, WAR5 (Appendix C, Fig.11), showed a thickness of 1.73 km of sediment with an average velocity of 2.13 km/s in the area. The reflection profile indicates that the deepest reflection recorded by the station is underlain by more sediments. Further northwest on Line 5/970, the sedimentation pattern is disturbed. A distinct, irregular, but continuous, reflector can be seen along most of the Line. This is marked 'B' on Fig.11 and is equivalent to 'B' on Line 30/70 (Fig.25). Several short, indistinct reflectors are seen beneath this reflector which suggests that it is not a basement reflection. The reflector can also be seen on Line 17+21 (Fig.24). It appears to be continuous with the basement of the Rise on this profile. The reflections beneath it on Line 5/970 may therefore not be real. Alternatively, the reflector may have sediments beneath it and yet appear to be continuous with the basement beneath the Rise on Line 17+21. Although the seabed is relatively flat to the southwest of the Rise, the basement appears to shallow gently from the south and forms a series of troughs and ridges adjacent to the Rise.

To the northeast of the Rise lies the junction of the Faeroe-Shetland channel and the Faeroe Bank channel. The profiles on Lines 30/70 and 17+21 (Figs 25 & 24) both show a basement reflection recognisable by tracing it from the Faeroe Plateau. The reflection on Line 30/70 is at a depth of 1.5 seconds of two-way time or about 1.6 km beneath the seabed and 2.5 km beneath sealevel assuming an average sediment velocity of 2.1 km/s. The maximum depth of the reflector on Line 17+21 is 0.5 seconds or about 0.55 km beneath the seabed and 1.65 km beneath sealevel. The maximum water depth on Lines 15/71 and 12/71 is about 1.2 km but no estimate of the sediment thickness can be made from the reflection profiles since there was little or no penetration of the seabed.

Although Line 18/71 does not cross the deepest part of the Faeroe Bank channel (Fig.6), it shows that at least 1.2 seconds (about 1.3 km) of sediment is present in the channel at the northeast end of the profile ( Fig.26). There is probably considerably more sediment present in the centre of this part of the channel. In the Faeroe Bank channel, Bott and Stacey (1967) suggested that up to 1 km of sediment is present beneath a water depth of 0.8 km.

The water depth in the trough increases from 0.8 km in the Faeroe Bank channel to 1.2 km in the southwestern end of the Faeroe-Shetland Channel. The sediment thickness increases from about 1 km in the Faeroe Bank channel to a maximum of 1.6 km beneath Line 30/70 and then probably decreases towards the junction with the Faeroe-Shetland channel.

A magnetic profile along the centre of the Faeroe-Shetland channel, Line 10/70 (Fig.6), has been used to estimate the depth of the magnetic basement using the power spectral analysis method at about 61°20'N, 4°W. The results estimate that the basement is at a depth of about 3.5 km below sealevel. The thickness of the sediment is therefore estimated to be about 2.3 km. The northeastern end of Line 12/71 (Fig.22) crosses the basement ridge which extends to the southeast from the Faeroe Plateau.

Bathymetric data (Deutches Hydrographischen Institut 1972) shows that the Line crosses close to the southeast end of the ridge. Although little penetration was obtained on the reflection profile (Fig.22), it is probable that at least 0.5 km of sediment has accumulated to the northeast of the ridge. The bathymetric map indicates that a thickening of the sediment has also occurred in the centre of the channel adjacent to the end of the ridge. The sediments in the Faeroe-Shetland channel thin towards the southwest end of the channel from a thickness of about 2.3 km. The thinning is caused by a rise in the basement rather than a fall in the seabed.

On the major, northeasterly ridge of the Wyville-Thomson Rise, no sediment is seen on any of the reflection profiles. Lines 17+21 and 30/70 (Figs. 24, 25 & 29) show, however, that over at least part of the southwesterly ridge there is between 0.25 and 0.5 km of sediment assuming a sediment velocity of 2.1 km/s. Between the ridges, the sediment thickness appears to be controlled by the heights of the ridges. The trough between the ridges is filled in by sediments up to about 1.5 km thick (Figs. 24, 25, 27 & 28).

### 5.2.2. The reflecting horizons and the ages of the sediments

The sediments on the southwest side of the Wyville-Thomson Rise can be divided into two distinct series. The stratigraphically lower series drapes the side of the southwesterly basement ridge. This can be seen on Lines 17+21 and 30/70 (Figs. 24, 25 & 29). The sediments appear to have been deposited from the top of the ridge onto the sloping basement floor. The slope of the basement is about 1 in 10. They are similar to the sediments found draping the sides of the Banks lying to the west of Rockall Trough (Section 4.2.2.). The upper series is composed of relatively flat-lying sediments typical of the Rockall Trough which have been deposited by turbidity currents below reflector 'R' and under the influence of deep-sea currents above reflector 'R' (Jones et al. 1970).

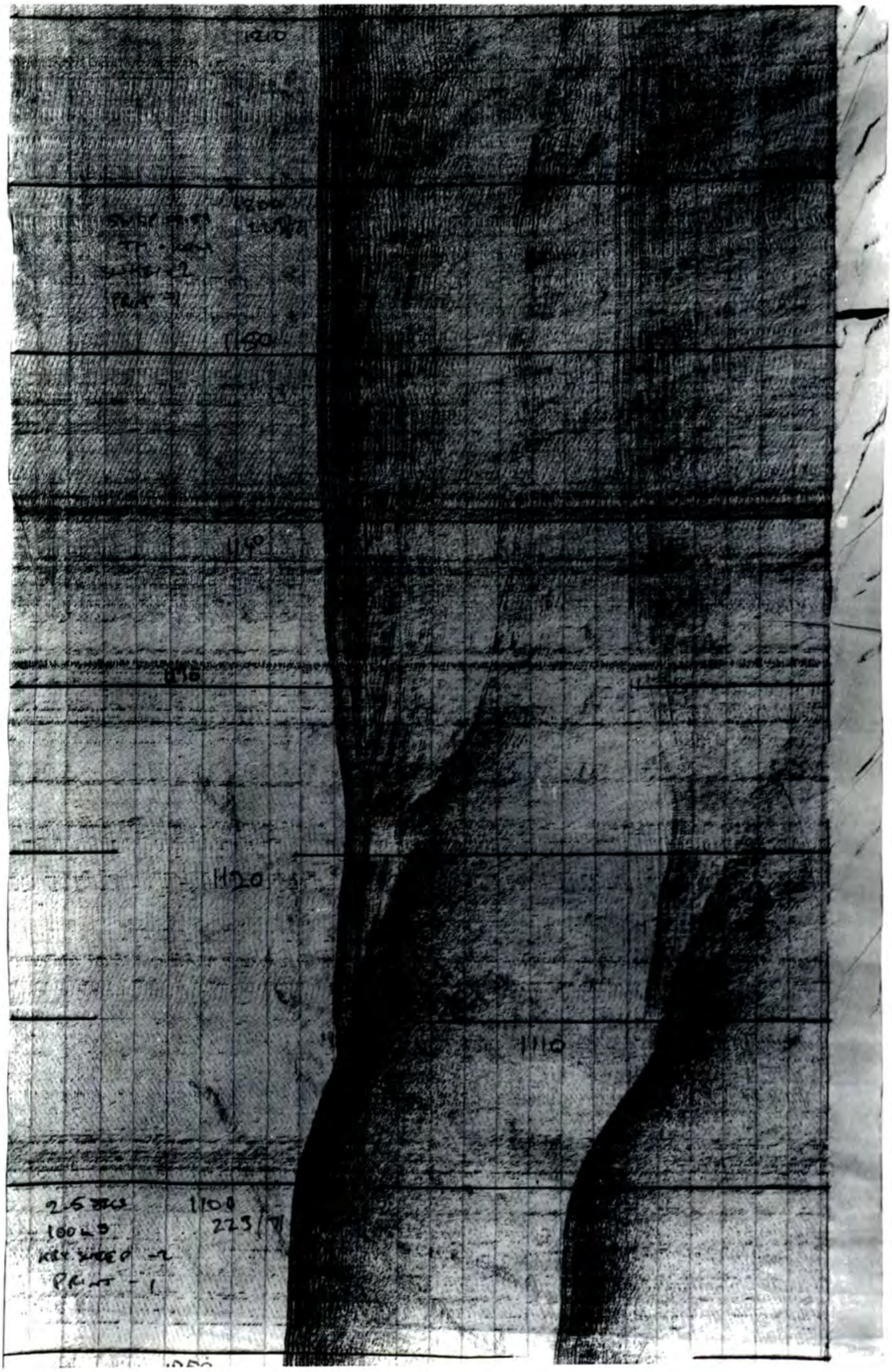


Figure 27. Seismic reflection record on the northeast ridge of the Wyville-Thomson Rise: 10 min markers horizontally. 100 m sec markers vertically.

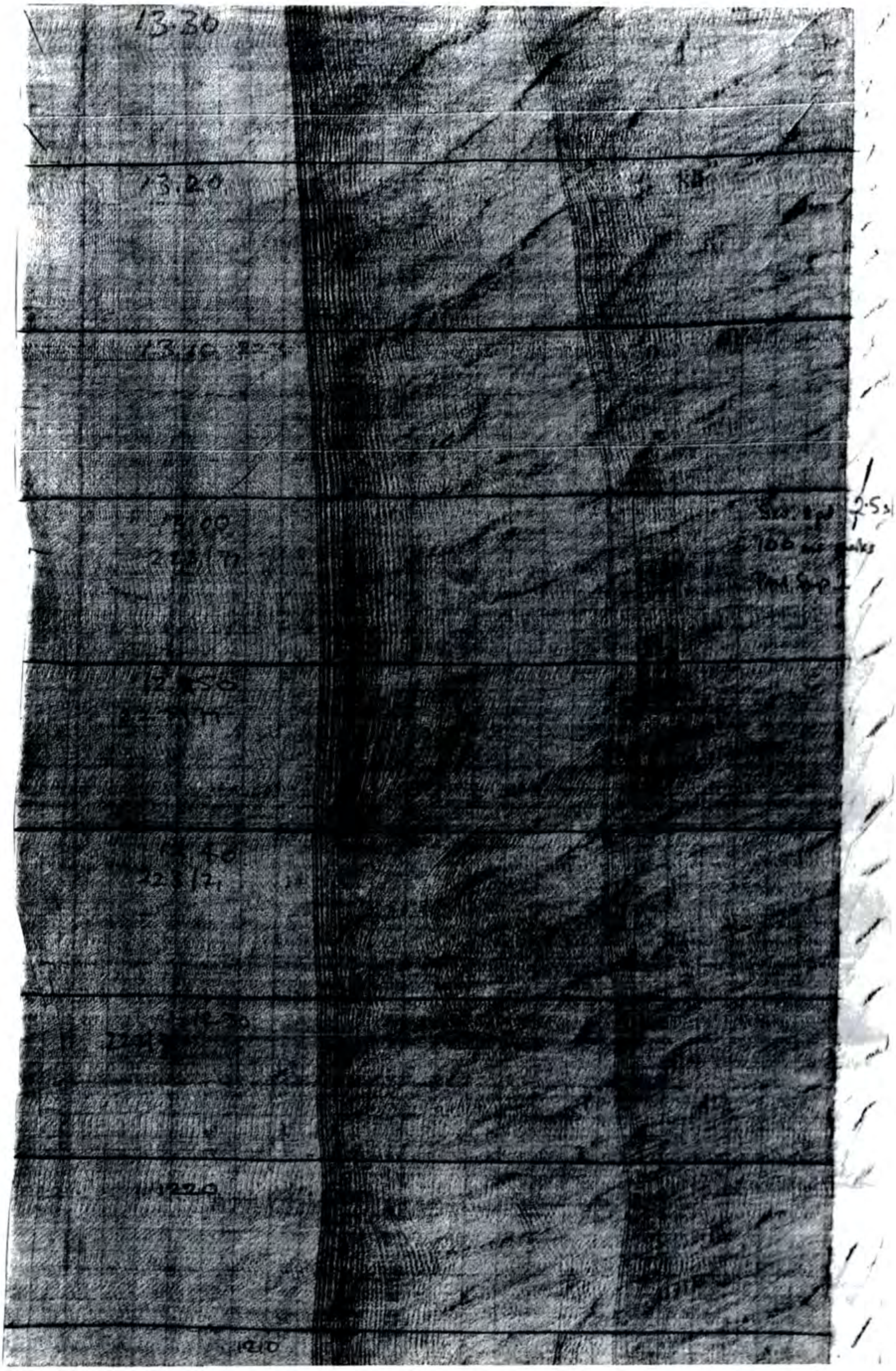
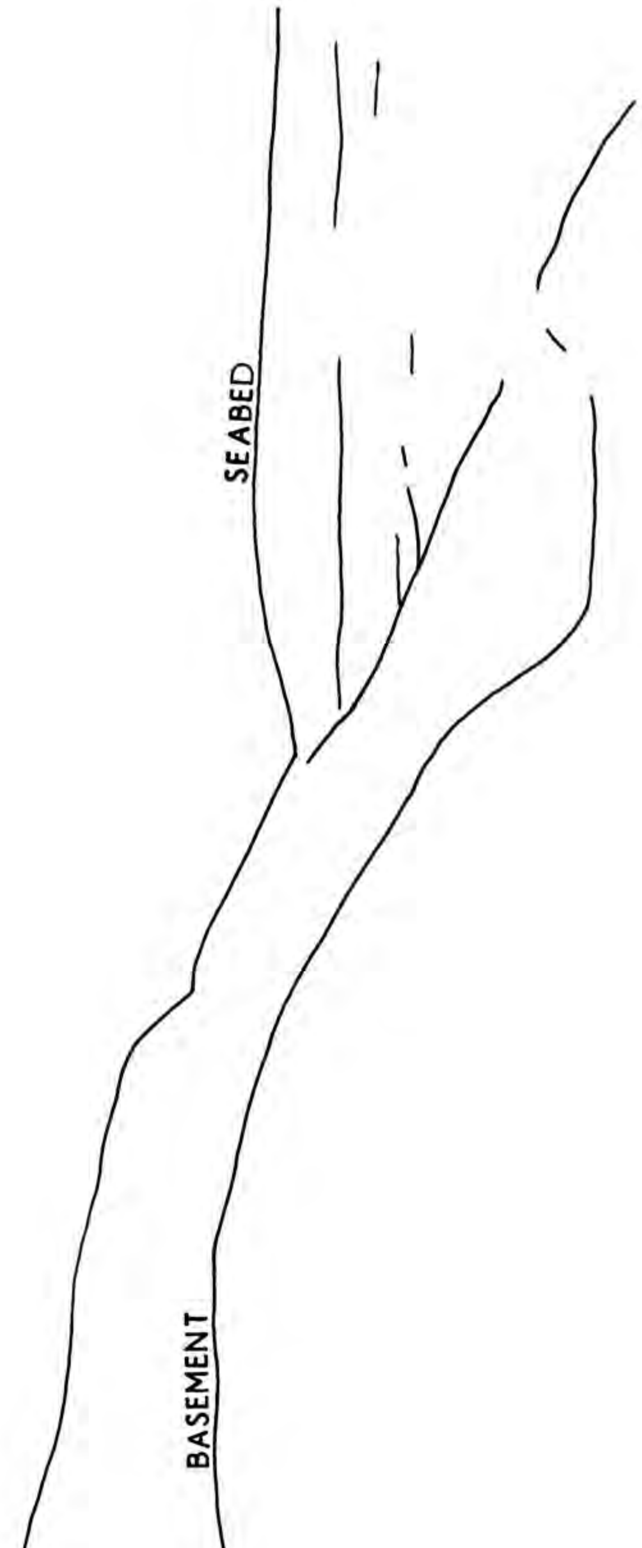


Figure 28. Seismic reflection record between the ridges of the Wyville-Thomson Rise from Line 17+21.

10 min markers horizontally. 100 m sec markers vertically.


SEABED
BASEMENT

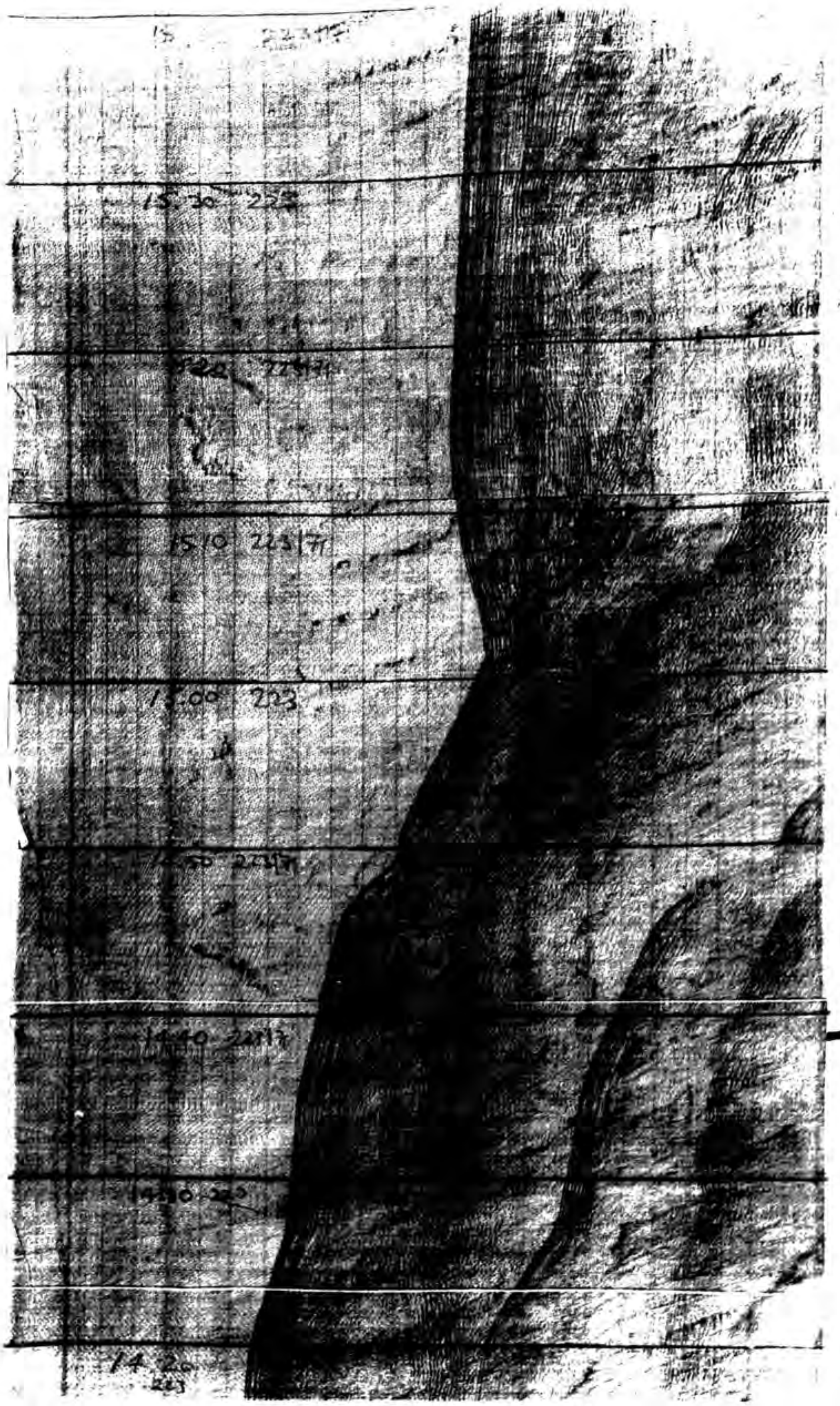
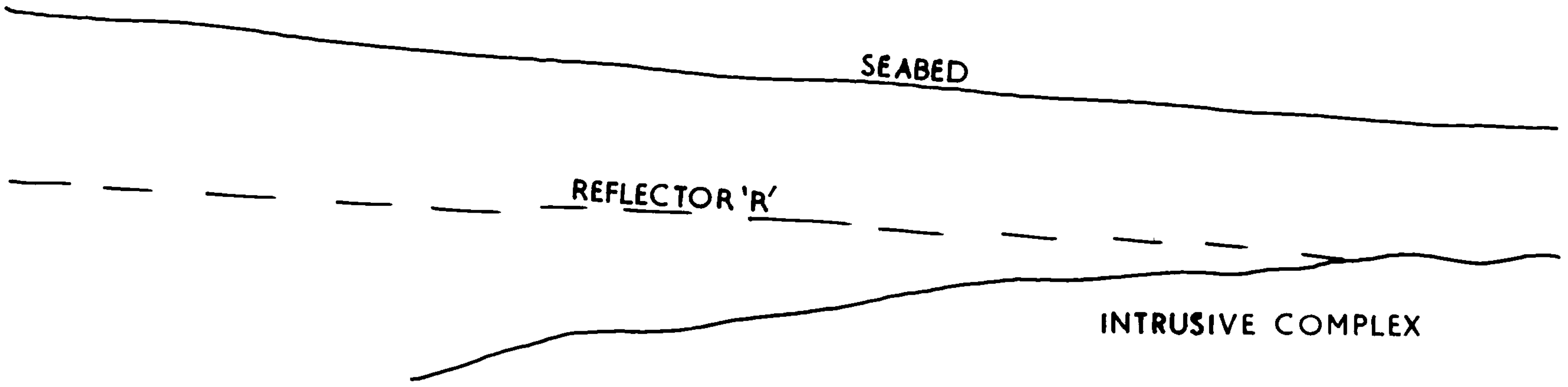


Figure 29. Seismic reflection record on the southwest ridge of the Wyville-Thomson Rise from Line 17+21.
10 min markers horizontally. 100 m sec markers vertically.


SEABED
REFLECTOR 'R'
INTRUSIVE COMPLEX

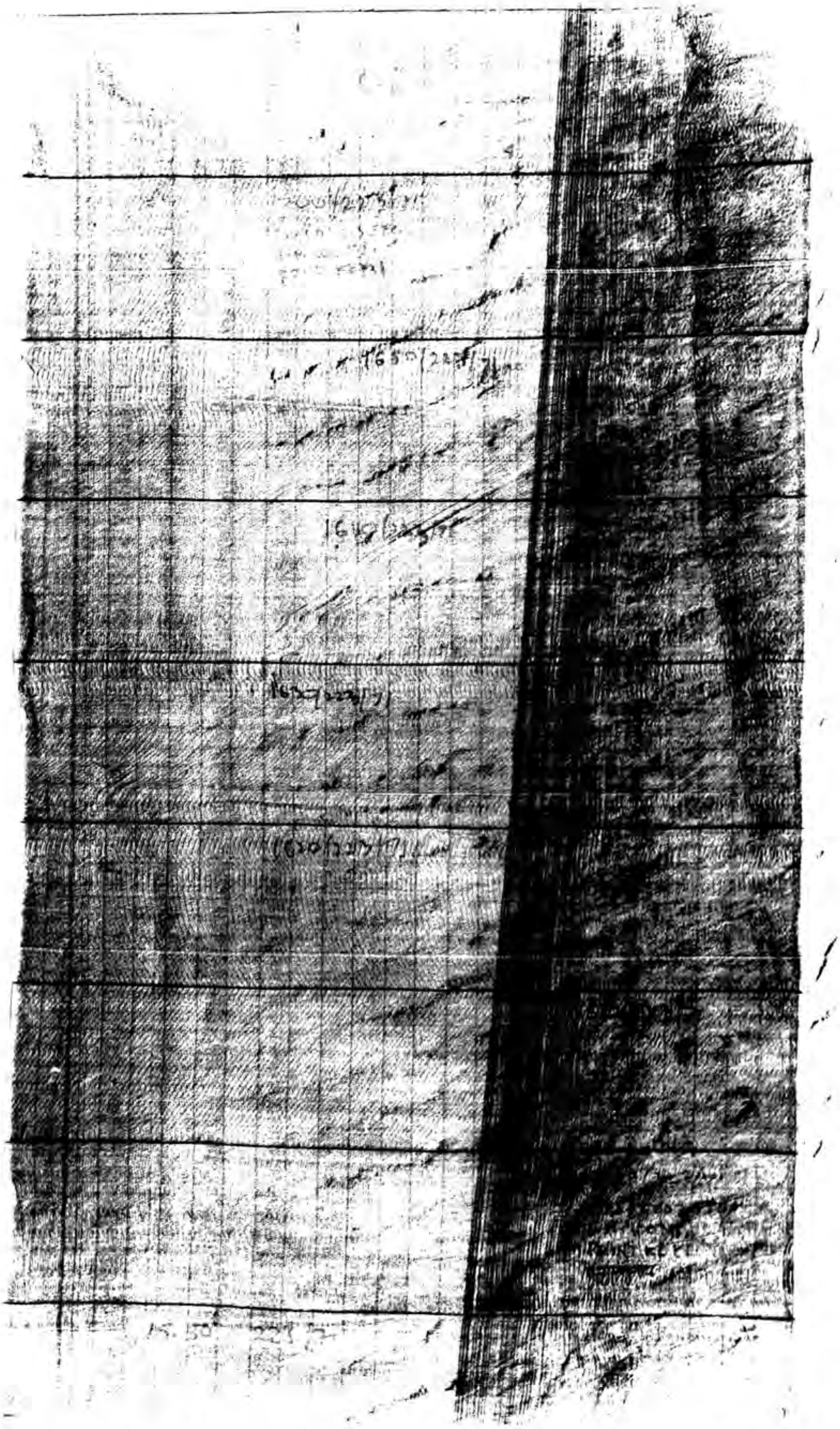


Figure 30. Seismic reflection record to the southwest of the Wyville-Thomson Rise from Line 17+21.

10 min markers horizontally. 100 m sec markers horizontally.

Reflector 'R' can be recognised on Line 17+21 by the series of small cuspate reflectors (Figs 24, 29 & 30) at the usual depth of about 0.5 seconds and on Line 30/70 by inference from its depth. The reflector can be clearly seen on Line 17+21 overstepping the lower series of sediments. The lower series must therefore have been deposited before the Lower-Middle Oligocene. The scoured trough and small associated sediment ridge lying along the foot of the southwesterly ridge (Figs. 24 & 29) indicates the presence of seafloor currents flowing along the side of the ridge.

Between the Faeroe Plateau and the Wyville-Thomson Rise, the sedimentary layering is not distinctive. Most of the sediments are relatively transparent on Line 17+21 (Fig.24). There are two or three reflectors lying parallel and adjacent to the sloping basement of the Faeroe Plateau which may represent a thin layer of beds similar to the lower series on the southwest flank of the Rise. In general, the beds in the bottom of the channel appear to have been deposited concurrently with the beds lying on the sides of the channel. Two series of differing ages cannot be distinguished as they can on the southwest flank of the Wyville-Thomson Rise. The lack of horizontal bedding in the bottom of the channel may be caused by the presence of strong currents preventing the deposition of sediments in a similar manner to the deposition in the Rockall Trough. The sediments may have been deposited by a process of slumping from the sides of the channel combined with continuous but gentle erosion by the water currents. The overstepping relationship of the seabed to the layering in the sediments on Lines 17+ 21 (Figs 24 & 26) shows that erosion has occurred on the surface of the sediments since they were deposited. An indistinct reflecting horizon on Line 30/70 (Fig.25) at a depth of about 0.5 seconds may be contemporary with reflector 'R' in the Rockall Trough but this cannot be definitely shown from the present information. The ages of the sediments between the Faeroe Plateau and the Wyville-Thomson Rise are not known.

The structure of the sediments lying between the two basement ridges of the Wyville-Thomson Rise is most clearly seen on the reflection profile from Line 17+21 (Figs 24, 27 & 28). The lower series of sediments lying on the southwest flank of the southwesterly ridge appears to be continuous with the sediments lying on top of the southwesterly ridge of the Rise. On top of the basement ridge they show no layering. The relationship of these sediments to the sediments lying between the ridges is not clear but they may have been deposited contemporaneously with a lower series of relatively transparent sediments. Alternatively they may be contemporaneous with all the sediments lying between the ridges. The lower, transparent sediments between the ridges vary in thickness from 0 to 0.5 seconds of two-way time. This is equivalent to 0 to about 0.53 km assuming an average velocity of 2.1 km/s.

The overlying sediments are also up to about 0.5 km thick and contain a well-developed layering throughout most of their thickness (Fig.28). The lowest layering is made up of a series of short cuspate reflectors. These form a horizon similar to that of reflector 'R' in the Rockall Trough. Reflector 'R' also overlies a series of transparent sediments therefore it is possible that reflector 'R' is present in the upper sediments lying within the Wyville-Thomson Rise. The evidence cannot be considered to be conclusive. The layering in the upper sediments is not horizontal particularly on the southwestern side of a minor basement rise near the centre of the basin (Figs. 24 & 28). The individual beds thin and turn up towards the surface over the rise. This effect is probably caused by the sediments being deposited by ocean-floor currents which passed over and round the minor basement rise when it formed a bathymetric feature on the old seabed. The apparent direction of the currents that deposited the beds is probably northeast to southwest but the true direction cannot be predicted from a single profile. This evidence of current action in the nature of the upper beds supports the theory that reflector 'R' is present beneath them. The present seabed is relatively flat and is therefore unconformable, on a small scale, with the bedding beneath. Some erosion of the uppermost beds has occurred over most of the basin. At the northeast side of the basin, adjacent to the northeasterly basement ridge, a broad scoured channel about 75 ms deep with an associated small sediment ridge (Fig.27) indicates the existence at present of a current flowing longitudinally along the side of the basement ridge. The scoured channel is not present in the underlying beds. The present current regime was therefore not in existence when the sediments were deposited. The scour and ridge effect is also seen on Lines 18/71, 30/70 and 15/71 (Figs. 26, 25 & 23) in a similar position along the southwestern side of the northeasterly basement ridge. Although only one basement ridge is present on Line 12/71, the same current effect can again be seen (Fig.22). The evidence may indicate that a current system flows along the southwestern side of the northeasterly basement ridge for almost the full length of the Rise.

## 5.3. The crustal structure beneath the Wyville-Thomson Rise

Two major basement ridges form the Wyville-Thomson Rise. The ridge forming the southeasterly extension to the Faeroe Plateau is both parallel to the Rise and, at its southeastern end, is similar in size and extent to the ridges of the Rise. This Faeroe ridge is considered here with the other ridges since it is possible that all three ridges have a similar or connected origin.

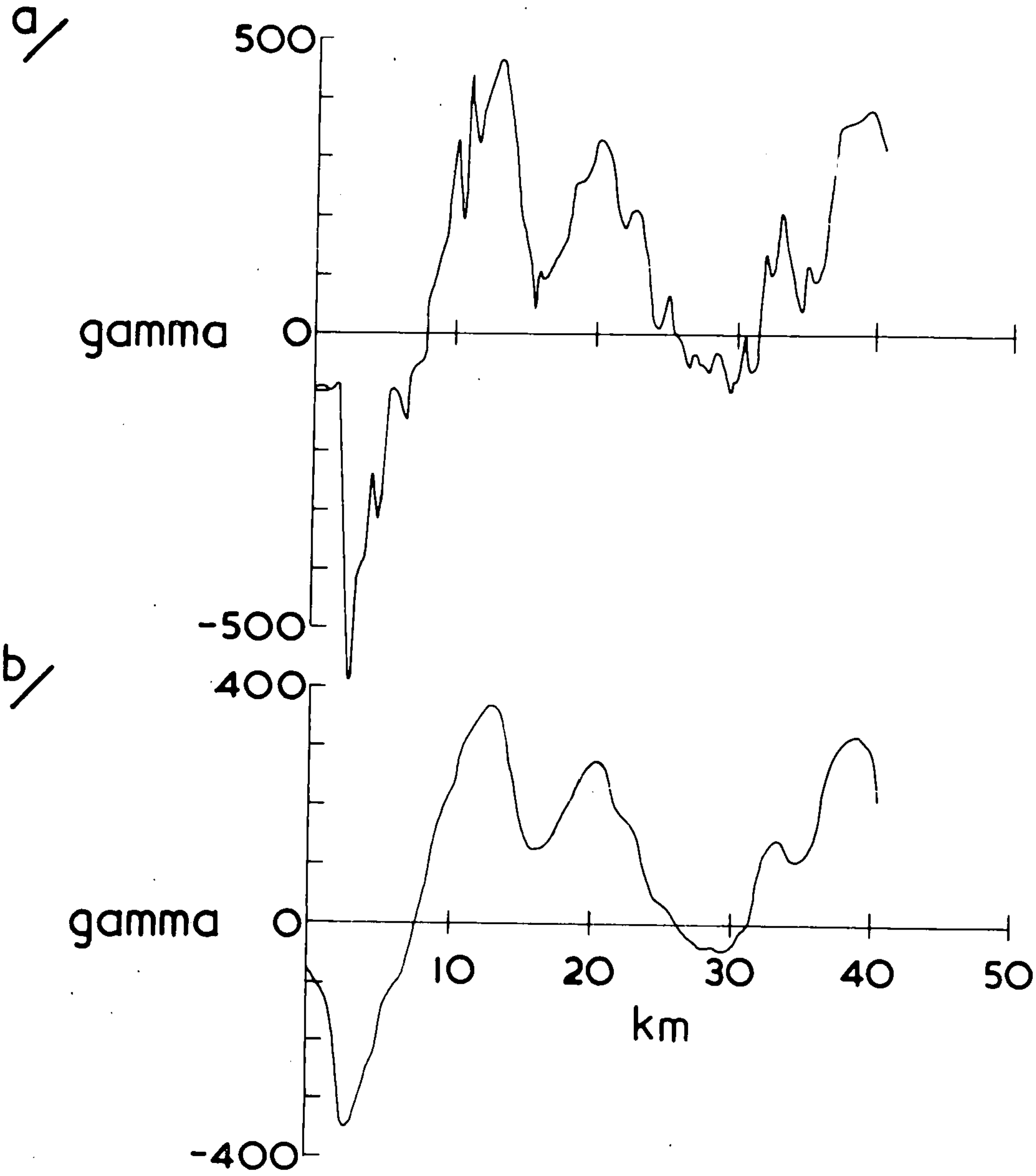
### 5.3.1. The upper crust

The magnetic profiles are shown in Figs. 22,23,24,25 & 26. The anomalies over the southeastern Faeroe ridge are principally of about 400 gamma amplitude with a wavelength of 5 to 10 km. Superimposed on these are anomalies of 50 to 100 gamma amplitude with wavelengths of about 1 km. The anomalies are similar to those over the Faeroe Plateau and the Faeroe Bank. The short wavelength anomalies may be caused by basaltic material in the form of dykes or perhaps plateau lavas as has been postulated on Faeroe Bank and Faeroe Plateau (Section 4.2.2).

Over the northeasterly ridge of the Wyville-Thomson Rise, the magnetic anomalies are similar to those over the Faeroe ridge except for the absence of the short wavelength anomalies. This absence could be caused by the absence of the source material or the greater depth of the ridge. The second hypothesis has been tested on Line 17+21 by upward continuing the anomalies over the Faeroe ridge by 0.5 km(Fig.31). The resulting anomalies are similar to those measured over the Wyville-Thomson Rise (Fig.24). It is therefore possible that the two northeasterly ridges have similar compositions.

Refraction Line E12, of Ewing and Ewing (1959)(Fig.1) traversed the southwestern side of the central ridge. It was located to the southeast of the south easterly limit of the southwesterly basement ridge. Since there was a change in water depth of about 0.73 km along the line and no knowledge of the sediment thicknesses was available, the results are largely unreliable. The velocity of the basement layer was measured to be 4.91 km/s. Since the line was reversed, this velocity should be accurate. The possible rock types applicable to this velocity are considered in Section 4.2.1. For similar reasons to those applied to the basement of the Rockall Trough, the material in this case is probably basaltic.

The magnetic profiles over the trough between the Faeroe ridge and the Wyville-Thomson Rise show a magnetic anomaly of between 400 and 700 gamma associated with the trough. On Lines 17+21 and 30/70 (Figs 24 & 25) this anomaly is restricted to the southwestern side of the trough. No basement feature is present on the reflection profiles which could explain the change in the anomaly over the centre of the trough. A lateral change in the magnetic properties of the basement in the trough must occur beneath these two profiles. The relative increase in the magnetic anomaly over the trough and decrease over the ridges has been investigated using the magnetic to gravity transform



LINE 17+21

Figure 31. The effect of upward continuation on the magnetic profile over the southeasterly ridge of the Faeroe Plateau.

a/ Original profile.

b/ Profile upward continued by 0.5 km.

method. Over the Faeroe ridge, the profiles on Line 15/71 were used since the magnetic profile on that Line shows the general trend of the anomaly most clearly (Fig.23). The results are shown in Fig. 32b. The correlation ratio is good and the value of T indicates that the magnetisation contrast at the ridge is approximately 0.007 emu assuming an average density contrast of about 1.5 g/cm$^3$. These are reasonable values for basaltic material. The magnetisation vector is reversed with respect to the present Earth's field. This indicates that the igneous material was extruded and cooled during a period of reversed magnetisation. The correlation between the anomalies over the north-eastern ridge of the Wyville-Thomson Rise was investigated on Lines 15/71, 17+21 and 18/71. The results (Figs. 33a, 34 and 32a) are less conclusive than those over the Faeroe ridge but a similar magnetisation contrast is indicated and the magnetisation vector probably lies in an approximately reversed direction. The profiles on Line 12/71 (Fig.22) were also studied. No significant correlation between the calculated and observed gravity profiles exists for any magnetisation vector. This indicates that the magnetic anomaly is not entirely caused by the basement ridge. A model body was calculated (Fig.35) using the magnetic profile and assuming that the magnetisation of the body is entirely induced. The calculated magnetic basement ridge is not in the position indicated by the gravity profile or by the reflection profile. A lateral change in the magnetisation of the basement is indicated. The position of the change, on the northeast side of the ridge, agrees well with that already postulated on Lines 30/70 and 17+21.

The southwesterly basement ridge of the Wyville-Thomson Rise has a covering of sediment about 0.5 km thick on Line 17+21 and about 200 m thick on Line 30/70 (Figs. 24,25 & 29). The basement is at a depth of about 1 km which is approximately 400 m deeper than the northeasterly ridge. On Line 17+21, the magnetic anomalies over the ridge have a relatively long wavelength and amplitudes of about 100 gamma. These

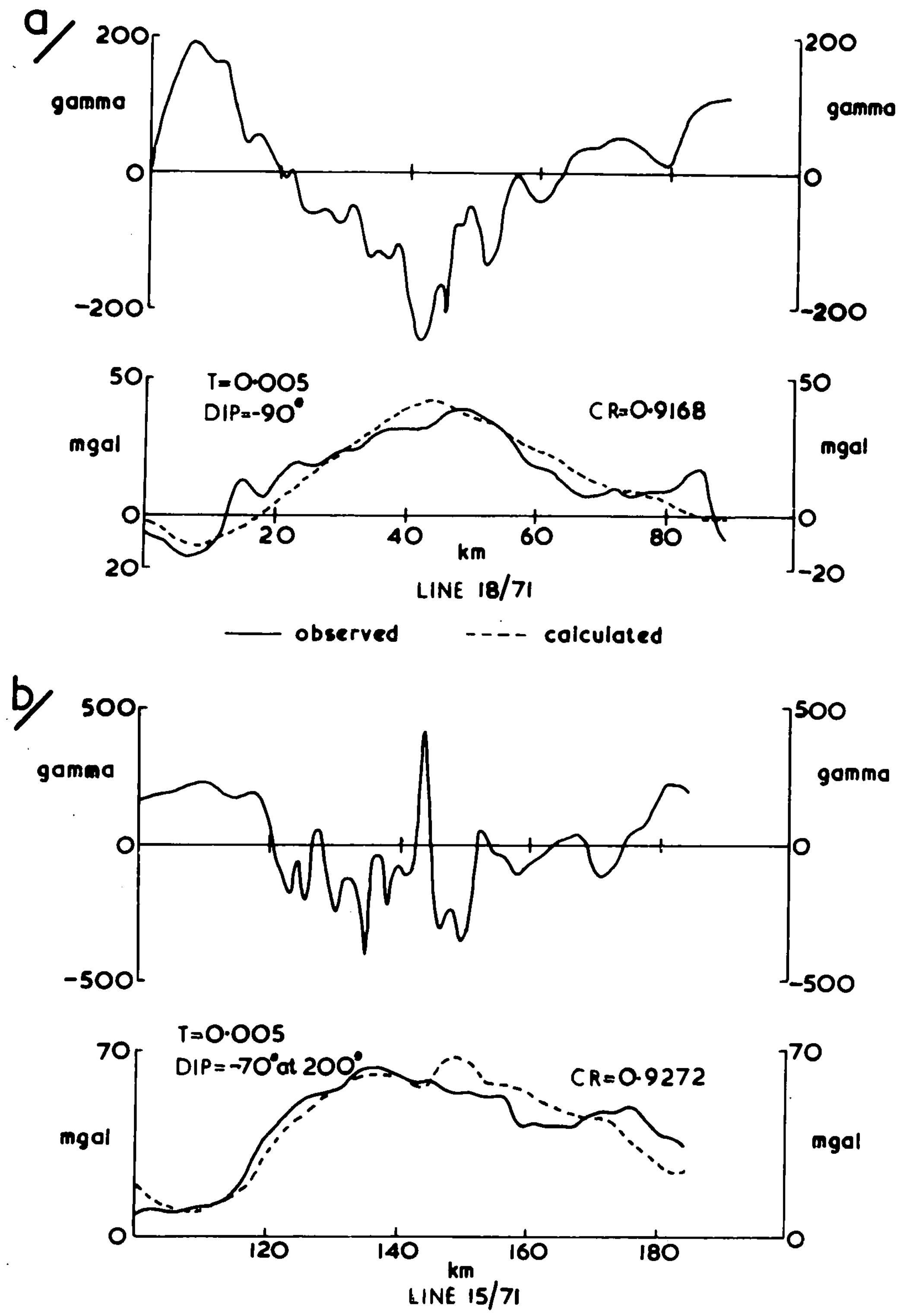


Figure 32. Results of gravity-magnetic.

a/ Line 15/71, 100-200 km.

b/ Line 18/71, 0-100 km.

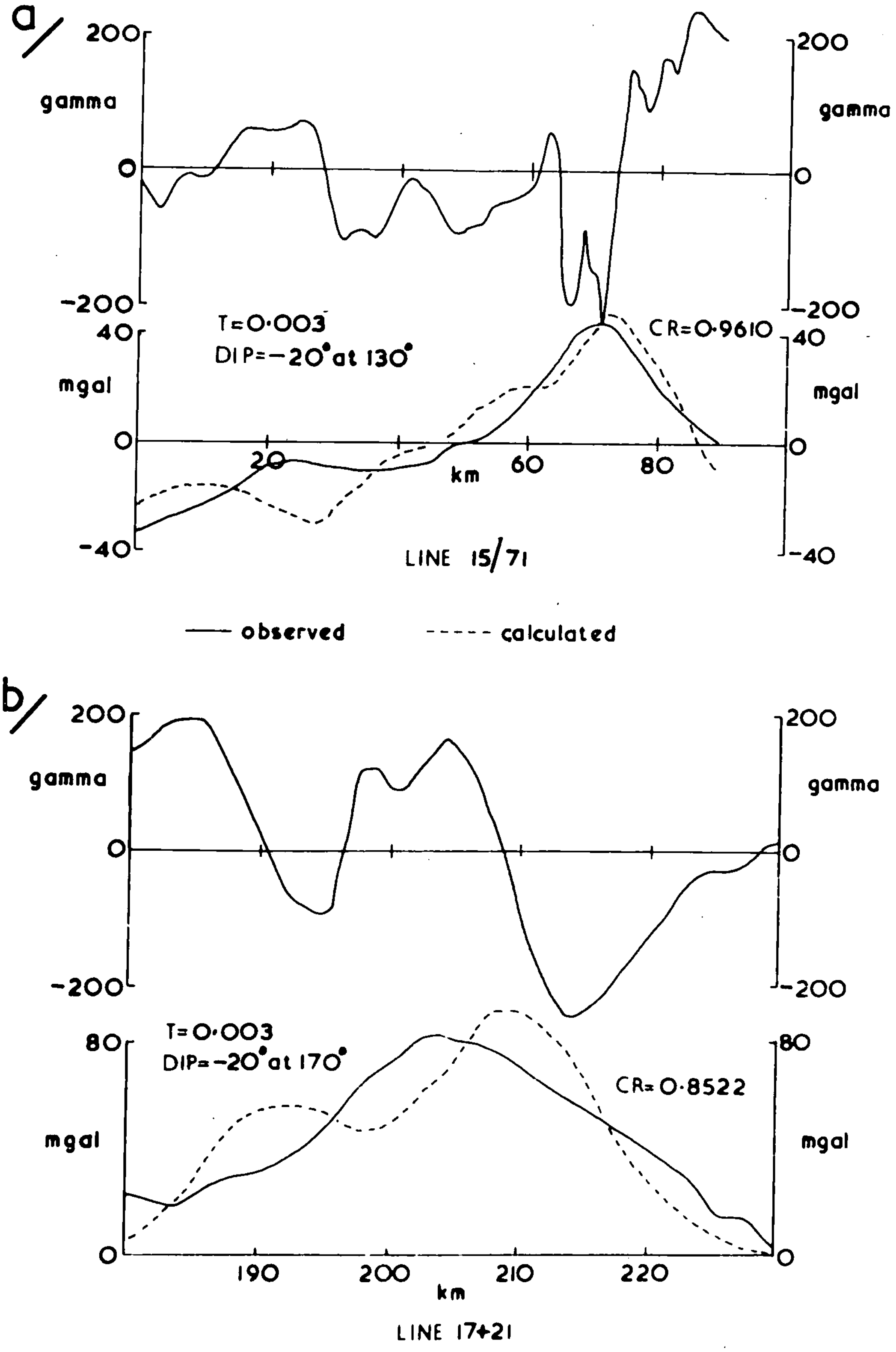


Figure 33. Results of gravity-magnetic transforms.

a/ Line 15/71,0-100 km.

b/ Line 17+21, 180-230 km.

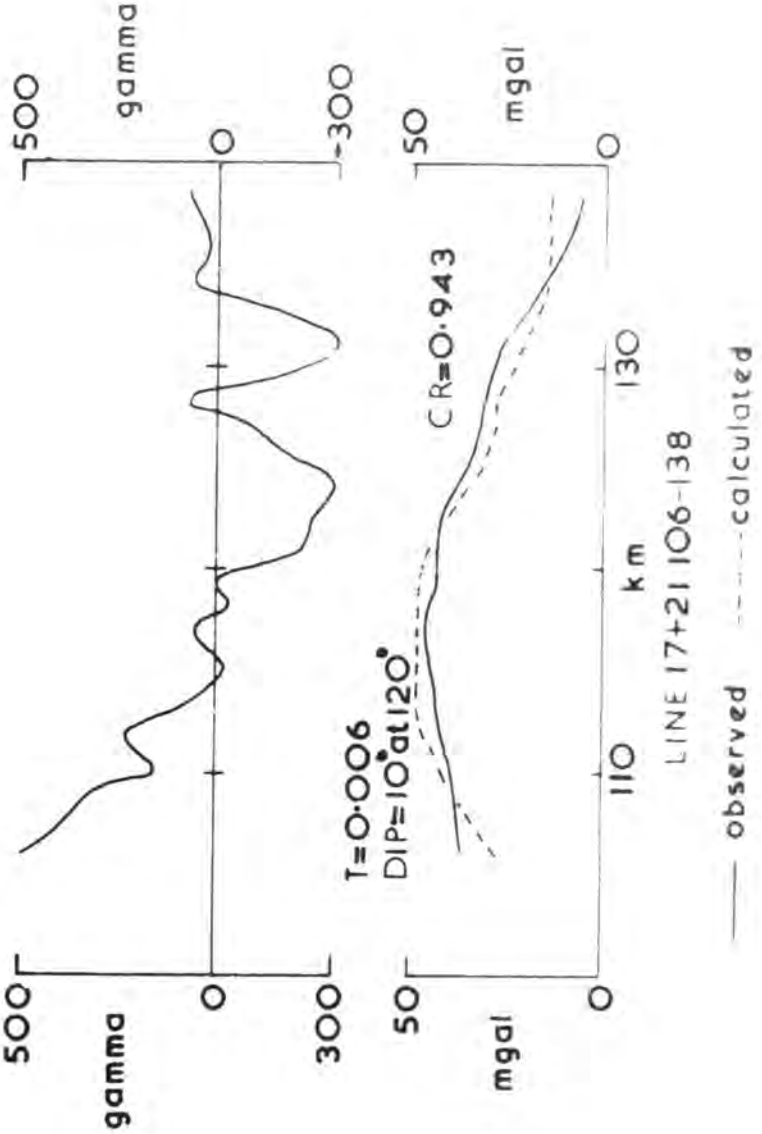


Figure 34. Results of gravity-magnetic transform on Line 17+21, 106-138 km.

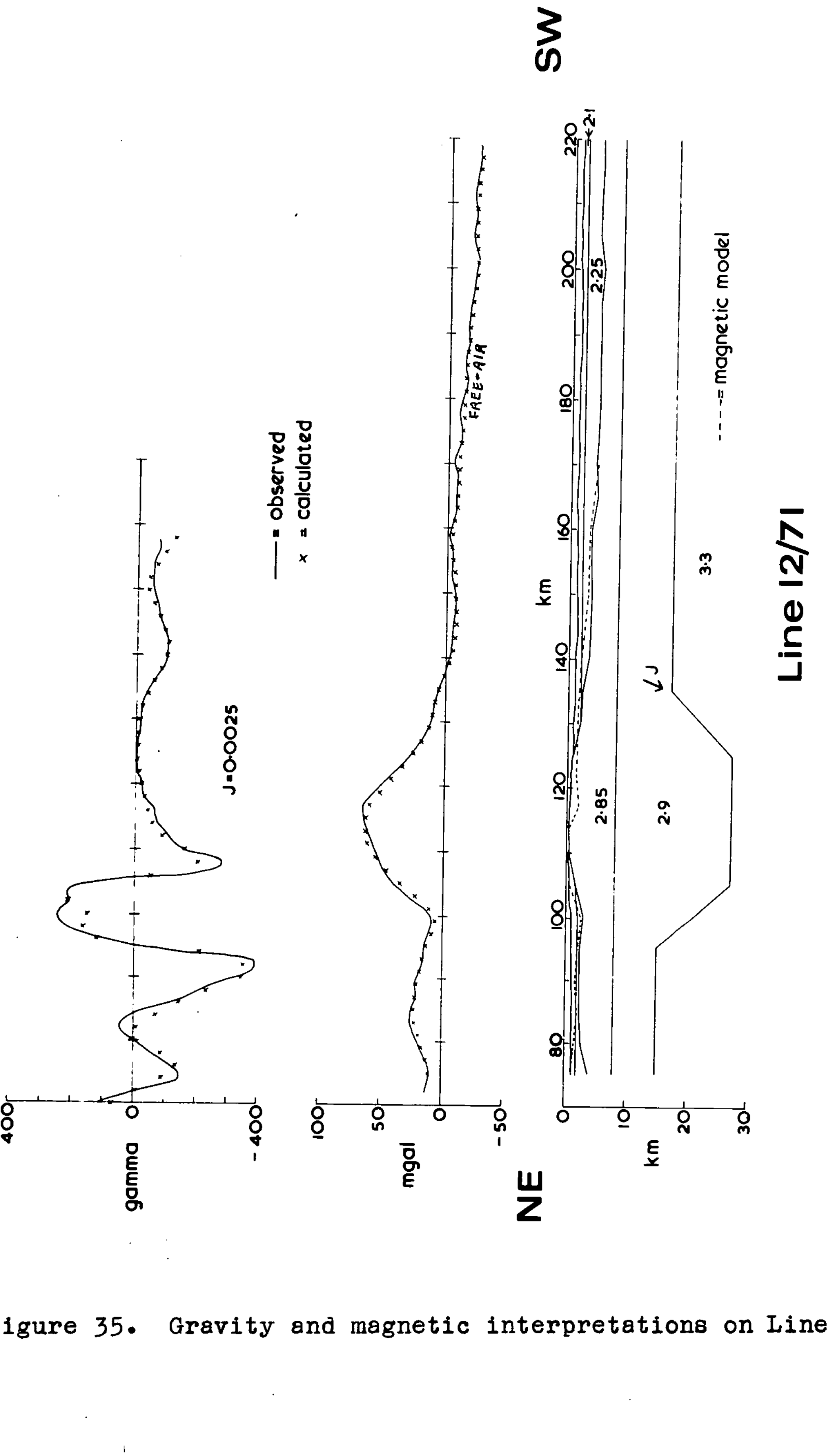


Figure 35. Gravity and magnetic interpretations on Line 12/71.

anomalies are not significantly different from the anomalies over the basin between the ridges of the Rise. A power spectral analysis of the anomalies over the basin indicates that the magnetic basement is at a depth of 0.7 to 0.8 km. This level is only slightly below the seabed and is well above the acoustic basement. A magnetic equivalent layer was calculated at this depth. The magnetisation of the blocks forming the layer varies between 0.0001 and 0.0002 emu/cm$^3$. This value is high for sedimentary material andindicates that a high proportion of magnetic minerals is present. Tuffs and a few sandstones have been found with magnetisation values as high as these values (Nagata 1961). Since heavy minerals are unlikely to be transported over long distances the provenance of the sediments in the basin is probably nearby. The erosion of the basaltic material on the basement ridges or on Faeroe Bank may produce sediment, with sufficiently high magnetisation. If the material has a volcanic source, this will indicate that there was volcanic activity in the area shortly before the time of deposition. The lack of a magnetic basement at a shallow level in the sediments in the Rockall Trough adjacent to the Wyville-Thomson Rise may indicate that the sediments in the Rise are considerably older than the upper sediments in the Trough. On Line 30/70 (Fig.25), where the sediment covering the ridge is thinner, the ridge has a magnetic expression but it is smaller than that over the northeasterly ridge. This may be caused by the depth of the ridge or by masking sediments. Since the reflection profiles show a continuous basement reflection between the two basement ridges of the Rise and the two ridges are similar in cross-sectional shape, they are probably composed of similar material.

To the southwest of the Rise, on Line 17+21, a magnetic anomaly of about 400 gamma amplitude and 20 km wavelength correlates with a free-air gravity anomaly high of 80 mgal and a basement rise beneath the overlying flat-bedded sediments (Fig.24). This feature is also crossed by Line 5/970 (Fig.11). Since these two Lines are orthogonal, the feature must be approximately circular in areal extent. It is probably an intrusive complex and is considered in Section 5.3.3. A similar basement rise occurs in a similar position on Line 30/70 (Fig.25). A negative magnetic anomaly of about 300 gamma amplitude can be correlated with the rise but no gravity data is available from this Line. The feature is also recognisable on Line 5/970 (Fig.11). No major gravity anomaly is associated with it. There is no obvious explanation for the feature. It may be a rise in the normal basement material. The relationships of the overlying beds to the two basement features are distinctly different. The reflectors wedge out against the probable intrusive complex whereas they rise up and over the other feature. The former relationship indicates that the complex was present before the beds were deposited. The latter relationship suggests that the basement has risen since the beds were deposited. This explanation is unlikely since there is no evidence of basement movement as late as the Oligocene elsewhere on the Wyville-Thomson Rise. A current regime, which would be unusual for the period, may have caused the relationship but the possibility of post-reflector 'R' movement cannot be discarded.

### 5.3.2. The deep crustal structure

Apart from Line E12 of Ewing and Ewing (1959), which had relatively little penetration, and the as yet uninterpreted, North Atlantic Seismic Project lines, no refraction lines have been carried out in the area. Interpretation of the deep crustal structure is therefore entirely dependent on gravity data. The gravity profiles on Line 17+21 and 12/71 have been interpreted (Figs. 35 & 36). The densities used are basically the same as those used in the Rockall Trough interpretation (Section 4.3.4). The sediments are assumed to have a density of 2.1 $g/cm^3$ above a depth of about 1 km and a density

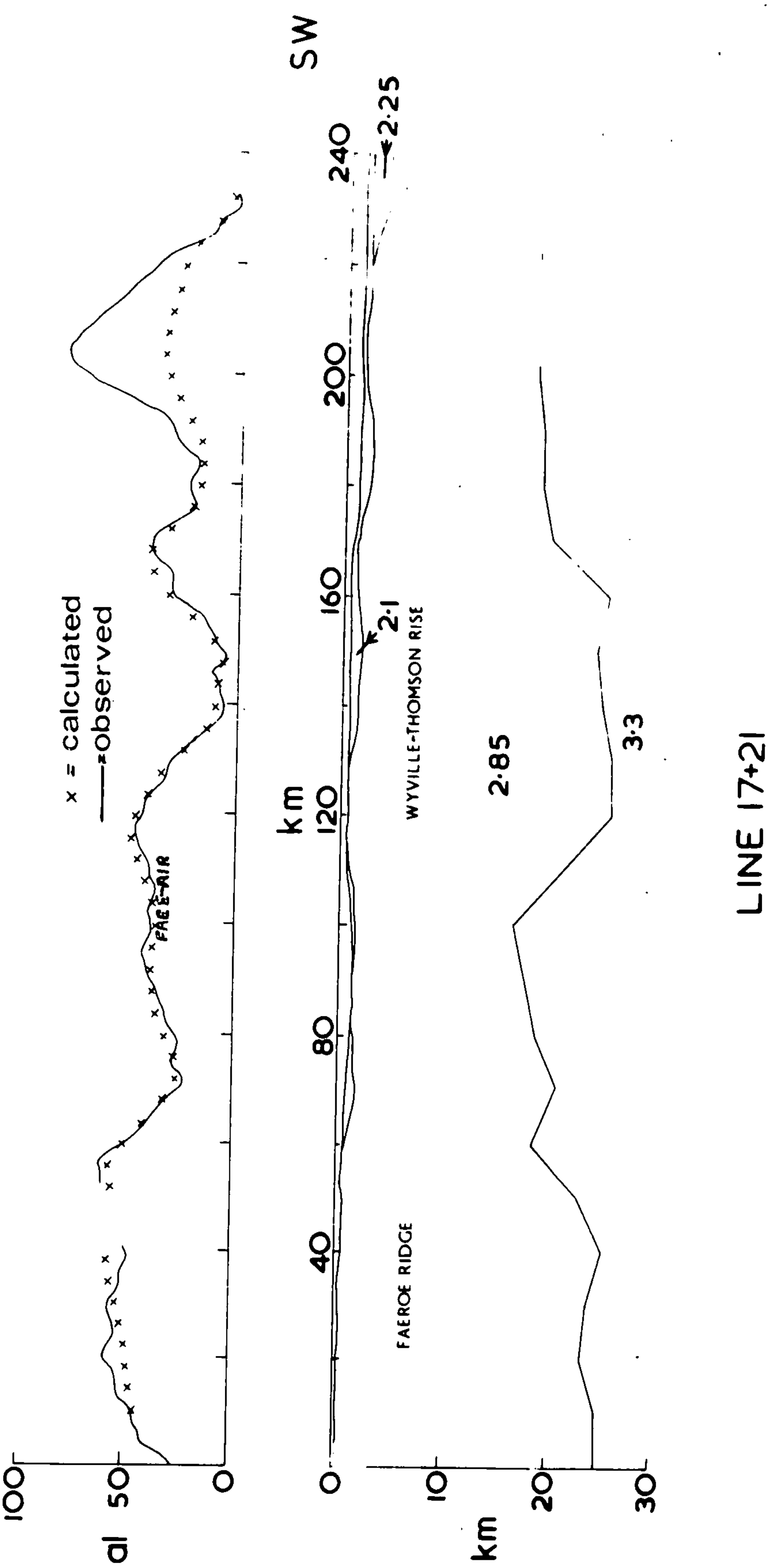


Figure 36. Gravity interpretation on Line 17+21.

of 2.25 g/cm$^3$ below this depth. The crustal layer on Line 17+21 has a density of 2.85 g/cm$^3$ throughout. On Line 12/71, the crust is divided into an upper layer with a density of 2.85 g/cm$^3$ and a lower layer with a density of 2.9 g/cm$^3$. This refinement is probably unwarranted on such an approximate model.

The depth of the basement on Line 17+21 was calculated from the reflection profile except at the southwestern end where the previously estimated value at the northeastern end of the Rockall Trough was used. On Line 12/71, the basement depth was estimated from the reflection profile, the magnetic interpretation and the calculated probable depths in the troughs on either side of the basement ridge. The gravity high at the southwestern end of Line 17+21 is considered in Section 5.3.3. The depth of the Moho on both Lines was fixed at 17 to 18 km in the Rockall Trough. The possible errors in the densities and basement depths limit the significance of the details of the model but the basic trends are probably correct.

The models indicate that a crustal thickening of 7 to 10 km occurs beneath the Wyville-Thomson Rise and beneath the southeasterly extension of the Faeroe Plateau. The depth of the Moho beneath these ridges is approximately 25 km. Beneath the trough between the Faeroe extension and the Rise, the Moho rises to a depth of between 15 and 18 km.

The gravity profile on Line 11/71, which crosses the eastern margin of the Faeroe-Shetland channel, has also been interpreted (Fig.37). The thickness of sediment in the channel was assumed to be about 3 km as calculated from the magnetic profile on Line 10/70. The Moho depth beneath the channel agrees well with that calculated on Line 12/71. (The sedimentary basins, shown on the interpretation lying on the continental shelf, have been described by Watts (1971).).

According to the gravity interpretation the depth of the Moho increases to the northeast in the Rockall Trough to about 18km. Beneath the basement ridges of the Wyville-Thomson Rise and the

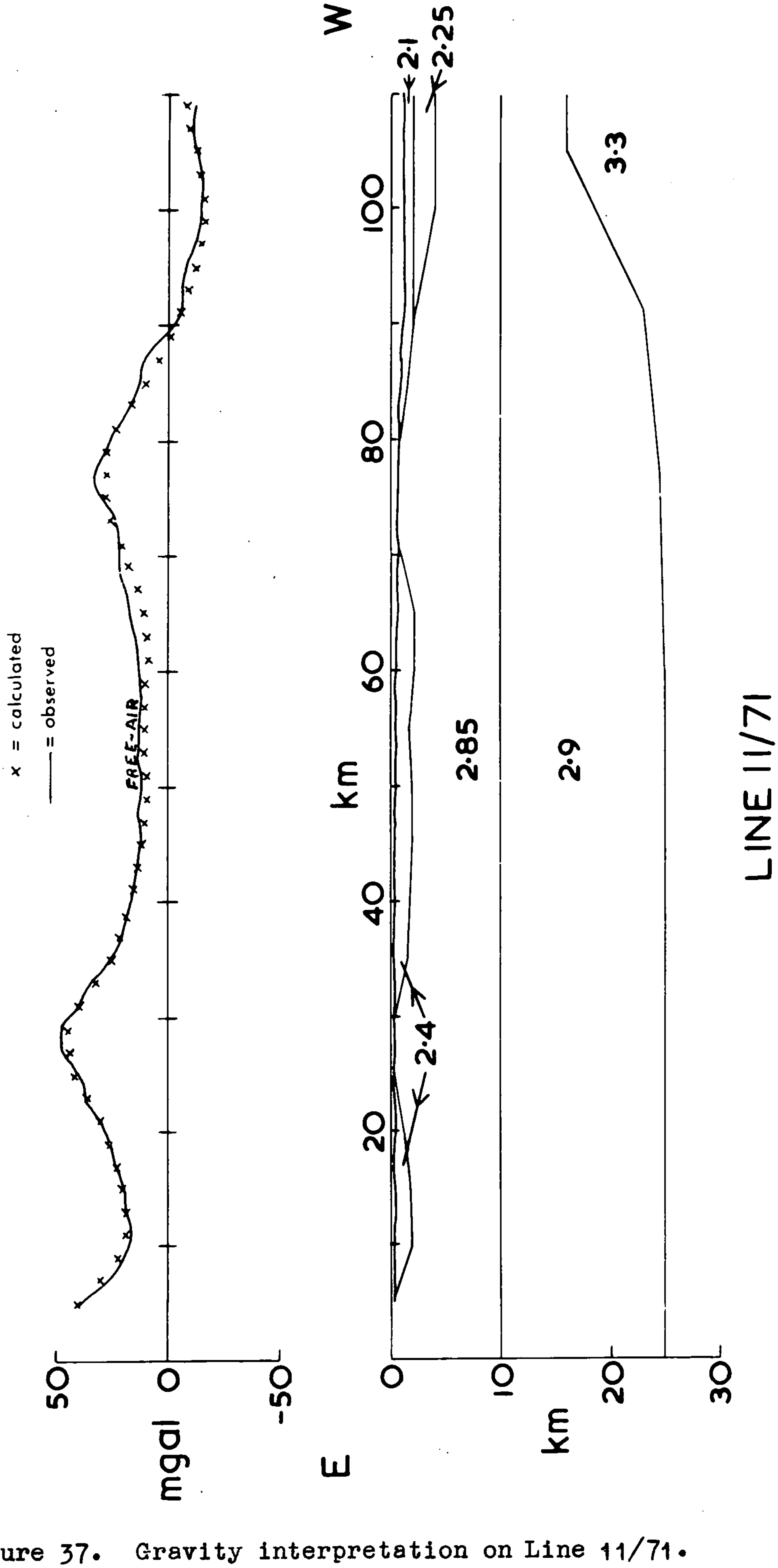


Figure 37. Gravity interpretation on Line 11/71.

southeastern Faeroe Plateau, there is a rapid increase in the depth to about 25 km. To the northeast of the ridges, the depth decreases to about 16 km in the Faeroe-Shetland channel.

### 5.3.3. The intrusive complex at 59°40'N, 8°40'W

The complex is recognisable by a rise in the basement of about 400 m, a free-air gravity high of 82 mgal peak value above a regional of about 30 mgal and a magnetic anomaly of about 400 gamma amplitude (Fig.24). A three-dimensional interpretation of the gravity anomaly (Fig.38), assuming a density contrast of 0.25 $g/cm^3$, indicates that an approximately cylindrical body with its base at a depth of about 14 km and a diameter of about 25 km is present. The assumed regional is that indicated by the two-dimensional interpretation of Line 17+21 (Fig.36). The density contrast of the body with the country rock is representative of a mixture of basic and ultrabasic material lying within the crust (Section 6.3.1). Since little is known of the geology of the region, there may be a considerable error in the assumed density contrast. A change in the contrast would alter the depth of the base of the model.

The correlation of the magnetic and gravity profiles over the body has been investigated using the magnetic to gravity transform method. The results (Fig.33b) are not conclusive. This is probably because the body is not a two-dimensional feature and the method is not therefore fully valid. The correlation ratio is not good but the results indicate that the intrusive body is reversely magnetised with respect to the present Earth's field.

Since the reflectors, which include reflector 'R', in the surrounding sediments wedge out against the basement rise (Sections 5.2.1 and 5.3.1, Figs. 24 & 30), the complex is older than most of the sediments in the Rockall Trough. It is therefore more likely to be of similar age to the intrusive complex of Rosemary Bank rather than

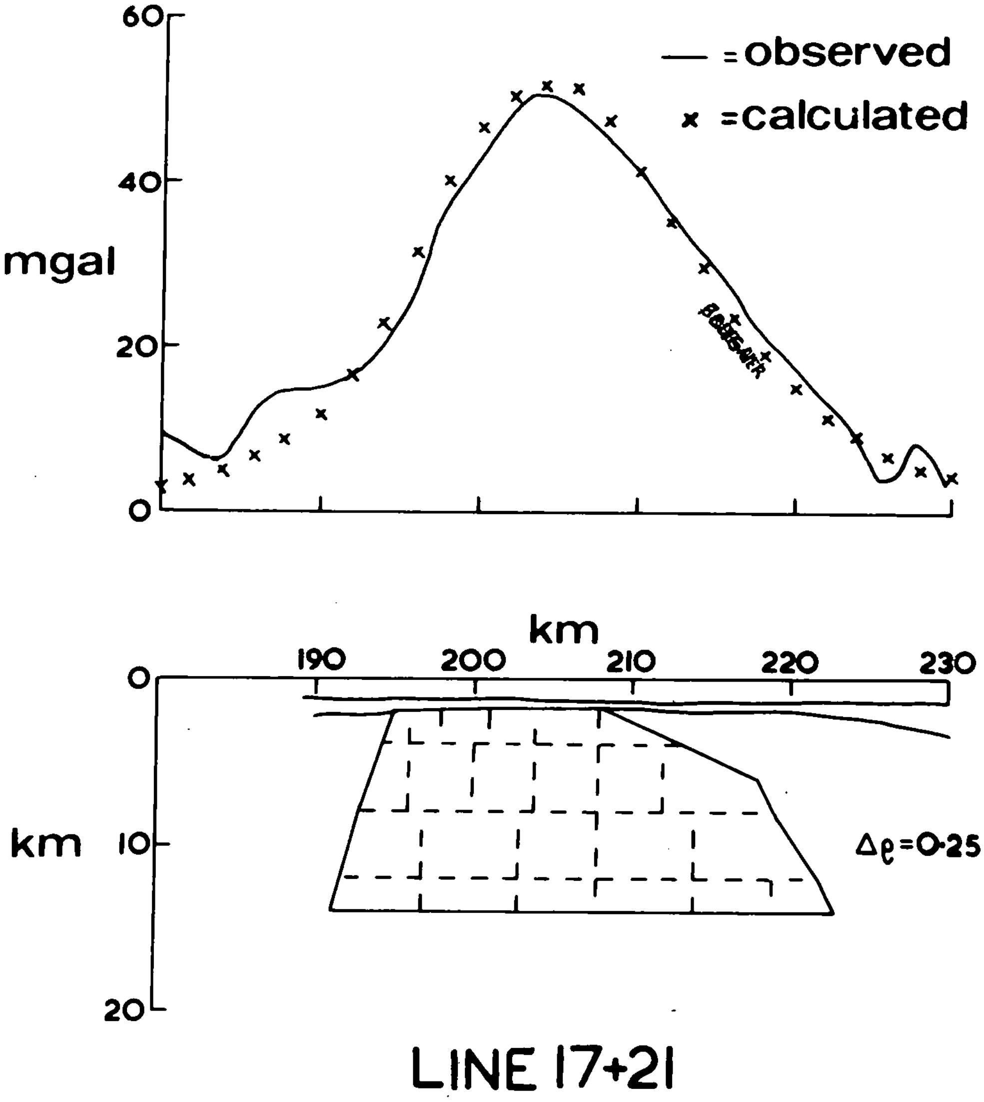


Figure 38. 3-D gravity interpretation over intrusive complex on Line 17+21.

to the complexes found in Scotland and on the continental shelf.

The intrusive complex has a diameter of about 25 km and its base is at a depth of approximately 14 km. It is reversely magnetised and is pre-Lower Oligocene in age. It may be as old as the basement of the Rockall Trough.

## 5.4. Conclusions

Three basement ridges with a northwest to southeast trend extend from Faeroe Bank and Faeroe Plateau towards the Scottish continental shelf. The two ridges to the southwest form the Wyville-Thomson Rise. The southwesternmost ridge is variable in cross-section and extends from Faeroe Bank to within 50 km of the continental shelf. The middle ridge is more uniform and is continuous from Faeroe Bank to the continental shelf. The northeastern ridge forms a gradually deepening, southeasterly extension to the Faeroe Plateau and terminates about 40 km from the continental shelf. Magnetic data shows that all three ridges are probably, at least partially, composed of basaltic material, much of which was extruded during a period of reversed magnetisation. Gravity evidence indicates that crustal thickening of 7 to 10 km occurs beneath the ridges. The Moho depth either side of the Wyville-Thomson Rise and in the Faeroe-Shetland channel is between 16 and 20 km.

Two series of sediments can be recognised to the southwest of the Rise on the reflection profiles. The lower series drapes the sides of and overlies the southwesterly ridge and is similar to the lower series found on George Bligh and Bill Bailey's Banks. The upper series is composed of flat-lying sedimentary layers typical of the Rockall Trough. The presence of reflector 'R' in these sediments shows that the ridges of the Wyville-Thomson Rise are at least as old as the Lower Oligocene and may be as old as the oceanic crust of the Rockall Trough. Between the ridges of the Wyville-Thomson Rise, strong currents have affected the later sedimentation. There is evidence that magnetic material is present in the upper layers of the sediments between the ridges. This may indicate that volcanic activity took place shortly before the sediments were deposited and that the sediments have a relatively local provenance. To the northeast of the Wyville-Thomson Rise, strong deep-sea currents have probably inhibited the deposition of horizontally-bedded sediments. The process of sedimentation has probably involved sedimentation by slumping from the adjacent ridges combined with erosion by the deep-sea currents. Reflector 'R' may be present to the northeast of the Rise indicating that deposition has occurred since, at the latest, Lower Oligocene times.

An intrusive complex lies on the southwest flank of the Wyville-Thomson Rise. It has a diameter of about 25 km and a probable depth of about 14 km. The complex is reversely magnetised and was formed previous to the Lower Oligocene and perhaps at a similar time to the basement of the Rockall Trough and the Wyville-Thomson Rise.

The intrusive complex on the southwest flank of the Wyville-Thomson Rise may have a similar origin to Rosemary Bank and the Anton Dohrn Seamount. All three centres may be associated with the opening of the Rockall Trough. The reflection profile evidence suggests that the northerly centre is of similar age to the basement ridges across the northeastern side of the Rockall Trough. The ridges may therefore have been formed simultaneously with or shortly after the opening of the Rockall Trough.

The lowest series of sediments on the southwest flank of the Wyville-Thomson Rise appears to be older than much of the sediment in the Rockall Trough. The variation in thickness and the type of bedding of the sediments suggests that they had a nearby provenance. This may have been the Faeroe Bank or even the Wyville-Thomson Rise itself. The sediments may be Lower Tertiary or Cretaceous in age. The high magnetisation of the sediments in the vicinity of the southwesterly ridge on Line 17+21 could be related to the nearby intrusive centre. This would imply that they are of similar age. This hypothesis is supported by the apparent absence of magnetic sediments in the upper sedimentary layers in the Rockall Trough.

The current deposited sediments lying between the ridges of the Wyville-Thomson Rise may be considerably younger than the previously mentioned series of sediments. They may only form the upper part of the infill of sediments in the Wyville-Thomson Rise. This could explain the apparent conflict between the ages of the sediments on the Rise.

# CHAPTER 6.

## The Hebridean continental margin.

### 6.1. Introduction.

Before 1970 the Hebridean continental shelf had received little attention. The I.G.S. aeromagnetic survey of Great Britain (I.G.S. 1968) covered part of the shelf adjacent to the land and a narrow strip extending out to St. Kilda. A seismic reflection profile across the shelf and margin has been reported by Stride et al. (1969). Geological investigations have been carried out on St. Kilda (Cockburn 1935) and on the Flannan Isles (Stewart 1933). The Flannan Isles are composed of hornblende gneiss with many veins of pegmatite. This probably belongs to the Laxfordian part of the Lewisian complex. The discovery of Mesozoic and Palaeozoic sediment-filled basins on the shelf further north (Fig.3, Bott and Watts 1970, Browitt 1972) increased the interest in the Hebridean shelf since it appeared possible that similar basins would be present. McQuillin and Binns (1973) described an assymmetrical basin beneath the Sea of the Hebrides, containing New Red Sandstone and more recent rocks, bounded on the west by the Minch Fault. Using gravity evidence they postulated a similar north-south basin bounded by a fault on its eastern margin to the southwest of the Outer Hebrides (Fig.42).

Beneath the continental slope, Stride et al.(1969) described a sequence of sediments showing an ill-defined, discontinuous bedding, which they classified as being of Palaeozoic aspect. This is overlain by up to 135 m of sediments showing clearly defined bedding. The overlying beds are probably Tertiary to Quaternary in age.

The investigated part of the continental shelf off northwest Scotland is underlain by a basement composed of Lewisian material with some Torridonian Sandstone. Sediment-filled basins are present in places. They contain Mesozoic and perhaps Palaeozoic sediments. No Tertiary sediments have been found on the shelf. Draped over the continental slope are Tertiary, Mesozoic and probably Palaeozoic sediments. Tertiary plateau lavas cover some of the shelf and igneous centres of the same age are also present.

## 6.2. Description of the data

The free-air anomaly map (Fig.39) and the Bouguer anomaly map (Fig.40) have been drawn using observations along the lines shown. The Bouguer map has been tied into gravity data supplied by the Institute of Geological Sciences in the northern and southern areas and on the Outer Hebrides. A density of 2.84 g/cm$^3$ has been used for the Bouguer reduction. This may be slightly too high but errors introduced by this over the shelf area will not exceed 2 mgal.

Magnetic measurements were obtained for all lines (Fig.41). The bathymetric data, which is available from most lines, has been of use in recognising basement outcrops and small sediment-filled troughs. Seismic reflection profiles are available from most of the lines (Fig.42) but poor resolution was obtained when the airgun energy source was in use.

### 6.2.1. Lines 1/970 and 27/71 (the southern area)

The gravity readings along Line 1/970 (Fig.43) show a constant Bouguer anomaly of about 55 mgal on the shelf. There is no indication of the gravity low found by McQuillin and Binns (1973) south of 57$^\circ$N. The level of the anomaly along the Line is in agreement with that found along the margins of this gravity low. It therefore appears that there is no extension northwards of the gravity low or the associated sedimentary basin. This conclusion is substantiated by the bathymetric and sparker profiles which show that the rough seabed occurring near the Island of Barra continues to the west to about 8$^\circ$5' W beyond where it becomes progressively covered by a thin layer of sediment (Figs 44 & 45). Flinn (1973) associated this type of 'spiky' bathymetry north of the

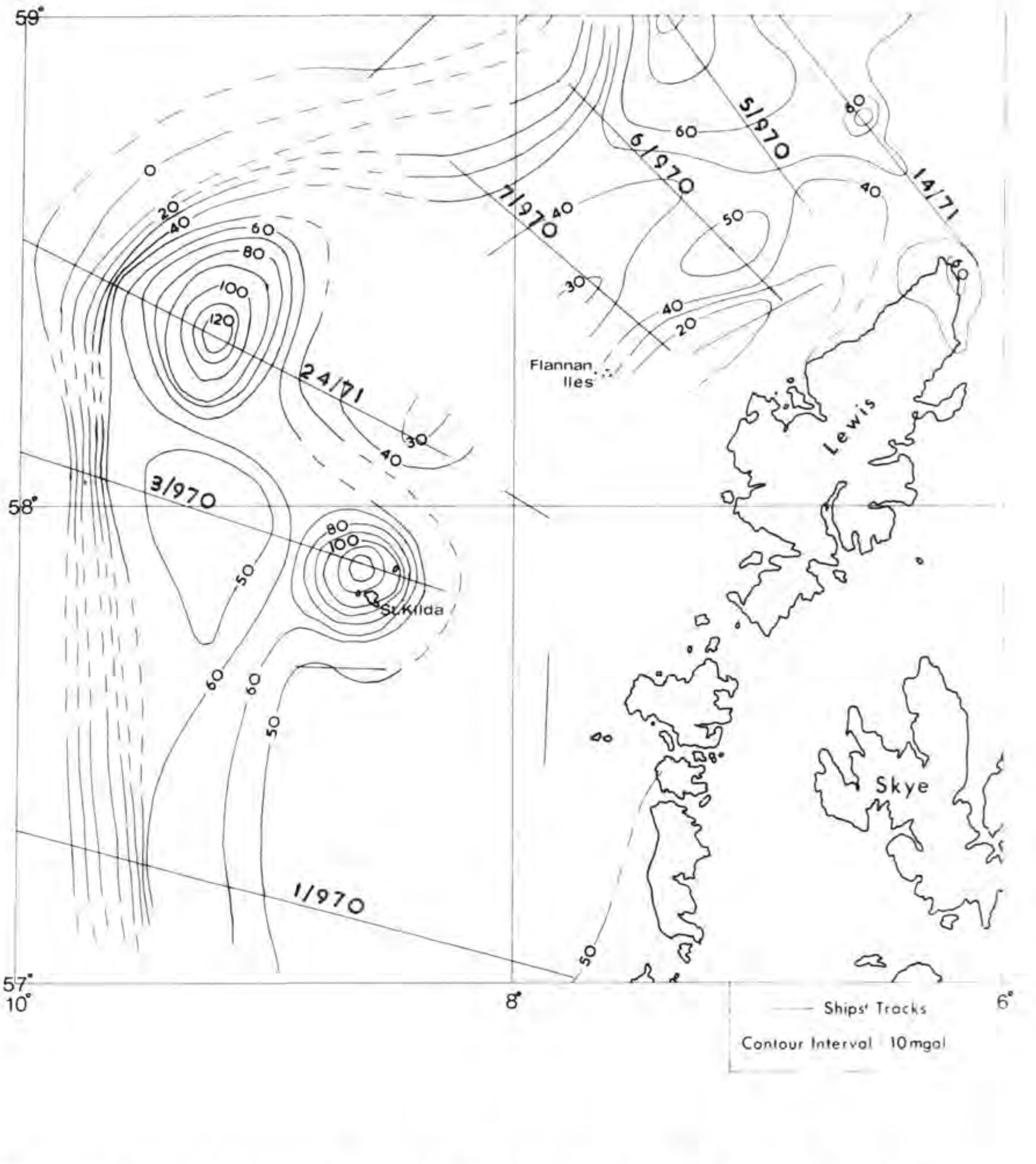


Figure 39. Free-air gravity anomaly map of the Hebridean shelf.

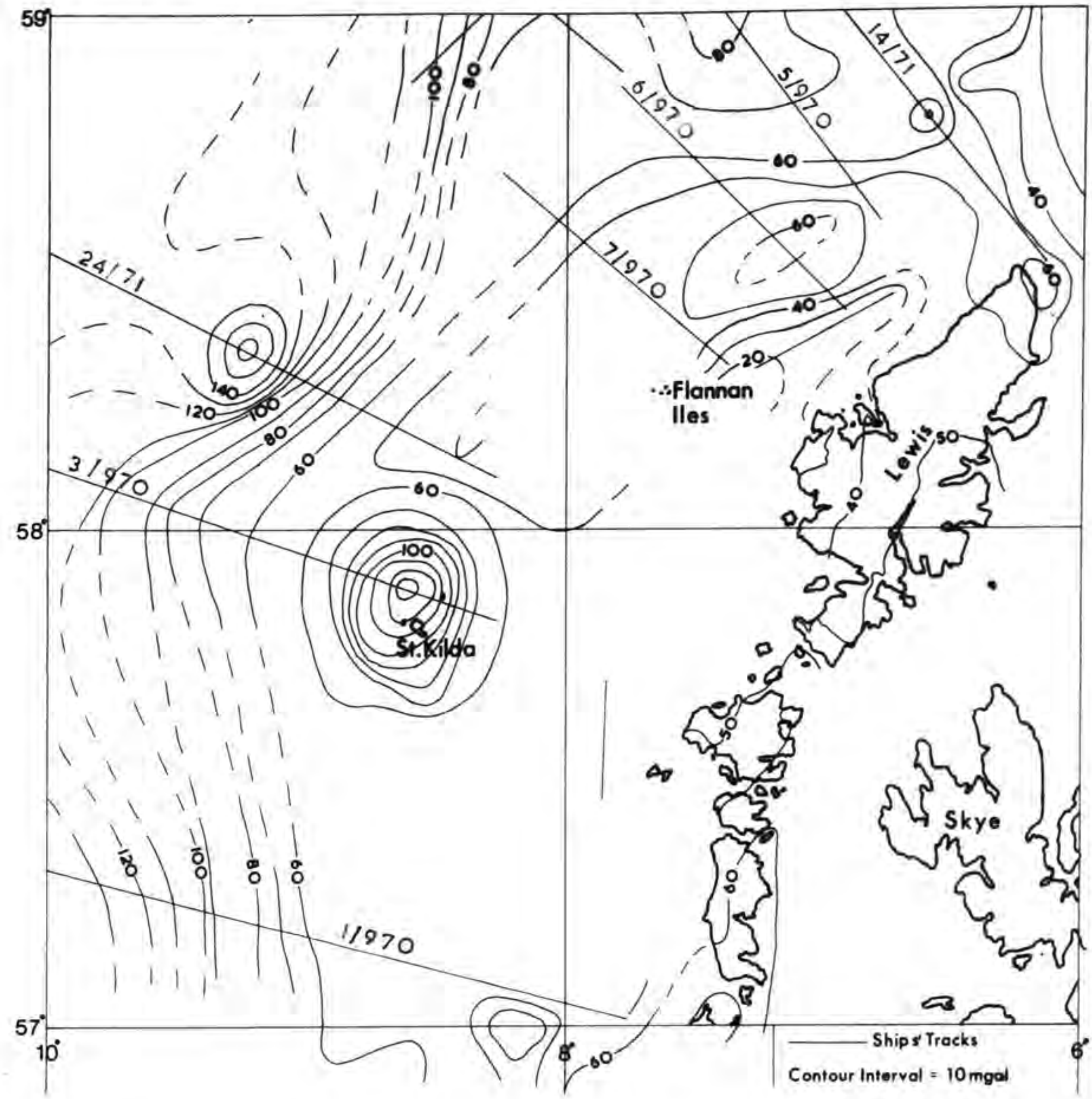


Figure 40. Bouguer anomaly map of the Outer Hebrides continental shelf. Bouguer density: 2.84 g/cm³. Gravity values on land and in the northeast corner are reproduced from I.G.S. data with their permission.

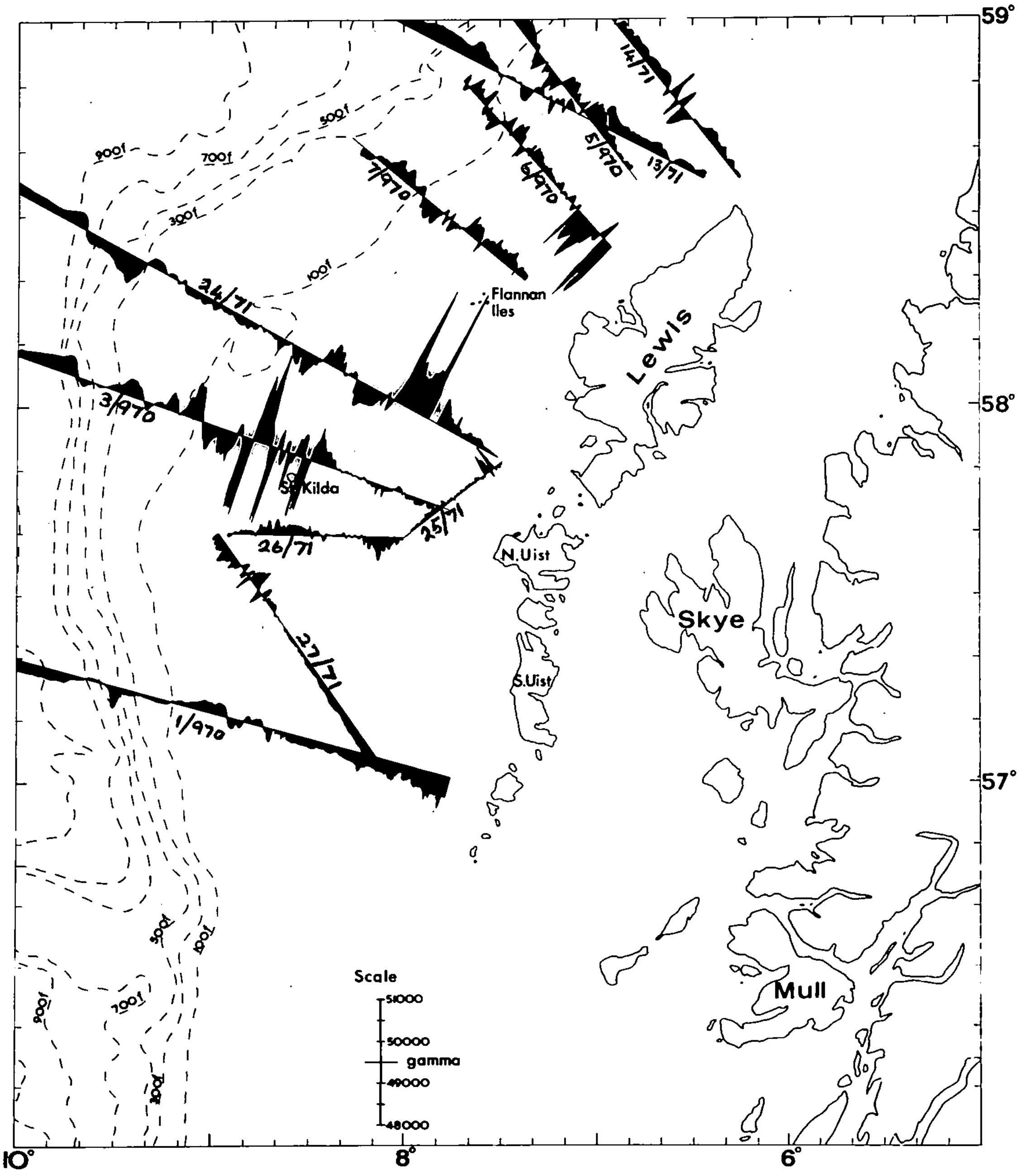


Figure 41. Magnetic profiles on the Hebridean shelf.

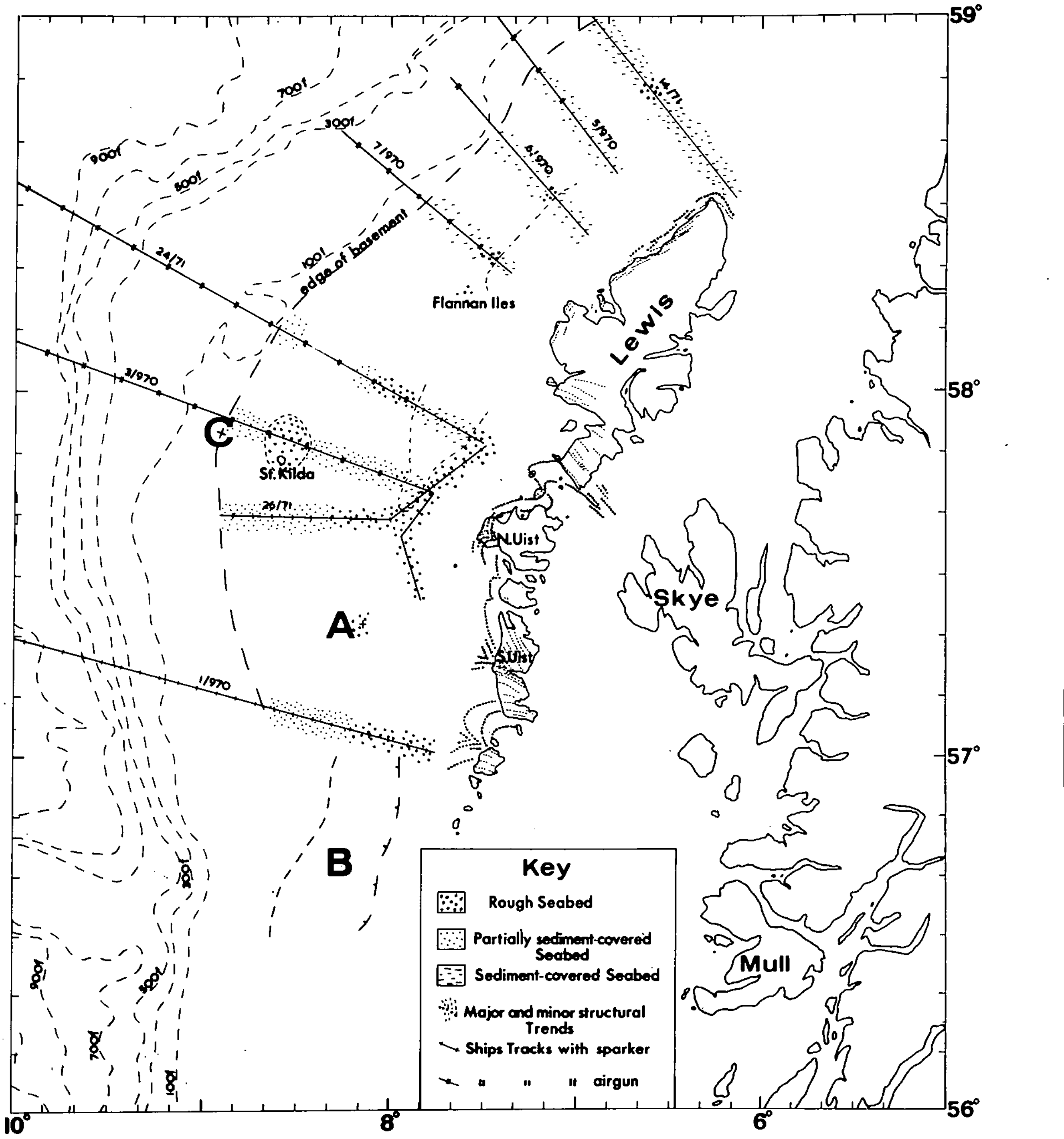


Figure 42. Summary map of the Hebridean shelf. Structural trends on the Hebrides are taken from Dearnley 1962.

A : Seismic basement on seabed found by Stride et al. 1969.

C : Edge of basement from Stride et al. 1969.

B : Sedimentary basin proposed by McQuillin and Binns 1973.

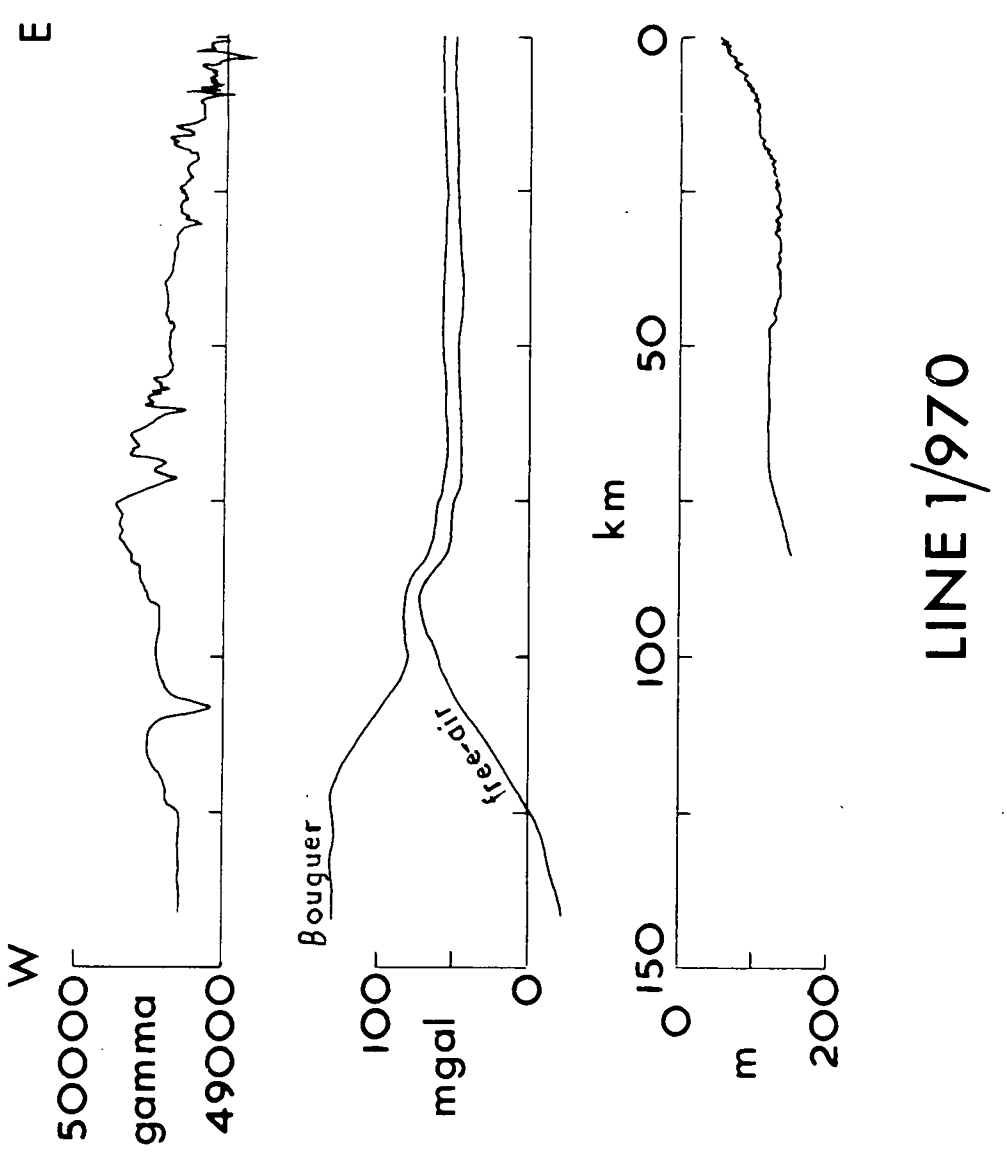


Figure 43. Profiles from Line 1/970 on the Hebridean shelf.

Hebrides with seafloor formed either of crystalline rock or Old Red Sandstone. Along Line 1/970, it probably represents a seaward extension of the Lewisian basement of Barra. To the east, the sediment lies in pockets among the basement irregularities but, further west, it becomes thick enough to mask the irregularities and form a smooth seabed (Fig.45). The furthest west that the basement can be clearly seen on the sparker records is at about 8°40' W (Fig.42). The eastern end of the magnetic profile along the same line shows short wavelength anomalies of about 500 gamma peak to peak amplitude (Fig.43). These can be correlated with similar anomalies shown on the aeromagnetic map (I.G.S. 1968, Fig.46) which have a NNW-SSE trend and cover much of South Uist and the adjoining region to the west.

On the land, the trends of the anomalies do not correlate with the Laxfordian $F_3$ fold trends which dominate the large-scale structural pattern of the Outer Hebrides (Coward et al. 1970, Fig.42) except in relatively restricted areas where the correlation may be fortuitous. The anomalies do, however, have a similar trend to the Tertiary dykes (Jehu and Craig 1923).

The central part of the magnetic profile varies from a relatively quiet region, with only small anomalies (less than 100 gamma), to regions with relatively long wavelength anomalies of about 400 gamma amplitude. There is no obvious correlation between the magnetic régimes and the topography of the underlying basement. The anomalies over the central part of the profile are thus probably caused by lateral variations of magnetization within the Lewisian but the trend of the Tertiary dykes may have some influence at the eastern end of the profile. The magnetic profile on Line 27/71 (Fig.41) shows a continuation of these magnetic anomalies as far north as 57°30' N at 8°35' W.

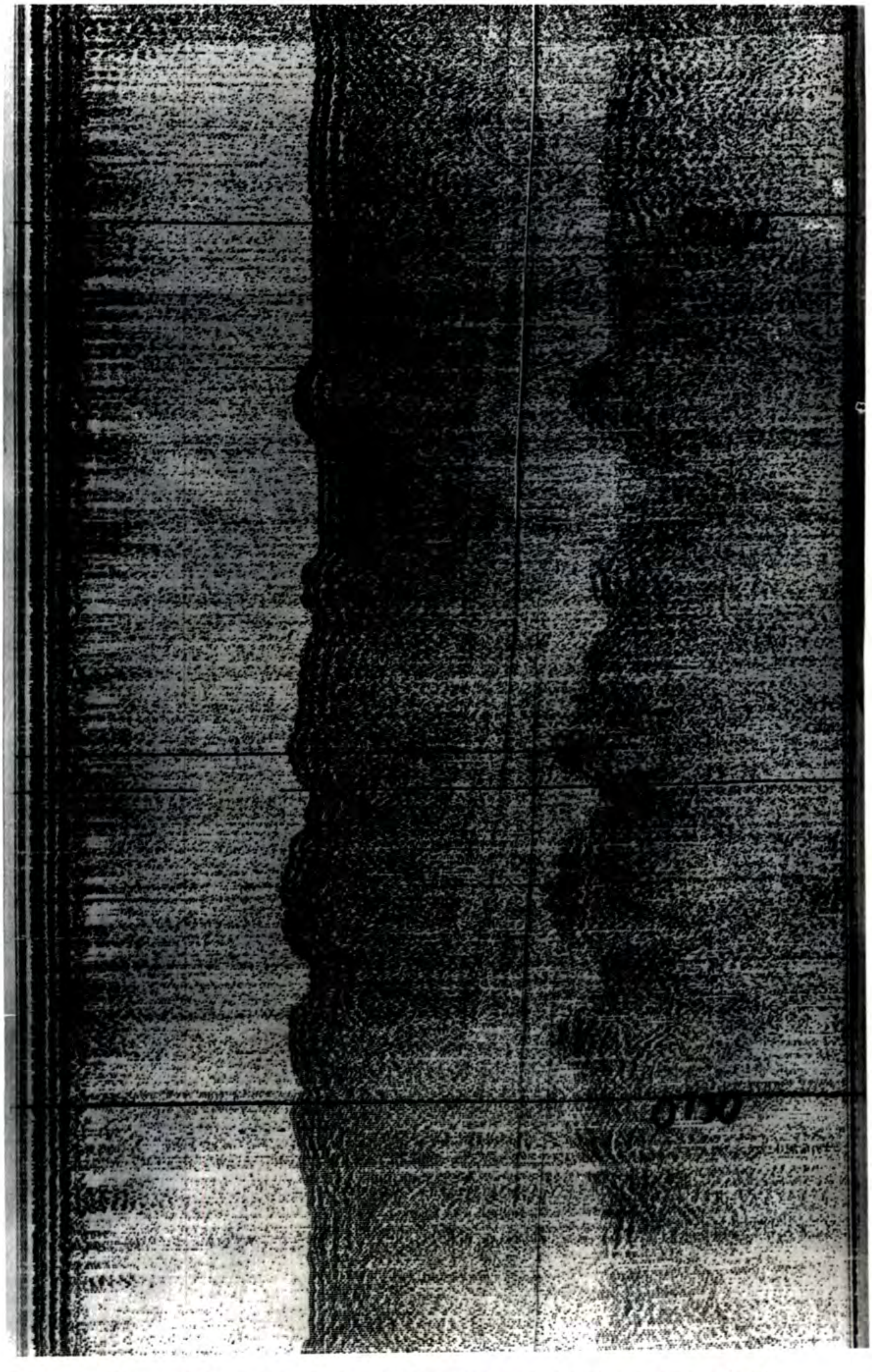


Figure 44. Seismic reflection record from Line 1/970 showing the irregular basement on the Hebridean shelf. 10 min markers horizontally. 0.5 sec full scale vertically.

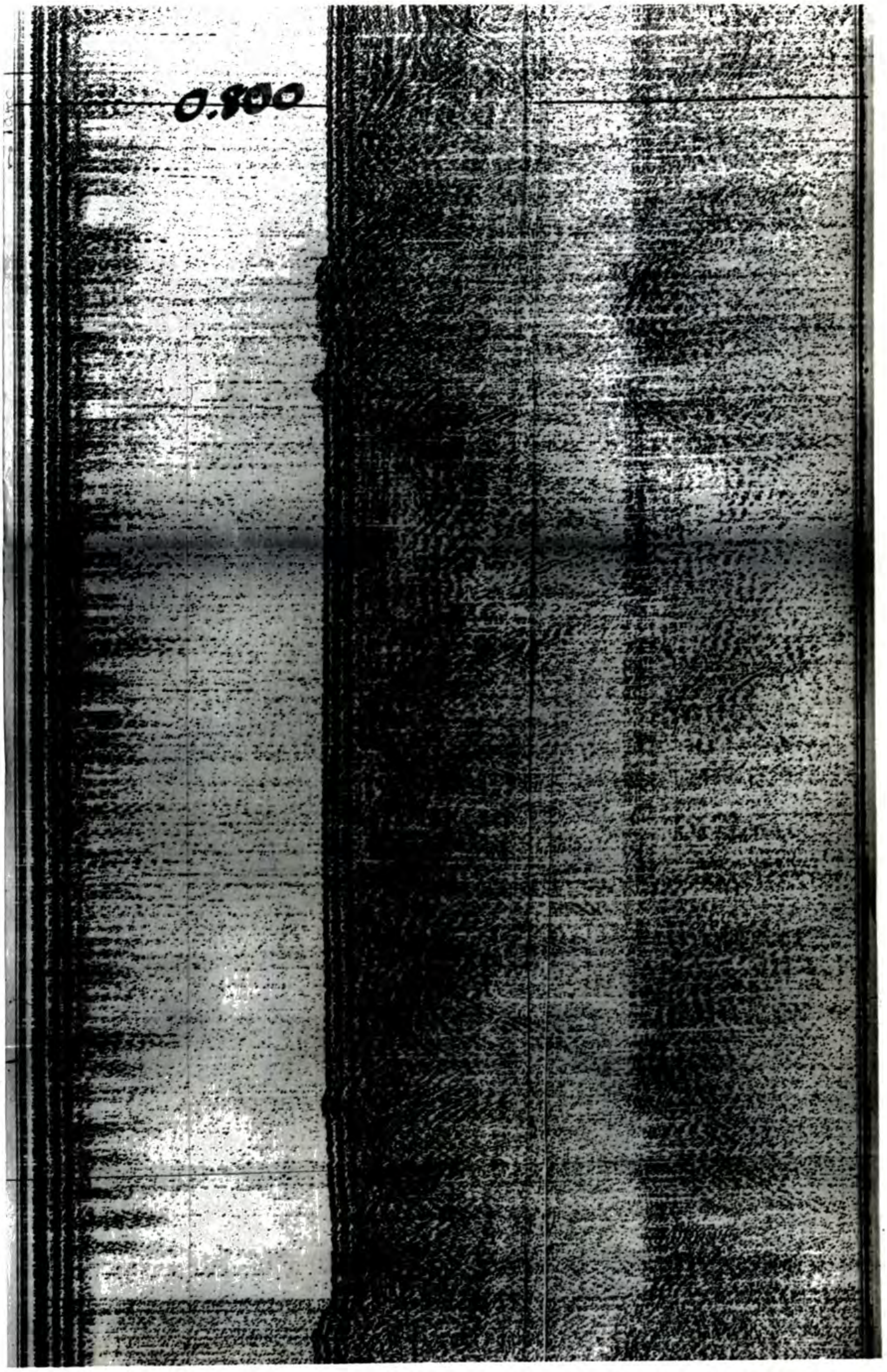


Figure 45. Seismic reflection record from Line 1/970 showing the sediment covered irregular basement on the Hebridean shelf. 10 min markers horiz. 100 m sec markers vert.

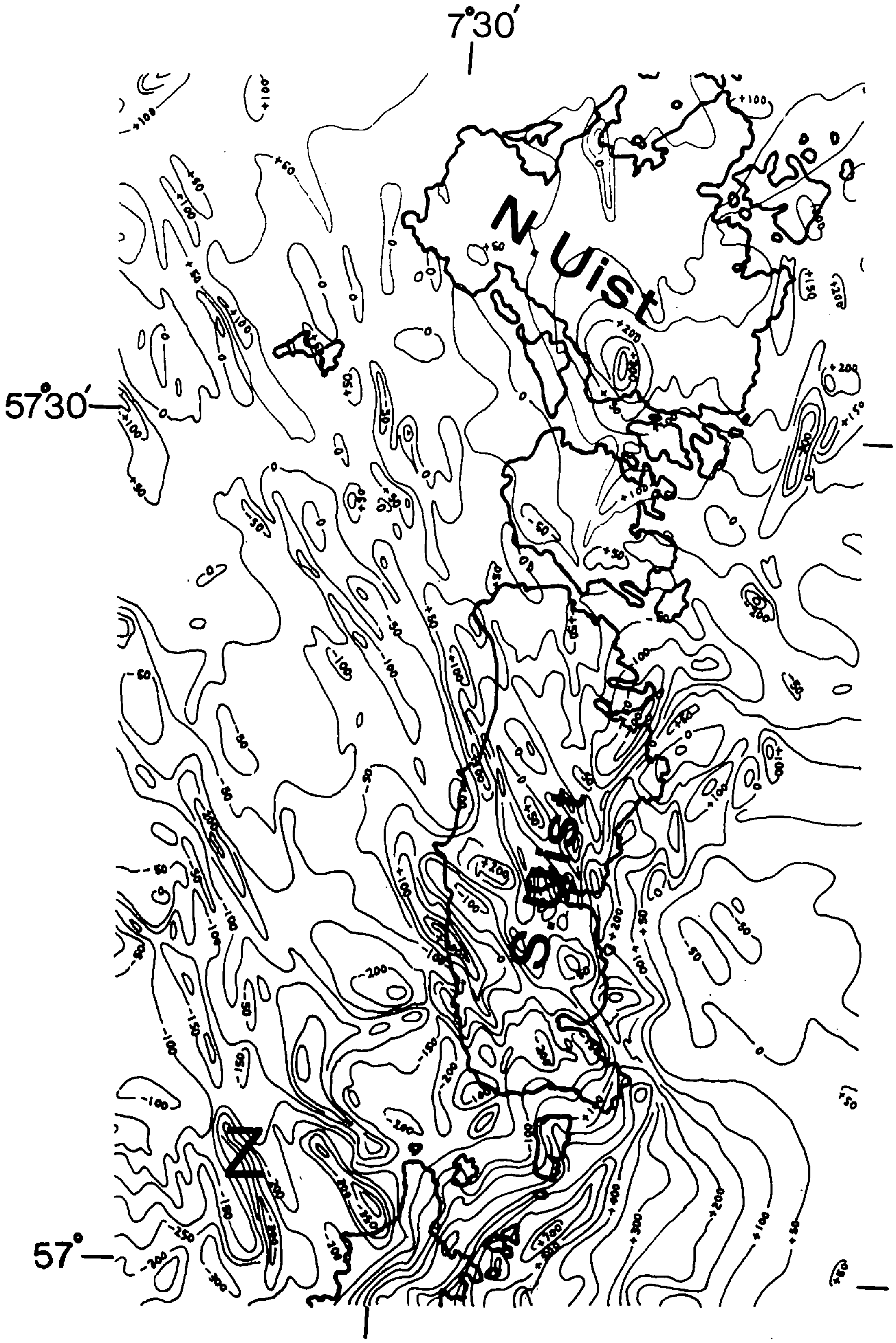


Figure 46. Aeromagnetic map of part of the southern Hebridean region.

Z : NNW-SSE trending anomalies found on Line 1/970.

### 6.2.2. Lines 3/970, 24/71, 25/71 and 26/71 (central area)

The gravity map over this area is dominated by two large gravity 'highs' (Figs. 39 & 40). One of these has a free-air anomaly peak of about 135 mgal above a regional value of about 55 mgal and is caused by the St. Kilda intrusive complex. The other high lies over the continental slope to the northwest of St. Kilda. It has a free-air anomaly peak value of about 130 mgal over a regional value of about 30 mgal. This is probably also caused by an intrusive complex. The two anomalies are interpreted in Section 6.3.

The bathymetric and sparker profiles on the Lines (Figs. 42 & 48) show that most of the central area is underlain by a rough basement similar to that found further south. The probable western extent of the basement, marked on Fig.42, has been estimated from the sparker and air gun profiles. The position correlates well with that found by Stride et al. (1969) on their reflection profile. The sedimentary cover is either thin (less than 100m) or absent over most of the area. Even on a regional scale the basement is not flat. Ridges, which can be seen in the bathymetry (Fig.48), are present. These rise to depths of about 60 m whereas the troughs, which are partially sediment filled, have depths of about 90 - 100m. The basement floor beneath one of the troughs is lost on the sparker profile (near the east end of Line 24/71, Figs. 42 & 48). The gravity on this part of the Line is not available because of equipment failure. A sedimentary trough of appreciable depth may underlie this part of the shelf. The aeromagnetic map (I.G.S. 1968, Fig.47) shows that the trough lies at the southwestern end of an area of relatively low (less than 100 gamma) magnetic anomalies which may be associated with a major sedimentary basin. This is discussed in Section 6.2.3.

To the west of this trough, on Line 24/71, a rise in the seabed of about 40 m to a depth of 60 m is associated with a rough part of the

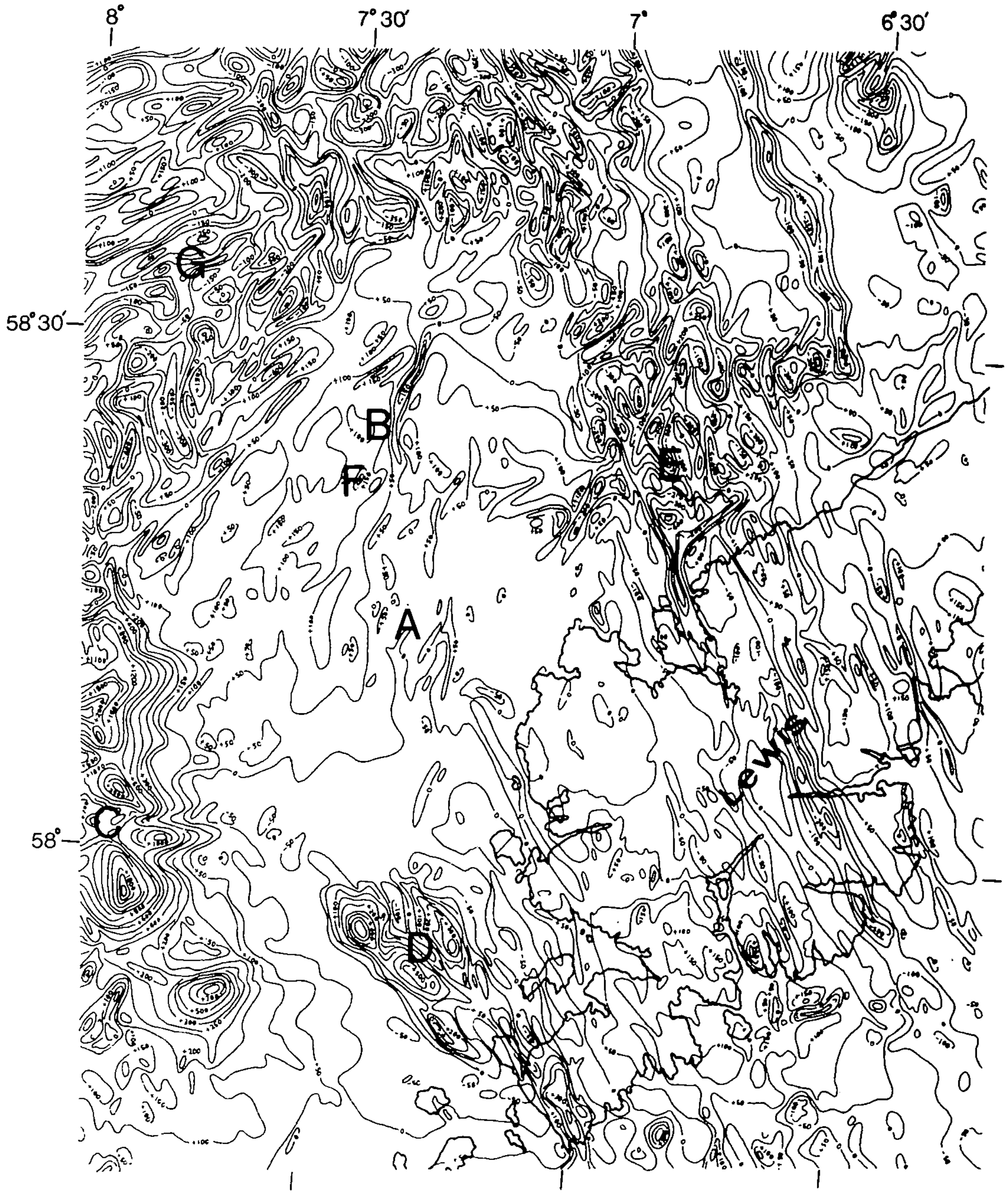


Figure 47. Aeromagnetic map of part of the northern Hebridean region.

A : Area of low magnetic anomalies.

B : Magnetic anomalies associated with postulated basement ridge.

C : High magnetic anomalies found on Line 24/71.

D : South Harris Lewisian igneous complex.

E : High anomalies over postulated sedimentary basin.

F : Flannan Isles. G : NNE-SSW trending anomalies.

seabed and large magnetic anomalies of about 2,500 gamma peak to peak amplitude (Fig.48). The correlation of the magnetic anomalies with the basement rise is similar to that found above the St. Kilda intrusive complex. The bathymetric rise is, however, shown by the Admiralty chart (Fig.49) to have a northeast to southwest trend which is not compatible with an igneous intrusive centre since these are usually radially symmetric (Bott and Tuson 1973, McQuillin et al.1973). The gravity profile here is unreliable, since engine trouble caused alterations in the ship's speed which affects the Eötvös correction, but a careful study of the records indicates that there is no large gravity anomaly associated with the feature. The magnetic anomalies are unlike the anomalies over the St. Kilda complex in that they are largely positive instead of being both positive and negative. The anomalies are more similar, in this respect, to the South Harris magnetic anomaly (Fig.47) which is caused by the meta-gabbros of the Lewisian igneous complex (Westbrook - in press, Powell 1970). The aeromagnetic map (I.G.S. 1968) shows that the anomalies are a series of approximately circular magnetic highs with little directional trend. The feature is unlikely to be a further intrusive centre and is probably a basement rise. The bathymetry of the area shows that it may be connected with a similar rise forming the Flannan Isles (Fig.49). This possibility is further considered in Section 6.2.3.

To the west of the basement high, on Line 24/71, but to the east of the break in slope, a gravity low of about 10 mgal is present (Fig.49). The air gun reflection profile is indistinct in this region and the basement cannot be seen beneath the overlying sediment. A sedimentary basin may be present but the depth of it is unlikely to exceed about 0.75 km.

The magnetic profiles on the other lines in the central area show mainly medium amplitude (about 200 gamma) anomalies with wavelengths

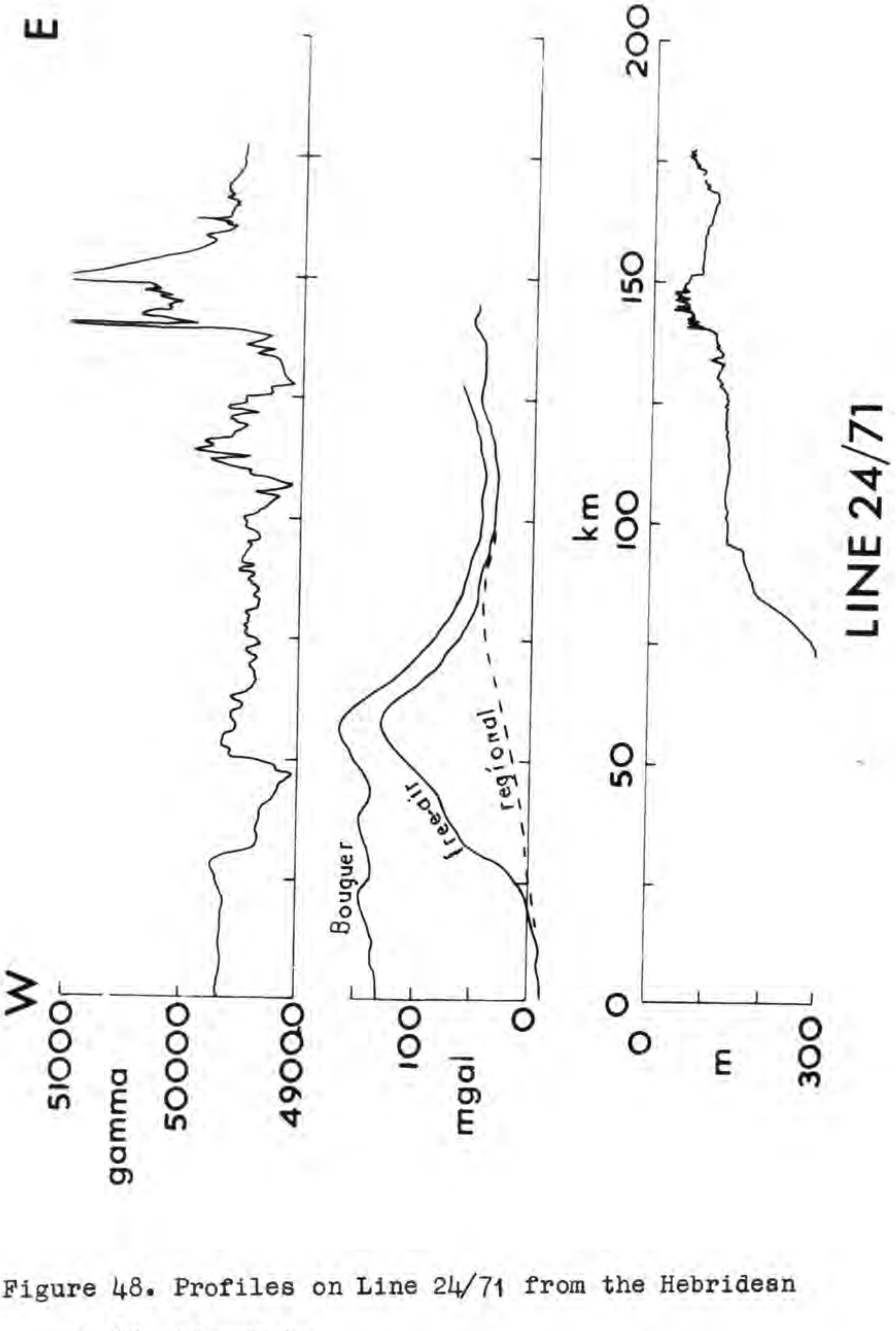


Figure 48. Profiles on Line 24/71 from the Hebridean shelf and margin.

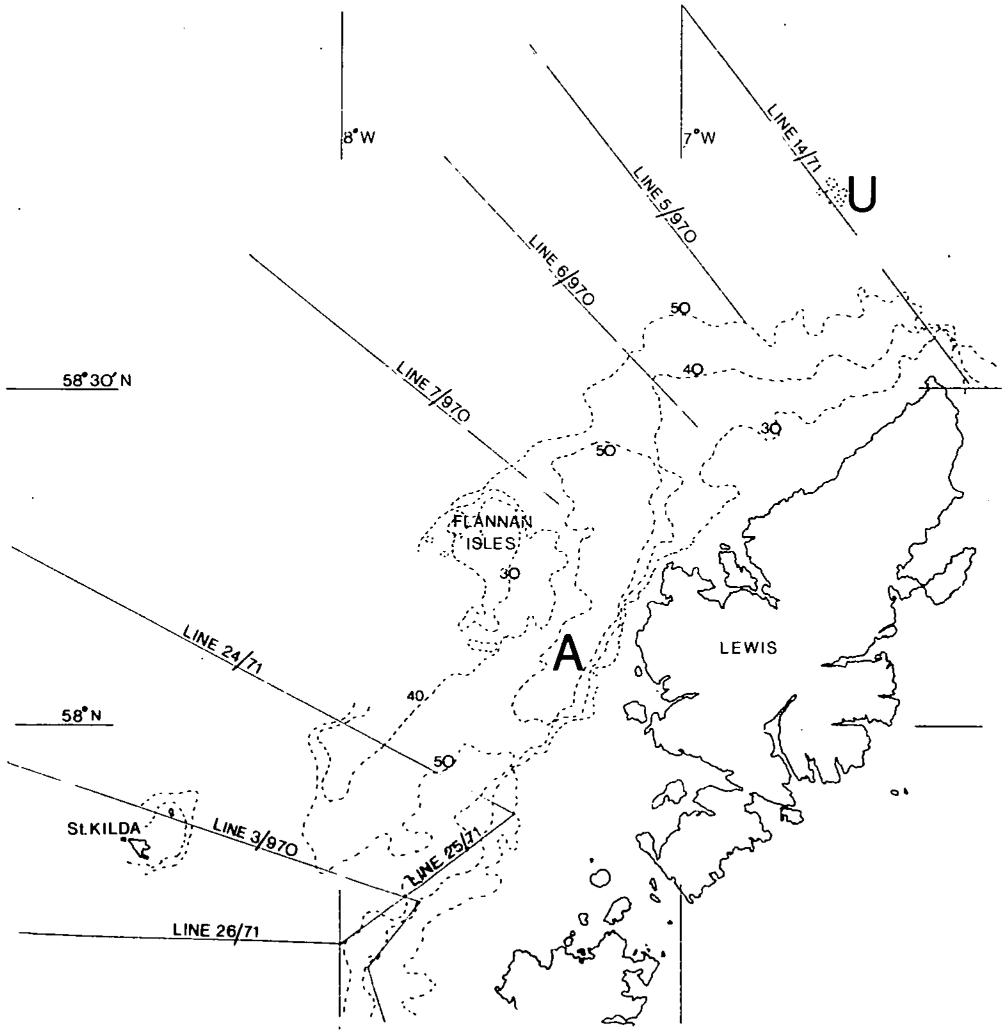


Figure 49. Bathymetry of part of the Hebridean shelf. (taken from the Admiralty chart).

of about 5 km which are probably caused by an underlying Lewisian basement.

### 6.2.3. Lines 14/71, 5/970, 6/970 and 7/970 (the northern area)

An elongated, northeast to southwest trending, gravity low lies to the west of Lewis (Figs. 39 & 40). This lies over a depression in the seabed which Eden et al. (1971) suggested may be underlain by a Mesozoic basin. The southwestern limit of the low is not defined but the admiralty chart (Fig.49) shows that the depression in the seabed continues to the southwest as far as the depression near the eastern end of Line 24/71 (Fig.48). To the west of the postulated basin, basement outcrops appear through the sediments on Lines 6/970 and 7/970 (Fig.42). A basement ridge probably connects these outcrops and the outcrops of the Flannan Isles. The bathymetry indicates that the ridge may be continuous with that found to the west of the sedimentary trough on Line 24/71 (Figs. 48 & 49). Magnetic anomalies of greater than 1000 gamma peak to peak amplitude occur over the ridge on Line 6/970 (Fig.50). These are similar in wavelength and amplitude to those over the ridge on Line 24/71. The aeromagnetic map (Fig.47, I.G.S.1968) shows anomalies of about 150 gamma peak to peak amplitude running parallel to the ridge except at the northeast and southwest ends. The Flannan Isles consist of hornblende-gneiss alternating with veins of pegmatite (Stewart 1933). They are presumably Lewisian in age and the whole of the basement ridge is probably composed of similar material. No indication as to the age of the sediments in the postulated basin can be drawn from the present data. By analogy with similar basins on the shelf further north (Watts 1971), the suggestion of Eden et al.(1971) that they are Mesozoic is reasonable. There may also be some Palaeozoic sediments present as has been postulated in one of the northerly basins (Browitt 1972). The gravity profile on Line 7/970 has been used to estimate the depth of the basin (Fig.51). The Line only crosses one side of the basin and may not

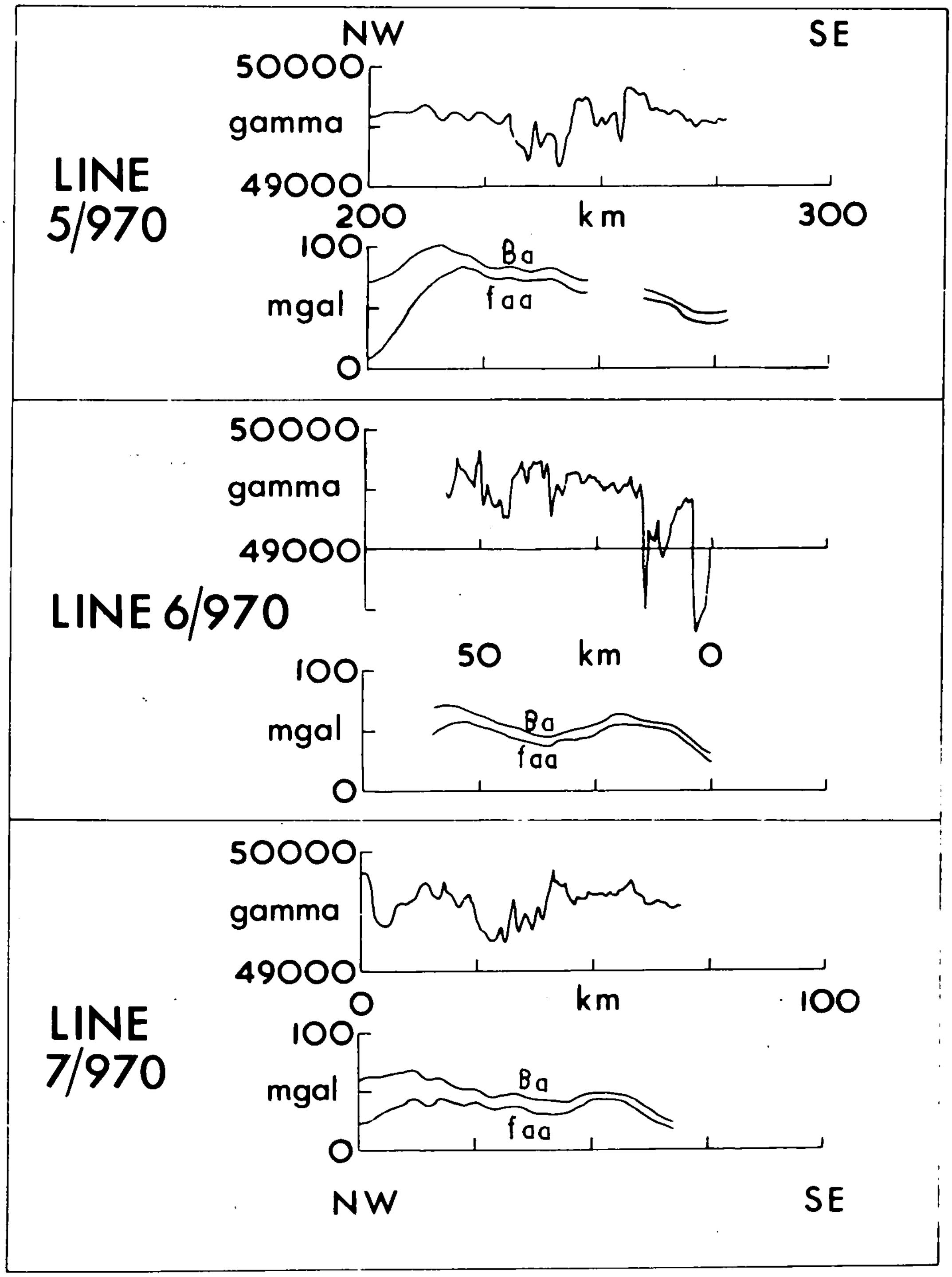


Figure 50. Profiles on Lines 5/970, 6/970 and 7/970 from the Hebridean shelf.

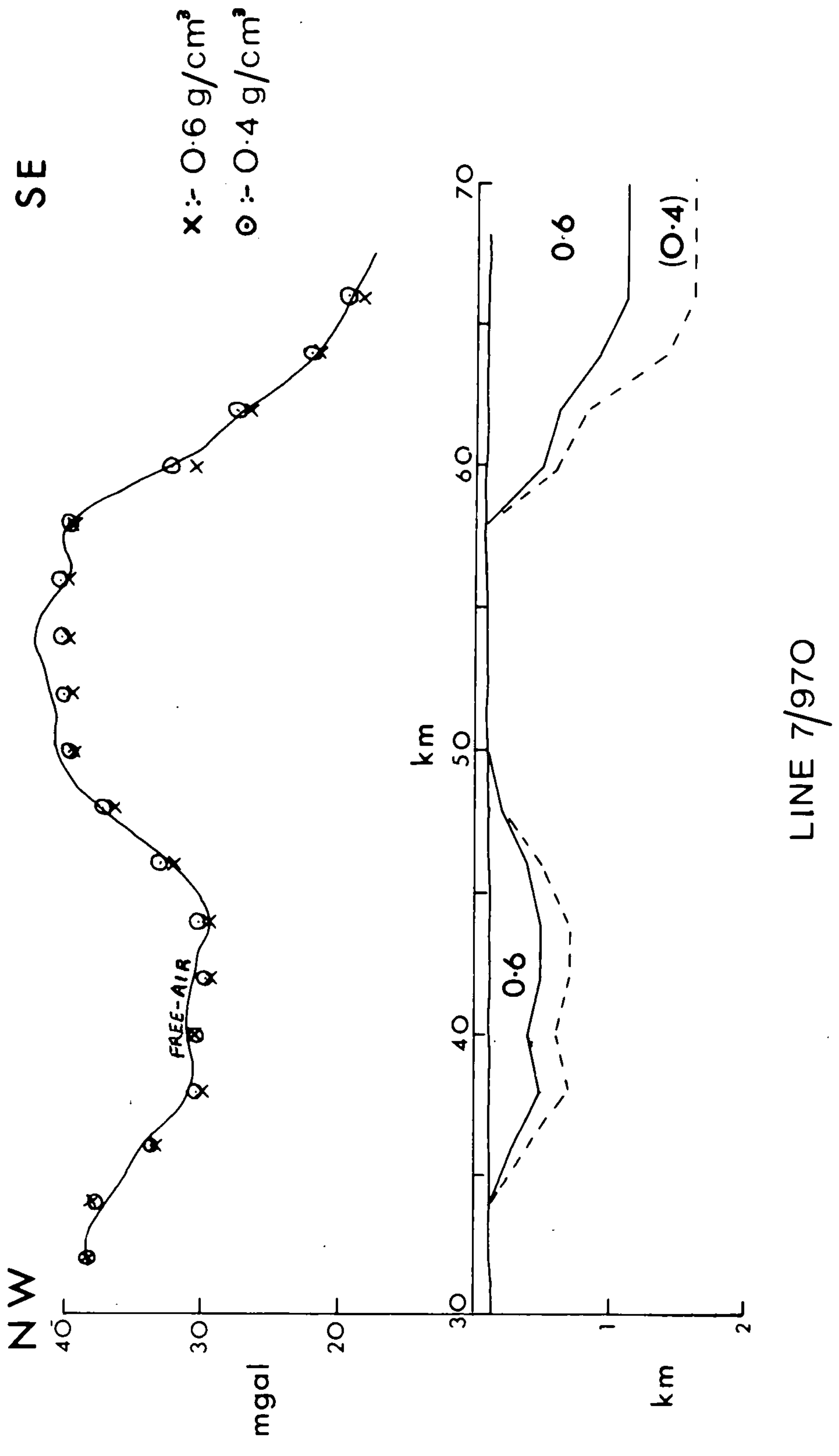


Figure 51. Gravity interpretation of part of Line 7/970 on the Hebridean margin.

have reached the gravity minimum. The estimates of the depth for the two density contrasts used, 0.4 and 0.6 g/cm$^3$, are therefore minimum estimates. The calculated depths are 1.6 and 1.1 km respectively. The regional anomaly was assumed to be equal to the anomaly over the basement ridge. The overall gradient of the contact between the basement and the sediment is about 1 in 5 which indicated that it may be composed of a series of normal faults. The aeromagnetic map (Fig.47) shows a loss of any distinctive trend in the anomalies and a fall in the amplitudes to about 50 gamma between the ridge and most of the basin. This substantiates the theory that the magnetic basement drops down to a greater depth. Over the northeast end of the basin, where the gravity indicates a rise in the basement, dominantly negative magnetic anomalies of up to 600 gamma amplitude cross the basin with a distinctive north-northwest to south-southeast trend. These are a continuation in trend of similar anomalies on Lewis (Fig.47) but they are of greater amplitude than those on the land. Over Lewis there is no correlation between the dominant structural trends and the magnetic anomalies (Figs. 47 & 42). The magnetic anomalies are, however, parallel to the Tertiary dykes found in the area (Jehu and Craig 1923). The anomalies over Lewis are therefore probably not related to lateral changes in the magnetic properties of the Lewisian but to the Tertiary basic intrusives. Since the magnitude of the anomalies increases over a postulated deepening of the basement, changes in the magnetic properties of the basement are an even more unlikely explanation of the anomalies. Tertiary igneous rock is probably present in the sedimentary basin. The increase in the intensity of the anomalies over the basin could be caused by the presence of plateau lavas in the basin whereas only dykes are present on Lewis. The plateau lavas may have, at one time, covered the land but have since been eroded. Tertiary lavas, with a similar magnetic expression, are present southwest of Skye covering part of the Sea of the Hebrides Trough which is another Mesozoic basin (McQuillin and Binns 1973).

To the northwest of the Flannan Isles, a second gravity low is seen on Line 7/970 (Fig.51). The aeromagnetic map shows a narrow area of relatively low-amplitude anomalies similar to those over the previous gravity low running from this point to the south-southwest for a distance of about 25 km. Another basin may underlie this area but more gravity data is required to confirm this. The interpretation on Line 7/970 indicates that about 0.5 km of sediment are present.

On Line 14/71, a gravity anomaly of about 20 mgal above a regional of about 60 mgal correlates well with a rise in the seabed of about 40 m at 58°47' N, 6°33'W. The feature has a bumpy surface and the Admiralty chart shows it to be approximately circular (Fig.49). Short wavelength magnetic anomalies are present above the feature. These characteristics may be indicative of another intrusive centre. This is considered in Section 6.3.3.

Over the remainder of the shelf west of the Outer Hebrides, the gravity appears to be fairly constant apart from near the continental margin where regional effects caused by major changes in crustal thickness are present. The aeromagnetic map over the area (I.G.S. 1968, Fig.47) is dominated by anomalies of up to 500 gamma peak to peak amplitude which are similar in both trend and wavelength to those over the Lewisian of Islay, Coll and Tiree, the area southeast of Barra and Mingulay and a small area 64 km north of Cape Wrath (Powell 1970). The trend in these areas may be partly related to basement relief and partly to lateral changes of magnetisation in the basement. The orientation of the trend suggests that a Caledonian control has had some influence. A similar situation may exist in the present area although the increased distance from the Caledonian front makes this unlikely.

Although seismic profiling was carried out along Lines 5/970, 6/970 and 7/970 an air gun energy source was being used and there is a lack of resolution on the profiles. The line marking the basement edge on Fig.42 passes through the positions on the profiles where a thickness of sediment can first be recognised. Magnetic power spectrum analysis on Lines 5/970, 6/970 and 7/970 indicates that the magnetic basement lies at a depth beneath the seabed of between 0.6 and 1.2 km. The bathymetric profiles show no basement outcrops over all this area. The area appears to consist of a Lewisian basement covered by sediment of up to slightly over one kilometre in thickness.

## 6.3. The intrusive centres

### 6.3.1. The St. Kilda intrusive complex

The position and extent of the St. Kilda intrusive complex, in an east-west direction, is clearly defined by the gravity, magnetic and bathymetric profiles along Line 3/970 (Fig.52). The admiralty bathymetric chart of the area (Fig.49) shows that the intrusion is approximately circular at the surface and, as suggested by Cockburn (1935), has its centre between St. Kilda and the adjacent island Boreray. Line 3/970 passes between these two islands and therefore probably crosses quite close to the centre of the intrusive area. The profile shows that the magnetic anomalies associated with the complex extend beyond the gravity anomaly to the west.

An interpretation of the gravity anomaly over the St. Kilda complex, assuming a two-dimensional body, has been carried out (Fig. 14). The density contrast between the intrusives and the country rock was taken to be 0.25 g/cm$^3$ above 8 km depth and 0.2 g/cm$^3$ below this depth. This contrast was estimated using the following information. Bott et al.(1972) determined the densities of the biotite-gneiss and the pyroxene-granulite, found in the Lewisian of northwest Sutherland, both by experiment, using a small number of surface samples, and by calculation which involved considering the weight percentages of the various major oxides in the samples. The experimentally determined values were 2.689 ± 0.016 g/cm$^3$ and 2.764 ± 0.021 g/cm$^3$ respectively but they considered that these

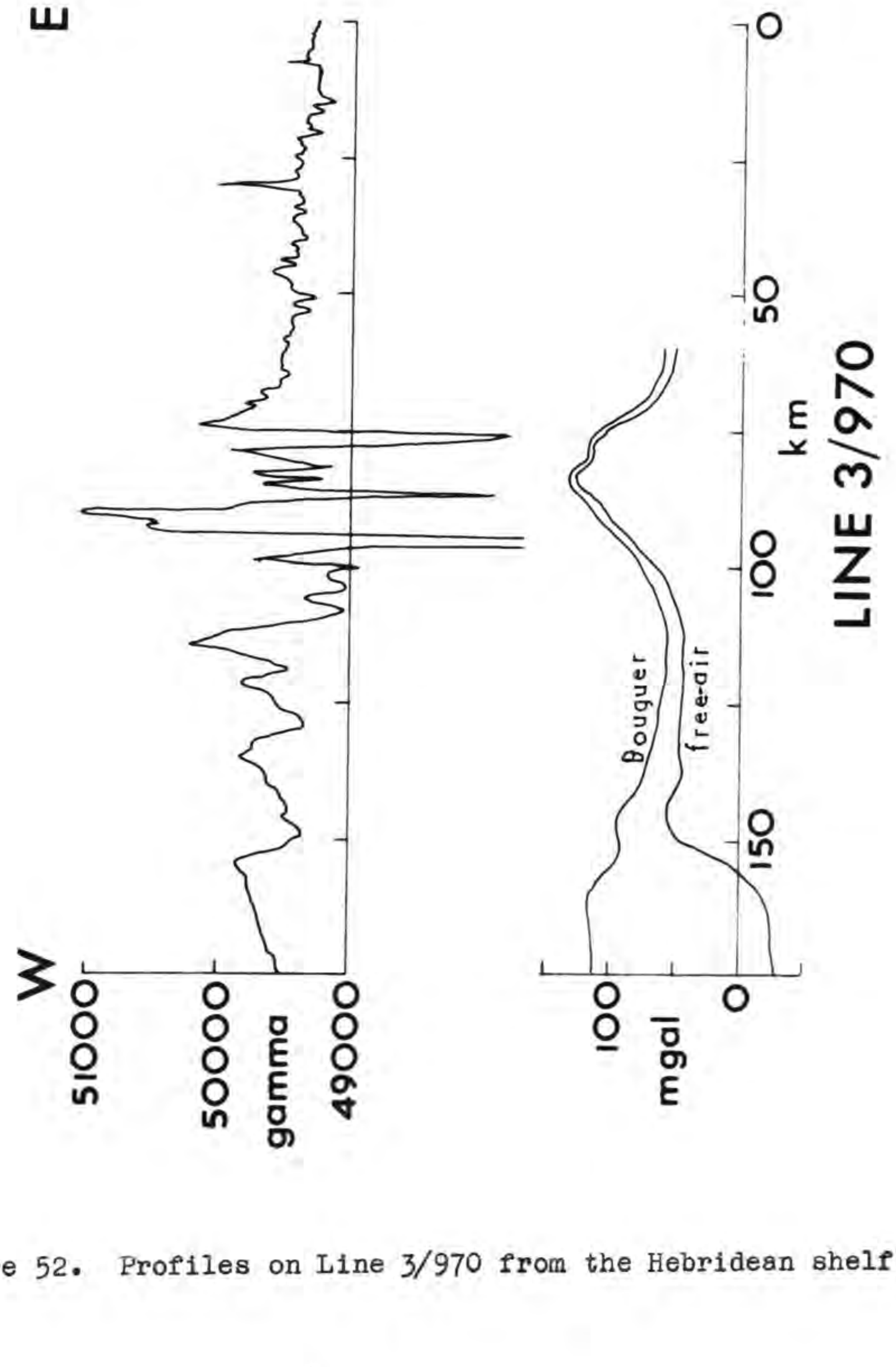


Figure 52. Profiles on Line 3/970 from the Hebridean shelf.

were probably inaccurate because of the small number of samples used. The calculated estimates were 2.69 $g/cm^3$ and 2.80 $g/cm^3$. The exact nature of the country rock surrounding the complex is not known but it has been shown (Section 6.2.3.) that the Lewisian probably extends to the continental margin. The country rock density is therefore likely to be between 2.69 and 2.80 $g/cm^3$.

Although the majority of the surface of the intrusive complex is under water, outcrops occur on St. Kilda and the adjacent islands (Cockburn 1935). The main intrusive body on St. Kilda, which is also the oldest, is composed of olivine-eucrite. More acid gabbros, some of which are almost olivine-free, are also common. These often have a high iron-oxide content which increases their densities. Dolerites and basalts, both olivine-rich and olivine-free, occur in sheets. Granophyres, lying in pockets within the eucrites, form the latest intrusions apart from some basalt dykes and cone sheets. The relative abundance of magnetite in most of the rock types explains the high magnetic anomalies measured over the complex.

The average density of five specimens of the olivine-eucrite is about 2.92 $g/cm^3$ but the more acid varieties have densities between 2.92 and 3.04 $g/cm^3$ because of their higher iron oxide content (Cockburn 1935). Ultra-basic segregations of augite and magnetite up to five feet in diameter and being 30% to 40% magnetite have densities as high as 3.71 $g/cm^3$. The various dolerites have average densities between 2.86 and 2.93 $g/cm^3$. The density of the granophyre bodies on St. Kilda is fairly constant and lies between 2.57 and 2.60 $g/cm^3$. The great variation in the densities of the rocks and their unknown relative abundance makes an estimation of the overall density rather difficult. The major unknown is the quantity of granophyre present. The average density, apart from the granophyre, is probably between 2.92 and 3.0 $g/cm^3$.

An assumed average of about 2.96 g/cm$^3$ agrees well with the mean density of the Skye basic intrusive rocks calculated experimentally and theoretically to be 2.95 g/cm$^3$ (Bott and Tuson - in press). Apart from the small segregations in the eucrite there appears to be no outcrop of ultra-basic material in the complex. Since ultra-basics are commonly found in the other Tertiary complexes on the mainland (Stewart 1965), this absence is probably due to their non-exposure in the complex rather than their absence. Bott and Tuson (in press) estimated an average value of 3.20 g/cm$^3$ for the ultra-basics on Skye and Rhum from various measured values.

Since the rock types underlying the profile are unknown, no attempt has been made in the interpretation to represent any less dense acid rocks in the model. This may affect the calculated shape and depth of the intrusion slightly. The lack of any information as to the relative abundance of basic and ultra-basic material has made it necessary to adopt a uniform density contrast with the country rock. If the assumed contrast is too low the calculated depth to the base of the body will be too large, whereas, if it is too high the depth will be too small.

The depth of the base of the body, in the two-dimensional interpretation, is 11 km. A three-dimensional interpretation is shown in Fig.53. This was carried out using the method described in Section 3.2.(1). and it was assumed that the profile crossed the centre of the body. A density contrast of 0.25 g/cm$^3$ was used. The base of the body is, in this case, at 21.5 km depth. This is slightly deeper than the values calculated by Bott and Tuson (1973) for the Skye and Mull intrusions but it is less than the value calculated for the Blackstone igneous centre (McQuillin et al.1973). The magnetic anomaly over the intrusion is complicated both on the profile and on the aeromagnetic map. A quantitative interpretation has not been attempted but the aeromagnetic map shows that the anomalies are mainly negative. This

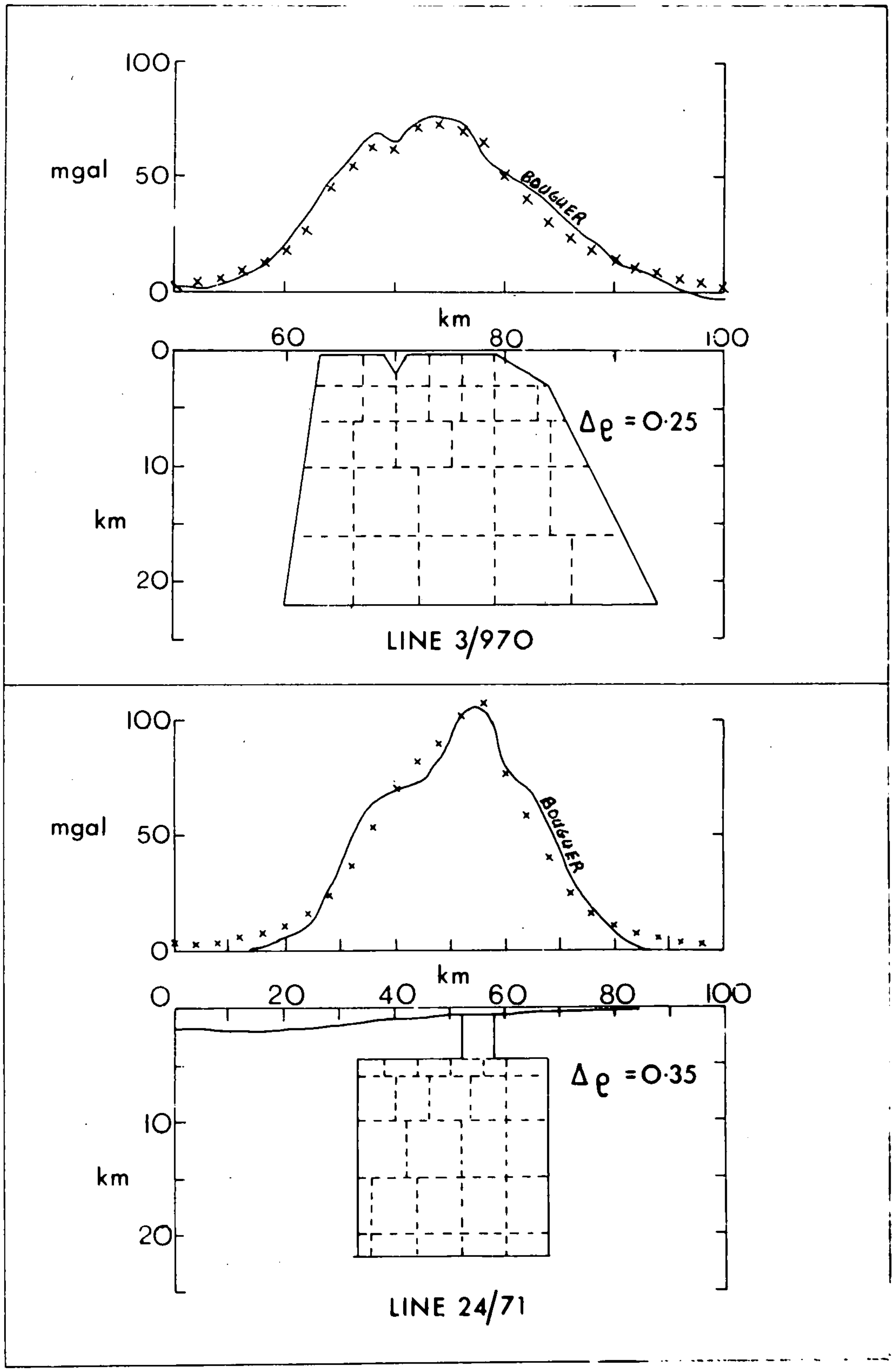


Figure 53. 3-D gravity interpretations of two intrusive complexes on the Hebridean shelf and margin.

indicates that the intrusive rock is largely reversely magnetised with respect to the Earth's present magnetic field which is a similar situation to that described for Rosemary Bank (Scrutton 1971). The Skye Tertiary lavas and the Blackstone igneous centre are also reversely magnetised (Wilson et al.1972, McQuillin et al.1973). The large magnetic anomalies to the west of the intrusion may indicate that there is an area of intrusive or extrusive basic rock associated with the major intrusion.

The St. Kilda intrusive complex appears to be similar to the Skye and Mull centres both in size and magnetic properties. It extends to a depth close to the base of the crust as does the Blackstone centre. There is some evidence that a dyke swarm or plateau lavas may be associated with the centre as there is with the other centres in northwest Scotland. The age of the intrusives ranges from about 60 to 35 m yr (Miller and Mohr 1965) which indicates that they are part of the Tertiary igneous province which is dated at about 60 m yr (Miller and Brown 1965). There is therefore good evidence that the St. Kilda intrusive complex is another typical centre belonging to the Tertiary igneous province.

### 6.3.2. The intrusive complex at $58^{\circ}20'$ N, $9^{\circ}15'$W.

This centre is recognised by the gravity 'high', with a free-air peak of about 130 mgal, and the magnetic 'low' of about 600 gamma on Line 24/71 (Fig.48). The anomalies lie over the continental slope where the depth of water increases from 150 m to 1.9 km. The intrusive rock may also be recognisable on the reflection profile (Section 4.1.2.).

A gravity interpretation of the centre is shown in Fig.53. The selection of a suitable regional gravity field is complicated by the presence of sediments draping the continental margin and the probable rise of the Moho beneath the crust. The increase in depth of the water and the gradient of the slope are similar to those beneath Line 1/970 therefore the gravity anomaly, measured over the margin on that Line, has been used as a basis for the regional field on Line 24/71 (Fig.48). This gave the anomaly a maximum value of 106 mgal above the regional. No geological information on the composition of the rocks forming the centre is available. A density contrast of 0.25 g/cm$^3$ was assumed initially but it was not possible to reproduce an anomaly of sufficient amplitude and with sufficiently steep gradients. A density contrast of 0.35 g/cm$^3$ was therefore used. Assuming a country rock density of 2.80 g/cm$^3$ the average density of the intrusives was therefore assumed to be 3.15 g/cm$^3$. This is equivalent to a mixture of 80% ultrabasics and 20% basics assuming average densities of the two as calculated by Bott and Tuson (in press) of 3.20 g/cm$^3$ and 2.95 g/cm$^3$ respectively.

The calculated model is a vertical cylinder of 22 km diameter with a small cylinder of diameter 6 km on top. The main cylinder has its base at a depth of 22 km, which is near the base of the crust, and its top at a depth of 4.5 km. Although the gravity fit is not particularly good and variations in the density and shape of the model are possible, the base of the model must be at approximately this depth since such a high density contrast has been used in the present model.

The magnetic anomalies over the body are dominantly negative and the intrusive rock is therefore reversely magnetised.

### 6.3.3. The intrusive complex at 58°47'N, 6°33'W

A gravity anomaly of 22 mgal above a free-air regional of 50 mgal and magnetic anomalies of up to 1200 gamma peak to peak amplitude are present on Line 14/71 over this centre (Figs. 41 & 15). The bathymetry rises from a smooth sediment-covered bottom at a depth of about 120 m to a rough bottom at 100 m depth. The Admiralty chart (Fig.49) shows an approximately circular shallow area with a minimum depth of about 45 m. Line 14/71 does not cross the feature centrally therefore the measured gravity anomaly is probably not the maximum over the complex. A two-dimensional interpretation of the gravity anomaly (Fig.15) shows a body, with a density contrast of 0.25 $g/cm^3$, of about 5 km width extending down to a depth of 5 km. These dimensions are minima since the profile was probably offset from the centre of the body. A three-dimensional interpretation would increase this depth by one or two kilometres. The body is therefore probably smaller than the St. Kilda intrusive complex and may be of similar size to the Ardnamurchan complex (Bott and Tuson 1973). The magnetic anomaly over the body is almost entirely negative indicating that the intrusive rocks are reversely magnetised with respect to the present Earth's field.

## 6.4. Summary

Magnetic evidence indicates that the southern Hebridean continental margin is probably underlain by Lewisian basement. Gravity and reflection profile evidence shows that there is no continuation, north of 57°N, of the Outer Hebrides Basin. Gravity profiles indicate that west of Lewis and Harris a Lewisian basement ridge lying in a north-northeast to south-southwest direction and including the Flannan Isles, is flanked on its eastern side by a fault-bounded basin. The basin is between 1.0 and 1.7 km deep and probably contains Mesozoic and perhaps Palaeozoic sediments. To the west of the Lewisian ridge a shallower basin may be present. The underlying basement is probably Lewisian with variable magnetic properties.

Gravity and magnetic evidence shows that three basic and ultrabasic centres are present under the shelf and the margin. The St. Kilda centre is Tertiary in age and gravity interpretation indicates that it extends to a depth of about 21 km, the exact value depending on the proportions of basics and ultrabasics present. Beneath the continental slope to the northwest of St. Kilda another centre probably extends to a slightly greater depth and has a density which indicates that ultrabasics are present in greater abundance than basic rocks.

# CHAPTER 7

# SUMMARY AND DISCUSSION

## 7.1. Introduction

The present knowledge of the structure of the northeast margin of the Atlantic is summarised in the first part of this chapter. Possible dates for the various major events in the region are then considered and finally brought together to give a suggested history for the region.

## 7.2. The west Scottish continental shelf

### 7.2.1. The basement and sedimentary basins

Magnetic and seismic profiling evidence indicates that the continental shelf west of the Outer Hebrides is largely underlain by Lewisian basement (Chapter 6) in common with most of the previously investigated continental shelf off northwest Scotland (Watts 1971, Flinn 1969, McQuillin and Binns 1973). Gravity interpretation indicates that a sedimentary basin about 1.5 km deep and probably with fault-bounded margins is present between Lewis and the Flannan Isles (Fig.54, Section 6.2.3). The southwestern limit of the basin is not defined by the gravity profiles but the bathymetry may be indicative of the extent of the basin. The basin has a Caledonian trend as do the other fault-bounded basins elsewhere on the shelf (Watts 1971, McQuillin and Binns 1973, Smythe et al. 1972). There is no direct evidence of the age of the sediments in the basin but, by analogy with the other shelf basins, they are probably Mesozoic and Palaeozoic in age. Bathymetric and gravity evidence indicates that the Flannan Isles lie on a north-northeast to south-southwest trending basement ridge (Fig.54) which is flanked to the east by the basin already described and to the west by a smaller, shallower basin which gravity interpretation indicates is about 0.5 km deep. The remainder of the shelf to the north and northwest of this westerly basin probably has a relatively thin cover of sediments which may be Tertiary-Quaternary in age. The basement of the continental

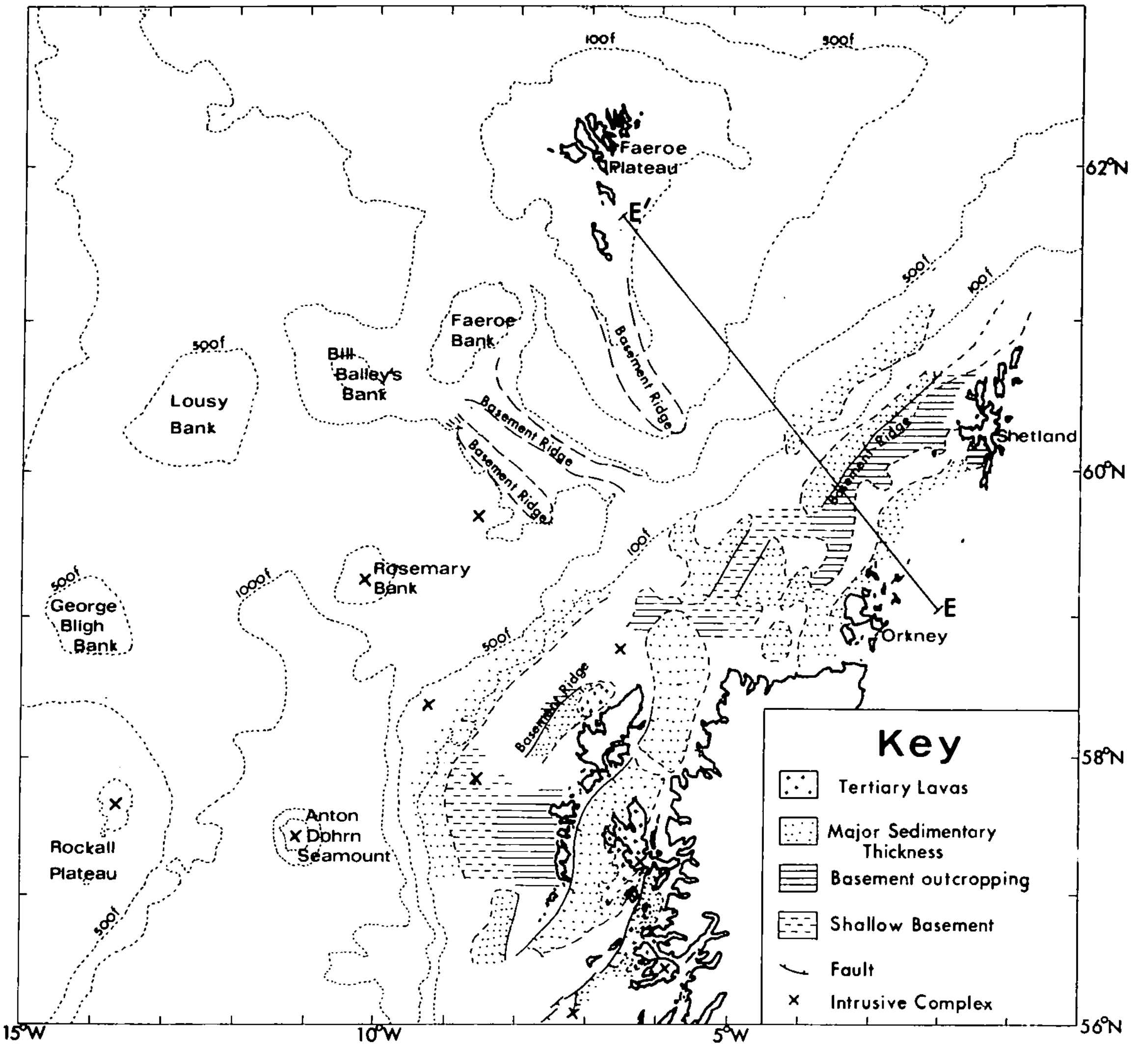


Figure 54. Summary map of the shelf region of northwest Scotland and the intrusive complexes in the northeast Atlantic.

Line E-E' is from Bott and Watts 1971. The interpretation is shown on Fig. 57.

shelf between $57^{o}48'$N and $57^{o}$N is almost devoid of sedimentary cover from the Outer Hebrides to about $8^{o}20'$ W. West of this longitude the basement is covered by a thin layer of sediment which gradually thickens towards the continental margin (Section 6.2.1).

The continental shelf west of the Outer Hebrides is therefore similar to the rest of the continental shelf to the northwest of Scotland.

### 7.2.2. Tertiary vulcanism on the shelf

Geological, gravitational and magnetic evidence indicates that the Tertiary igneous activity in the British Isles extended to the margin and slope of the Scottish continental shelf. Three intrusive complexes west and northwest of the Outer Hebrides have been investigated. These lie beneath St. Kilda, beneath the continental slope northwest of St. Kilda ($58^{o}20'$N, $9^{o}15'$W) and beneath the shelf 40 km north-northwest of the Butt of Lewis ($50^{o}47'$N, $6^{o}33'$W)(Fig.54). All three complexes are similar in size to the complexes described elsewhere in northwest Scotland and on the continental shelf (Bott and Tuson 1973, McQuillin et al.1973) and all exhibit reversed remanent magnetisation in common with the other Tertiary complexes and lavas (McQuillin et al.1973, Wilson et al.1972). There is magnetic evidence that basaltic plateau lavas and perhaps dykes cover and lie in the northeastern part of the sedimentary basin between the Flannan Isles and the Outer Hebrides (Section 6.2.3).

All this Tertiary igneous activity lies in the broad linear region over which similar activity has previously been found in Britain and on the British continental shelf (Fig.54).

## 7.3. The Rockall Trough

Although no seismic refraction experiment has conclusively determined the Moho depth beneath the Rockall Trough, the gravity, magnetic and seismic reflection interpretation shows that the Trough is probably underlain by standard oceanic crust from about $58^{o}$N to its southern extremity (Section 4.3, Scrutton 1971). To the north of this latitude, gravity interpretation indicates that the crust gradually becomes thicker

(Section 4.3). This thickening may be connected with the complicated Faeroe-Wyville-Thomson Rise region. The central and southern part of the Rockall Trough is flanked to the west by the microcontinent of Rockall (Scrutton 1971) and to the east by the British continental shelf. This part of the Trough appears to be a narrow but normal oceanic area. If this is correct, it has presumably been formed by oceanic spreading from a mid-oceanic ridge as suggested by Vine (1966) and implied by Bullard et al. (1965). In common with most oceanic areas in the world, magnetic reversal lineations may be expected in the Trough and perhaps also the remanants of a mid-oceanic ridge. The magnetic profiles across the Trough (Section 4.3, Roberts 1971) show that no lineations of the typical oceanic amplitude of about 500 gamma are present. An absence of magnetic lineations has also been found on both sides of the southern North Atlantic (King, Zeitz and Dempsey 1961, Heirtzler and Hayes 1967). Several explanations for this absence have been suggested and discussed (Heirtzler and Hayes 1967, King, Zeitz and Dempsey 1961, Drake et al. 1968, Funnell and Smith 1968, Taylor et al. 1968). The only explanation which appears possible in the light of present knowledge is either that the quiet zone represents a period of ocean floor spreading when there were no reversals of the Earth's magnetic field (Heirtzler and Hayes 1967) or that the North Atlantic was never closed to the extent suggested by the continental fit of Bullard et al. (1965) (Drake et al. 1968). Since it is now almost certain that oceanic crust is present beneath the quiet zones and since there is no great change in sediment thickness and no structural expression at the edges of the quiet zones (Windisch, Ewing and Bryan 1965), which might be expected if the adjacent parts of the oceanic crust had been formed at widely separated times, the former explanation is the most probable. Possible ages for the oceanic crust are considered later.

The gravity interpretation (Section 4.3.4) indicates that the surface of the oceanic crust in the centre of the Rockall Trough, at about 58°N, may be about 1 km higher than it is near the sides of the Trough. A ridge system with a half-width of about 65 km may therefore be present down the centre of the Trough. However, recent work by Haigh (1973) suggests that, for a normal lithospheric thickness, the elevation of an oceanic ridge would sink to 1 km only about 25 m yr after the cessation of spreading. Spreading probably ceased in the Rockall Trough over 200 m yr ago (Section 7.7.2) therefore there is unlikely to be any expression of a ridge left today.

Sediment thicknesses in the Rockall Trough range from about 5 km in the south and central parts to about 3 km in the northern part next to the Wyville-Thomson Rise (Section 4.2.1). A change in the sedimentation pattern took place shortly before reflector 'R' was deposited in Middle-Lower Oligocene times (Jones et al. 1970). The lower series of sediments was probably deposited by turbidity currents whereas the upper series was deposited under the influence of deep-sea currents which formed sedimentary ridges. Reflection profiles show that subaerial erosion on the western banks and the subsequent deposition of sediments on the western margin of the Trough ceased before Oligocene times whereas, on the eastern margin, deposition from the continental margin continued until fairly recently (Section 4.2.2). This indicates that the western Banks subsided more quickly than the Scottish continental margin assuming that they were originally at similar levels.

## 7.4. The western Banks

Recent sampling by drilling of solid outcrops in two localities on Rockall Bank (Roberts et al. 1973) has confirmed the previous theory, which was based on geophysical evidence, that the Bank is composed of continental material. Petrographic and radiometric dating evidence has shown that the sampled material is similar to the Lewisian basement found on the Outer Hebrides and the Scottish mainland. The whole of the Rockall Plateau is therefore probably a microcontinent.

To the north and northeast of Rockall Plateau lie the relatively shallow areas of George Bligh, Lousy, Bill Bailey's and Faeroe Bank and the Faeroe Plateau (Fig.2). Gravity interpretation over the northwest (Bott et al. 1971) and the southeast (Bott and Watts 1971) margins of the Faeroe Plateau and the inclusion of the Plateau in the pre-North Atlantic fit of the continents of Bott and Watts (1971) indicate that the Faeroe Plateau is also a continental fragment. The pre-North Atlantic fit of the continents of Bott and Watts (1971)(Fig.55) also shows that, if Rockall Plateau and Faeroe Plateau are correctly fitted against the Greenland continental margin, there is a gap between the Plateaus into which the four Banks can be fitted. This may imply that the Banks are also continental fragments. Gravity interpretation has shown (Section 4.4.1) that George Bligh, Bill Bailey's and Faeroe Banks probably have crustal thicknesses of about 26 km. This result supports the theory that they are continental and it is reasonable to assume that Lousy Bank, which has not been investigated, is similar to the others. The gravity evidence indicates that the Banks do not have dense igneous plugs beneath them as does Rosemary Bank (Scrutton 1971) and they are therefore not old volcanoes. The estimated depth of about 26 km of the Moho beneath the Banks is 5 km less than the depth estimated by Scrutton beneath Rockall Bank using seismic refraction (Scrutton 1970) and gravity evidence (Scrutton 1971). Scrutton based his gravity profile interpretation on a Moho depth of 31 km beneath the continental shelf of northwest Ireland. If this value had been 26 km, as was assumed for the depth beneath the Hebridean margin in the present interpretation, the Moho depth beneath Rockall Bank would have been 26 km. The seismic refraction experiment of Scrutton (1970) was carried out in bad weather. No reversed upper mantle velocity was obtained and the lower crustal velocity of 7.02 km/s was not well determined. It is possible that there is a significant error in the calculated Moho depth. If the other Banks are continental, the evidence available cannot demonstrate that there is any significant difference in the depths of the Moho beneath Rockall Bank and George Bligh, Bill Bailey's and Faeroe Banks.

Evidence from magnetic profiles suggests that Faeroe Bank is intruded by several basaltic dykes and probably has at least a partial covering of basaltic lavas (Dobinson 1970). Magnetic evidence from George Bligh and Bill Bailey's Banks indicates that basaltic material is not common on these two Banks. Similarities between the profiles over George Bligh and Bill Bailey's Banks and those over Faeroe Bank suggest that the only difference between the Banks may be the presence or absence of basaltic material. There is a similar relationship between magnetic profiles over the northern and southern parts of Rôckall Bank which Roberts and Jones (in preparation) have attributed to a similar presence and absence of basaltic material.

The available evidence suggests that George Bligh, Bill Bailey's and Faeroe Bank are continental fragments but the evidence is not conclusive. Apart from Rockall Bank there is a gradual increase in the depths of the Banks from the Faeroe Plateau to Hatton Bank. Since Hatton Bank is considerably larger than George Bligh, Lousy, Bill Bailey's and Faeroe Banks, the depth of each Bank cannot be related to its size. Faeroe Plateau forms the shallowest proposed continental fragment and it is situated at the southeastern end of the Iceland-Faeroe ridge. The depths of the Banks may be related to their distances from the Iceland-Faeroe ridge. This is considered in Section 7.8. The northern end of Rockall Bank forms one of the shallowest bank areas. This may be partly because the intrusive centre (Roberts 1969) in the Bank has caused a reduced rate of erosion but the overall height of the Bank is more probably related to its relative remoteness from the most recent oceanic spreading area and its proximity to the now relatively stable Rockall Trough region.

## 7.5 The Wyville-Thomson Rise and associated regions

Reflection profiles show that two basement ridges extending from Faeroe Bank to the southeast underlie the sediments of the Wyville-Thomson Rise (Fig.54). The southwesterly ridge terminates about 50 km from the Scottish continental shelf whereas the northeasterly ridge is continuous from Faeroe Bank to the continental shelf. Magnetic evidence indicates that the ridges are composed of magnetic igneous material and are probably reversely magnetised. No geological evidence on the composition of the material is available but the velocity of the upper layer on the northeastern ridge is about 4.91 km/s (Ewing and Ewing 1959). This velocity is likely to be representative of basalt. To the southwest of the southwesterly ridge of the Rise, several basement irregularities and minor ridges are present.

Gravity evidence indicates that the oceanic crust beneath Rockall Trough thickens towards the northeast end of the Trough to a maximum thickness of about 15 km next to the Wyville-Thomson Rise. Beneath the ridges of the Wyville-Thomson Rise crustal thickening to a maximum of about 25 km is indicated by the gravity. Although this thickness is similar to that estimated beneath Rockall Plateau and the other Bank areas there are several distinct differences between these areas and the ridges of the Wyville-Thomson Rise. The present minimum depth of the basement ridges is much deeper than the depths of the continental fragments. There is no evidence that the ridges have ever been subaerial. The magnetisation of the ridges is probably considerably greater than that of the Banks. The narrow linear nature of the ridges is atypical of the Bank areas. It therefore seems unlikely that the ridges are in any way continental. The directional trend of the ridges is similar to that of the fissure system indicated by the magnetic anomalies on Faeroe Bank (Dobinson 1970) and to the dominant structural trend of the Faeroe Islands clearly shown by the present topography of the Islands. It is possible that the ridges forming the Wyville-Thomson Rise are composed of igneous material which was extruded through vents in the oceanic crust with a similar trend to those on Faeroe Bank and Faeroe Plateau. The minor ridges to the southwest of the Rise may have been formed by the extrusion of material through subsidiary vents or by flows of viscous material from the major vents. The possible cause of such a large vent system in the crust allowing basalts to be extruded over both continental and oceanic areas is considered in Section 7.8.

To the northeast of the Wyville-Thomson Rise lies the Faeroe-Shetland channel (Fig.54). Magnetic evidence indicates that the magnetic basement in the channel lies at a depth of about 3 km below sealevel and gravity interpretation indicates that the Moho is at a depth of about 17 km below sealevel. Although no seismic refraction results are as yet available to confirm this, the Faeroe-Shetland channel appears to be underlain by thick oceanic crust. At the southwest end of the Faeroe-Shetland channel a southeasterly protrusion from the Faeroe Plateau (Fig.54) confines the deep waterway to a narrow channel close to the Scottish continental rise. This channel turns to the northwest and joins onto the Faeroe Bank channel along the northeast side of the Wyville-Thomson Rise. Seismic reflection profiles (Section 5.2) show that the southeasterly Faeroe Plateau extension is made up of a basement ridge surrounded by sediments. The sediments are particularly thick on the northeast side of the basement ridge. The basement ridge is connected to the main Faeroe block at its northwest end and becomes lower and smaller towards the southeast. Reflection profiles show that the ridge extends to within 40 km of the Scottish continental shelf. Magnetic profiles over the ridge indicate that lavas are present on the ridge and a comparison of the magnetic profiles to those over the ridges of the Wyville-Thomson Rise shows that there may be little difference between the ridges (Chapter 5). The ridge also shows reversed magnetisation as do the Wyville-Thomson Rise ridges. Evidence has been described which indicates that the Faeroe Plateau is continental but it is difficult to associate a long, tapering, deepening ridge with a continental area. There is no indication that the summit of the south-easterly part of the ridge has ever been subaerially eroded as has the rest of the Faeroe Plateau. The depth of the ridge cannot be attributed to the foundering of a continental fragment. The similarity of the ridge to the ridges of the Wyville-Thomson Rise in shape, size, gravity and magnetic effect and particularly structural trend suggests that the ridge was formed in a similar manner to the other ridges. This theory is supported by the problems of continental fitting discussed in Section 7.6.

Gravity, magnetic and reflection profile evidence indicates that an intrusive centre is present amongst the minor basement ridges (59°40'N, 8°40'W) to the southwest of the southwesterly ridge of the Wyville-Thomson Rise (Fig.54). The intrusion has a diameter of approximately 25 km and its base is probably at a depth of about 14 km. The intrusive rock is probably reversely magnetised with respect to the present Earth's field. Sedimentary evidence shows that the intrusive complex pre-dates reflector 'R', which is Lower-Middle Oligocene, as do the basement ridges of the Wyville-Thomson Rise. Two other intrusive complexes occur in the Rockall Trough. These are Rosemary Bank and the Anton Dohrn Seamount (Fig.54). Both are located in the centre of the Trough. Gravity and magnetic interpretation (Scrutton 1971) shows that the intrusive complex beneath Rosemary Bank is of a similar size and has similar magnetic properties to the complex next to the Wyville-Thomson Rise.

Sedimentary evidence shows that Rosemary Bank also pre-dates reflector 'R'. Since the intrusive complex next to the Rise is also located in the centre of the Rockall Trough it is similar in all respects to Rosemary Bank and probably to the Anton Dohrn Seamount. No conclusive evidence is available that determines whether the complex is associated with the basement ridges or whether it is simply another complex of similar origin to those further south.

## 7.6. Continental fitting

If the oceanic crust in the North Atlantic has been formed by the now well-proven theory of oceanic spreading and plate tectonics (Hess 1962, Dietz 1961), it should be possible to close the North Atlantic and fit the surrounding continental regions together. If, before spreading began in the North Atlantic, there were any minor ocean basins present these would have to be included in the fit. This possibility seems unlikely in the North Atlantic since a great thickness of sediment would overlie such a piece of oceanic crust as is the case at present in the Black Sea (Menard 1970). Bullard et al. (1965) computed a fit for all the continents round the whole Atlantic. They assumed that the 500 fathom bathymetric contour marked the ocean-continent transition line. From this fit Bullard et al. suggested that Rockall Plateau may be continental since it conveniently filled a gap in the fit but they did not consider the possibility that Faeroe Plateau or any of the Banks may be continental. Their fit to the north and northwest of Scotland was particularly poor.

By rotating Greenland 14° about a pole situated at 58°N, 117°E, Bott and Watts (1971) fitted the edge of the Greenland continental shelf to the western edges of Rockall Plateau and Faeroe Plateau (Fig.55). They did not move either of the Plateaus or any of the Banks relative to Europe. This fit leaves the Rockall Trough, which is almost certainly an oceanic area, and the Faeroe-Shetland channel, which may be oceanic, open. These two can only be closed, assuming that the continents either

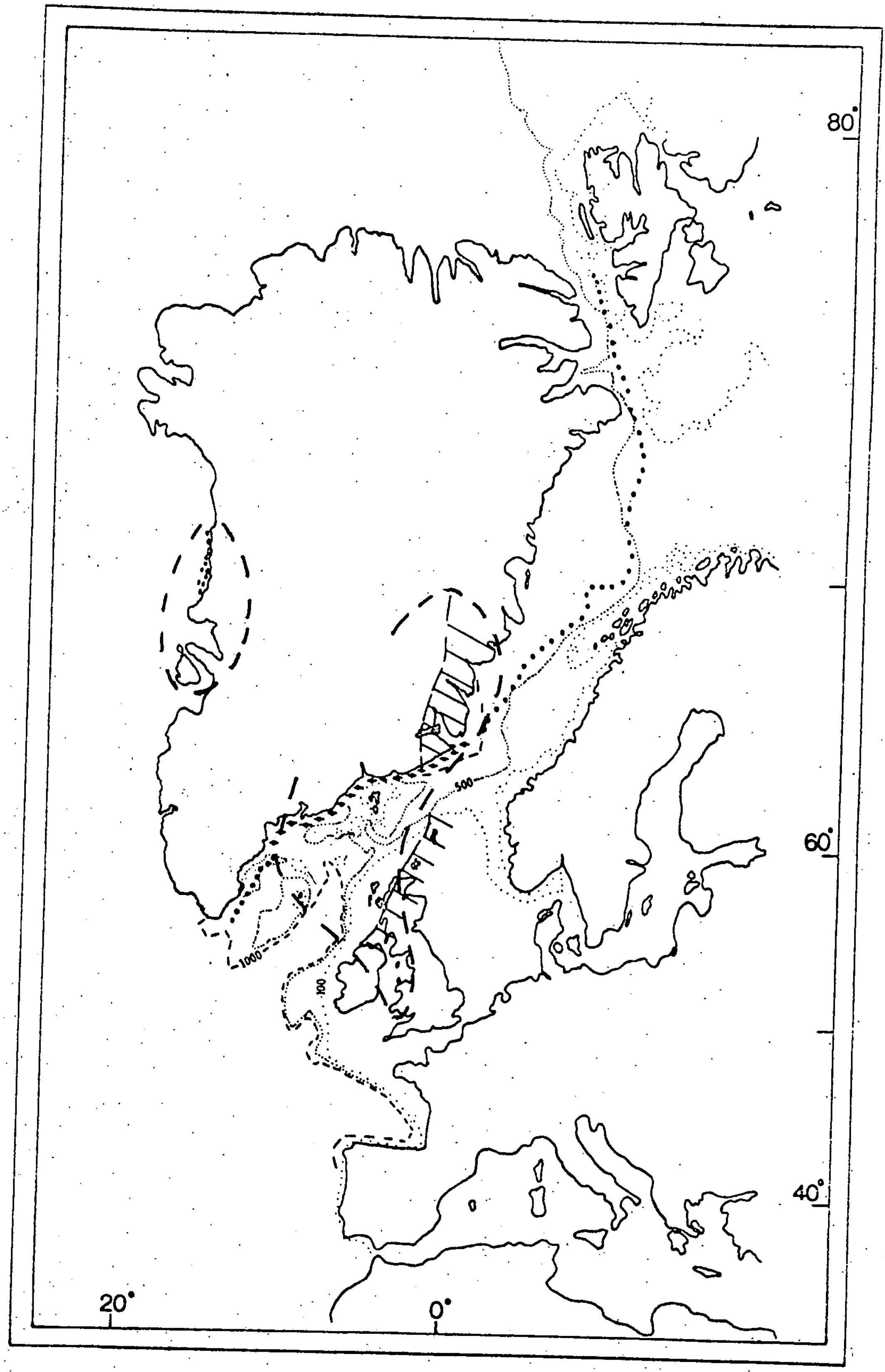


Figure 55. Fit of the continents around the northern North Atlantic from Bott and Watts 1971.

The heavy dashed line marks the extent of the Tertiary igneous province.

side remain rigid, if the Wyville-Thomson Rise and the southeasterly Faeroe ridge were formed since or during the period of opening. The possible continental margins are marked on Fig.56. These have been deduced from the reflection profiles, the bathymetry, the evidence concerning the basement ridges (Section 7.5) and the information concerning a possible basement block connecting George Bligh and Bill Bailey's Banks (D.G. Roberts - personal communication). Even with this evidence the suggested margin is somewhat subjective. The theory requires that there is a wide area of thick sediments lying along the southeast margin of the Faeroe Plateau. Reference to the magnetic and gravity profiles along line E-E' (Fig.54) of Bott and Watts (1971) substantiates this theory. The gravity interpretation along this line (Fig.57) which crosses the margin of the Faeroe Plateau to the north of the southeasterly basement ridge includes a wide, thick sequence of sediments along the northwest margin of the Faeroe-Shetland channel and the magnetic profile indicates that the magnetic basement rises to the surface about 50 km to the northwest of the bathymetric margin of the Plateau.

Since the northwestern continental margin of Scotland and the proposed southeastern continental margin of the Faeroe Plateau are relatively straight, they can give little indication as to the exact fitting position. The northeastern edge of Rockall Plateau has, however, two distinct corners which determine the position of fit relatively precisely. Lines indicating the approximate direction of opening are marked on Fig.56. The required amount of opening decreases from the southern Rockall Trough to the Faeroe-Shetland channel. The splitting must have extended into the eastern Norwegian Sea. The line along which splitting must have occurred in the Norwegian Sea is followed by a relatively quiet magnetic area on the aeromagnetic residual contour chart of Avery et al. (1968 - Fig.5).

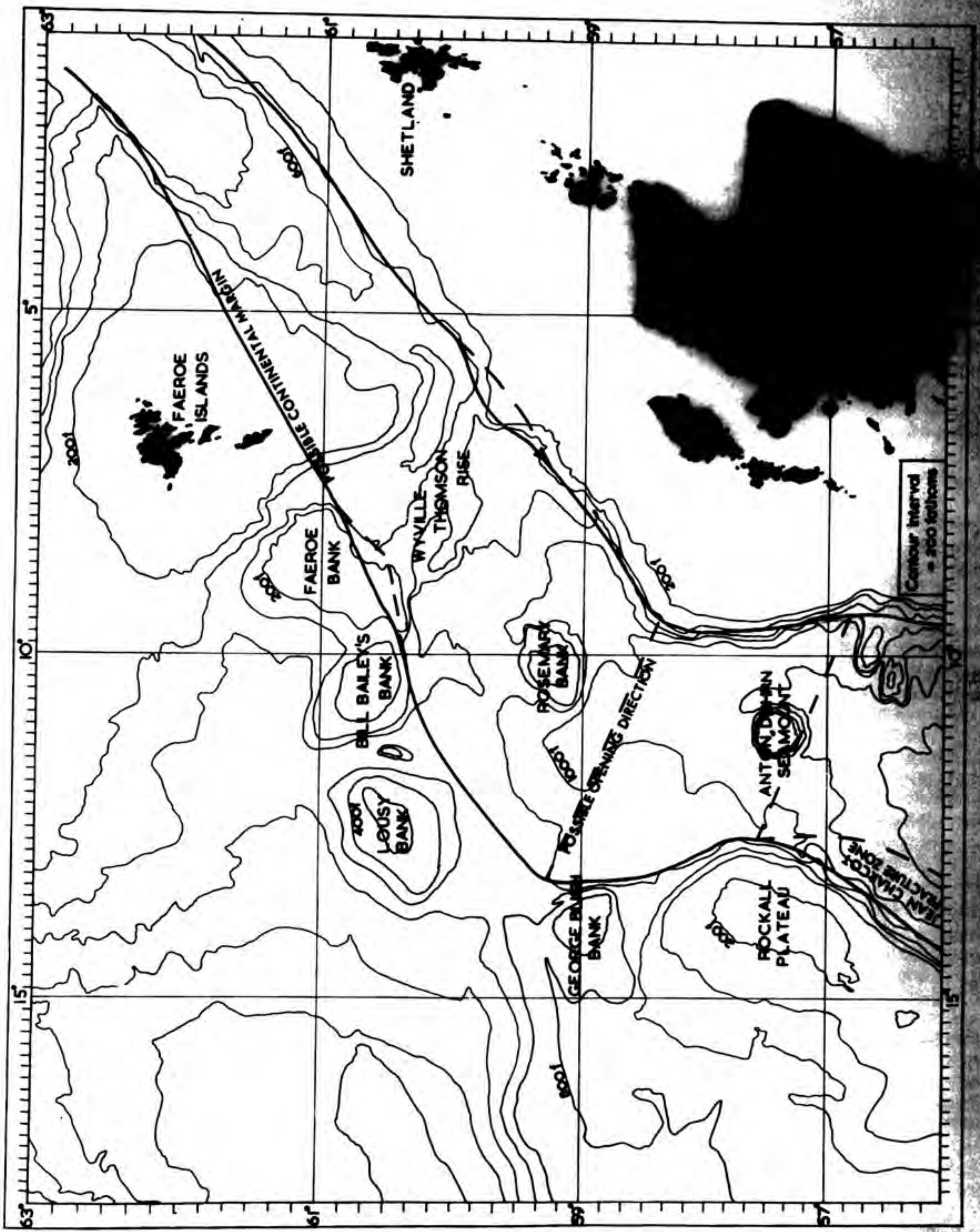


Figure 56. The Rockall Trough region with possible continental margins.

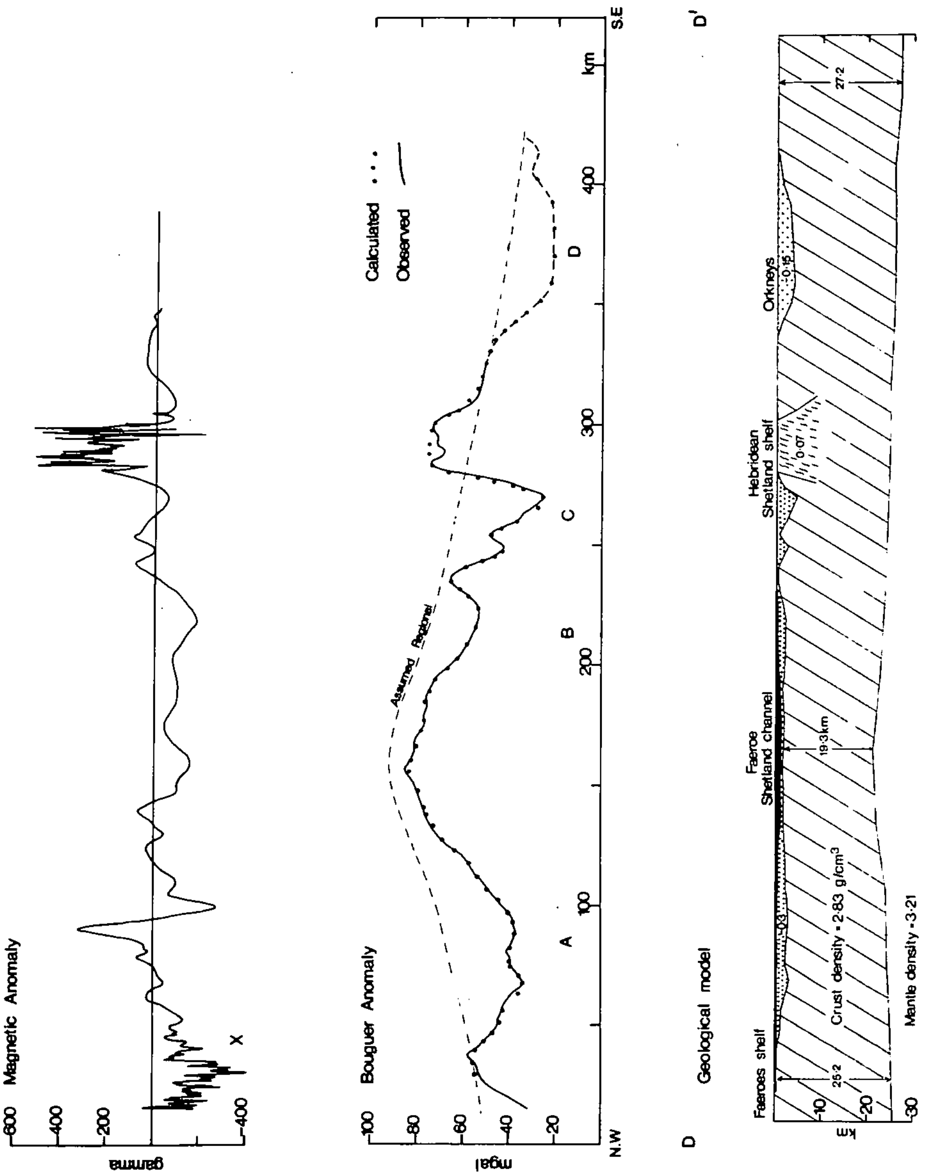


Figure 57. Gravity interpretation across the Faeroe-Shetland channel. Line E-E' from Bott and Watts 1971.

## 7.7. Dating of events in the northeast Atlantic

Several important events have occurred in the evolution of the northeast Atlantic region. Before the events and their relationships can be fully understood absolute ages must be applied to as many events as possible. Where this is not possible relative ages must be deduced.

### 7.7.1 The opening of the Atlantic along the Reykjanes ridge

This event has been dated using the magnetic lineations in the northeast Atlantic (Le Pichon et al. 1971, Laughton 1971). The earliest lineation adjacent to the western side of the Rockall Plateau and the eastern margin of Greenland is anomaly 24. This has an age of about 60 m yr (Heirtzler et al. 1968). The initial rifting probably occurred shortly before this date.

### 7.7.2 The opening of the Rockall Trough

Evidence indicating the time of opening of the Rockall Trough is scanty. Reflection profile evidence from the southern part of the Trough (Scrutton and Roberts 1971) shows that at least 3 km of sediment are present beneath reflector 'R' which is of Lower-Middle Oligocene age. Opening must therefore have occurred long before the Oligocene. Stride et al. (1969) suggested from reflection profile evidence that sediments of Cretaceous age are present on the Hebridean continental slope indicating that opening occurred before that time. No typical oceanic magnetic lineations are present in the Trough therefore age correlations with lineations elsewhere cannot be carried out. The absence of lineations may however indicate that the Trough opened fully during one period of magnetisation. If opening occurred at a rate typical of those measured in other oceans, the period of time with no magnetic reversals must have been relatively long.

Assuming that large continental regions remain relatively rigid, no opening can have occurred in the Rockall Trough until the southern North Atlantic began to open. Laughton (1971) and Le Pichon et al. (1971)

have proposed models of the opening of the North Atlantic based on magnetic lineations and other information. The two models do not completely agree but they both suggest that the Rockall Trough opened simultaneously with the early opening of the North Atlantic. The magnetically quiet Rockall Trough probably corresponds in age to the quiet zones of the North Atlantic (Heirtzler and Hayes 1967). Emery et al. (1970) have used magnetic reversal and sedimentary evidence to suggest that the initial splitting between North America and Africa occurred at the beginning of the long Kiaman interval (Irving 1966) of reversed magnetisation. This was about 290 m yr ago. The opening of the Rockall Trough probably occurred during the period between 290 and 220 m yr ago. This would imply that the oceanic basement of the Trough is reversely magnetised. This correlates with the reversely magnetised volcanic centres of the Anton Dohrn Seamount, Rosemary Bank and perhaps the complex adjacent to the Wyville-Thomson Rise if they were formed during the opening of the Trough.

### 7.7.3 The formation of the basement ridgesof the Wyville-Thomson Rise and the southeast Faeroe extension.

A maximum age for these ridges is given by the age of the Rockall Trough. The ridges must have been formed either contemporaneously with or subsequent to the opening. The relationship of reflector 'R' to the ridges clearly shows that they are pre-Lower Oligocene (Section 5.4). No other direct evidence as to the ages of the ridges is available. Although the sediments overlying the southwesterly ridge are older than the Lower Oligocene no definite age can be attributed to them. The suggested possible origin of the ridges (Section 7.5) does, however, indicate that they may be contemporaneous with the extruded lavas on Faeroe Plateau and Faeroe Bank. The lower series of sediments on the ridges may have been deposited whilst Faeroe Bank was uplifted (Section 7.8) shortly after the oceanic spreading began along the Reykjanes ridge.

### 7.7.4 The sinking of the outer Banks

If Rockall Plateau, Faeroe Plateau and the Banks between them formed, at one time, a continuous upstanding continental area, there must have been one or more periods of irregular sinking. The relationships of the sediments on the margins of the Banks (Section 4.2.2) show that subaerial erosion ceased some time prior to the Lower Oligocene. Reflector 'R' is found overlying a downfaulted block between George Bligh and Bill Bailey's Banks (Section 4.1.1, D.G. Roberts - personal communication). About 0.5 km of sediment is present between the reflector and the block therefore it is likely that sedimentation began on the block sometime in the Lower Tertiary. Data from the Deep Sea Drilling Project holes at Sites 116 and 117 (D.S.D.P. Scientific Staff 1970, Fig.1) has provided relatively accurate information on the periods of sinking of the Hatton-Rockall Basin. In the Palaeocene the basaltic basement of the basin was subaerial. Rapid sinking occurred 55 m yr ago followed by relative stability for 12 m yr. There was further sinking in the Late Eocene (39 m yr ago) followed by relative stability for about 20 m yr. The final period of sinking, which was also that of greatest sinking, occurred in the Middle Miocene (15 - 10 m yr ago). This history of subsidence is likely to have affected all the continental fragments.

### 7.7.5 The formation of the continental shelf sedimentary basins

Direct evidence on the ages of the shelf sedimentary basins can only be gained from a study of the sediments which have accumulated in and around the basins. On the Scottish shelf the sedimentary basins are largely fault-bounded. Since many of the faults are probably reactivated faults of much greater age the problem of deciding when the main period of subsidence in the basins started is more complicated. Many speculations as to the oldest age of the sediments in the basins have been made (Watts 1971, Smythe et al. 1972, McQuillin and Binns

1973, Hallam 1972, Hall and Smythe 1973, Steel 1971). The best available evidence that can be used to date the initiation of subsidence in the basins accurately is sedimentary evidence from and around the Sea of the Hebrides Trough and the Inner Hebrides Trough. Steel (1971) suggests that sediments near Stornoway on the Outer Hebrides indicate that there was vertical movement on the Minch Fault in New Red Sandstone times. The downthrow was to the northwest which is opposite to the later movement but this may represent an initial stage of the major subsidence. Torridonian sediments probably form a major component of the sedimentary infill of the basins (Browitt 1972, McQuillin and Binns 1973). Old Red Sandstone and Carboniferous sediments may also be present. Sediments of these ages have probably been downfaulted into the basins and are unlikely to have been original basinal deposits. Permo-Triassic samples have been recovered from the margin of the Sea of the Hebrides Trough and rocks of this age also occur on Rhum and Skye (Richey 1961). Samples of probable Jurassic age have been recovered from the deeper parts of the basin but relatively thin Jurassic occurrences on land in the area suggest that there was little subsidence in the basin at that time (McQuillin and Binns 1973).

Although deep drilling will probably be necessary to establish the exact time of the initial subsidence in the shelf basins, it is likely that this occurred in Permo-Trias times or about 250 m yr ago.

Bott (1971a) has suggested that continental shelf basins may be formed by the interaction of normal faulting in the upper crust with oceanward creep in the lower crust of a newly formed continental margin. This theory suggests that shelf basins should form relatively soon after the initial development of a new ocean and that the basins should be approximately parallel to the new continental margin. The suggested age of the basins on the Scottish shelf indicates that they could be related to the formation of the Rockall Trough but not to the splitting at the

Reykjanes ridge (Hall and Smythe 1973). The trend of the basins correlates well with the trend of the Rockall Trough. The change in trend of the basins between the Lewis-Flannan Isles basin (Section 6.2.3) and the Outer Hebrides Basin (McQuillin and Binns 1973) may even correlate with the adjacent change in trend of the continental margin (Fig.54). The age of the initial subsidence in the basins may therefore be another indicator to the time of the initiation of splitting of the Rockall Trough.

### 7.7.6. The Thulean igneous province

Radiometric dating of samples collected from various parts of the province has provided relatively accurate ages for the development of the province. Evans, Fitch and Miller (1973) have summarised the available information. In Britain, magmatism began in either the latest Cretaceous or earliest Palaeocene (65 - 66 m yr ago). The climax occurred when the main plutonic centres developed about 59 m yr ago and activity continued until at least 50 m yr ago. Activity occurred through approximately the same period of time in the Faeroe Islands. In East Greenland the latest plateau basalts are Palaeocene (55 - 60 m yr ago) and the latest activity was probably 50 m yr ago. The entire activity lasted only about 15 m yr in East Greenland. Activity in West Greenland and Baffin Island is of a similar age to that in the rest of the igneous province. The activity throughout the province was probably confined to the Palaeocene and the Eocene.

## 7.8. The development of the Thulean igneous province

The known extent of this province is shown on Fig.55. The evidence outlined in Sections 7.5 and 7.7.3 suggests that the basement ridges of the Wyville-Thomson Rise and the southeast Faeroe extension may also belong to the province. The correlation of the age of opening of the Atlantic along the Reykjanes ridge with the age of the igneous material in the province suggests that the opening and the igneous activity are related. The anomalous nature of the crust beneath

Iceland and beneath the Greenland-Iceland-Faeroe ridge, which formed during the later spreading of the Atlantic, provides evidence which may help to explain the relationship of the splitting to the igneous activity.

The Iceland-Faeroe ridge is underlain by an anomalously thick oceanic crust (Bott et al. 1971). This was probably formed by an anomalous type of accretion caused by a mantle 'hot spot' which is now beneath Iceland (Wilson 1963, Bott et al. 1971). This 'hot spot' may be caused by a rising mantle plume (Morgan 1971) which may have caused the initial splitting of the continents and perhaps the widespread contemporaneous vulcanism. Bott (1973) considers that a single plume would not produce such widespread vulcanism and suggests that a single convective overturn in the asthenosphere beneath the region of the igneous province could have caused both the vulcanicity and the initiation of spreading along the northern limb of the Atlantic. No matter which mechanism operated, the lithosphere at the forthcoming splitting point would be stressed and domed (Bott 1973, Brooks 1973). Brooks (1973) suggests that such doming caused a 'Y' shaped configuration of rifting through which lava was extruded. He suggests that two arms of the 'Y' then formed the spreading axis of the North Atlantic and the third arm became the now-inactive Kangerdlugssuaq rift in Greenland. The lava extruded on Faeroe Plateau and Faeroe Bank and that forming the basement ridges of the Wyville-Thomson Rise and the southeasterly Faeroe extension may have been extruded through now-inactive rifts which were originally caused by the doming. This would explain the diminution in size of the ridges away from the Faeroe Plateau and Bank. Brooks considers that the doming in Greenland has not fully subsided. The increase in the depths of the Banks between Faeroe Plateau and Hatton Bank away from the Faeroe Plateau (Section 7.4) may be caused by a similar lack of complete subsidence of the doming on the eastern side of the Atlantic.

### 7.9. The development of the northeast Atlantic

(1) About 290 - 220 m yr ago: Probable formation of the Rockall Trough and Faeroe-Shetland channel by crustal splitting occurring contemporaneously with the initial opening of the North Atlantic basin. The split probably continued some distance into the present Norwegian Sea region.

The volcanoes of the Anton Dohrn Seamount, Rosemary Bank and perhaps the intrusive complex now lying to the southwest of the Wyville-Thomson Rise probably formed on or near the spreading centre. Shortly after the splitting block faulting occurred on the Scottish and Greenland continental shelves. The faults developed either approximately parallel to the new continental margins or followed the lines of former transcurrent faults.

(2) 220 - 65 m yr ago: The continental shelves and margins sank slightly and sediments were deposited over the continental slopes. The shelf basins continued to develop and were gradually filled with sediments.

(3) 65 m yr ago: Disturbances in the asthenosphere caused the Thulean igneous province to begin to develop. Doming of the lithosphere occurred to the west of the Faeroe-Shetland channel causing rifting in both the continental and the oceanic crust accompanied by the extrusion of large volumes of basaltic lava. The lava formed the plateau lavas on East Greenland, the Faeroe Plateau and probably Faeroe Bank and the basement ridges in the Rockall Trough and Faeroe-Shetland channel.

(4) 60 - 55 m yr ago: The northern part of the Atlantic Ocean began to form. Subsidence occurred in the microcontinent on the east side of the new ocean. The subsidence was probably facilitated by the fracturing which the initial doming must have caused.

(5) 55 m yr ago to present: Subsidence of the fractured microcontinent continued at irregular intervals. The cold Norwegian sea water formed deep water currents and affected the previous turbidity current sedimentation in the Rockall Trough. The Scottish continental shelf gradually sank and was eroded until it reached its present level.

## 7.10. Further work

Many of the conclusions reached in this chapter are based on little or indecisive evidence. Much of the area needs further investigation in order to confirm or refute these conclusions.

Although the evidence that the Rockall Trough is oceanic is fairly convincing, seismic refraction evidence could confirm this if sufficient penetration were attained. The crustal thicknesses in the north of the Trough are based on gravity interpretation which could be in error if any of the control parameters has been wrongly deduced.

The evidence from the Faeroe-Shetland channel does not prove conclusively that it is underlain by oceanic crust. Refraction evidence could both confirm the sediment thicknesses and the crustal velocities and thicknesses.

Many of the conclusions depend on the southeasterly Faeroe basement ridge being of a different composition to the remainder of the Faeroe Plateau. A gravity profile along the ridge, with seismic reflection control on the sediment thicknesses, could provide evidence of this. Similarly, gravity interpretation along the ridges of the Wyville-Thomson Rise and onto Faeroe Bank would probably show if basic changes in the crustal composition are present between the ridges and the Bank.

Seismic refraction experiments have already been carried out on the Faeroe Plateau during the North Atlantic Seismic Project, 1972. These have confirmed that continental crust is present beneath the Plateau (M.H.P. Bott and P.J. Smith - personal communication). George

Bligh, Lousy and Bill Bailey's Banks may present difficulties for seismic refraction work since the upper structure is probably variable and affected by faulting. Refraction work may be possible on Faeroe Bank. Seismic reflection profiles over the Bank areas may allow the basement to be traced from Rockall Plateau to Faeroe Plateau and show that the continental crust is probably continuous between them. Reflection profiles should also define the probable continental margins both on the western side of the Rockall Trough and on the eastern side of the main North Atlantic Basin and so allow continental fitting to be carried out more accurately.

Although reflector 'R' has been used as an age marker over most of the Rockall Trough, several older reflectors are present in the Trough. If these were dated they could provide more definite and precise ages for the major events in the Trough and perhaps also in the whole northeast Atlantic.

## Appendix A

## Navigation program ANAV

The program calculates courses, headings, velocities and Eötvös corrections from a series of position fixes defined by latitudes and longitudes.

### Input.

The input is as follows:-

| | | Time | | | Day | | Latitude | | Longitude |
|---|---|---|---|---|---|---|---|---|---|
| | | Hours. | Minutes. | | | | (degrees) | | (degrees) |
| Format: | 5X, | I2 | I2 | 2X. | I3 | 15X, | F9.6 | 9X, | F9.6 |

The data is ended by an ENDFILE.

### Output

The output is as follows:-

| | | Time (days) | | Latitude (degrees) | | Longitude (degrees) | | Eöt. Corr. (mgal) | | Velocity (knots) | | Headings (degrees) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Format: | 5X, | F10.6, | 5X, | F9.6, | 5X, | F9.6, | 5X, | F10.5, | 5X, | F5.2, | 5X, | F7.3. |

The output is usually stored on file and then read directly into the gravity reduction program.

```
      T3=FIX(J+4,1)
      CA3=FIX(J+4,2)
      CO3=FIX(J+4,3)
      CALL CCHEC(CA1,CA2,CA2,CA3,CO1,CO2,CO2,CO3,IANS)
      V=VEL(CA2,CA3,CO2,CO3,T2,T3)
      IF(V.LT.15..AND.V.GT.3.5)GO TO 1
      IANS=1
    1 IF(IANS.EQ.0)GO TO 10
      IF(J.GE.JQ2)GO TO 12
      T4=FIX(J+6,1)
      CA4=FIX(J+6,2)
      CO4=FIX(J+6,3)
      CALL CCHEC(CA2,CA3,CA3,CA4,CO2,CO3,CO3,CO4,IANS)
      V=VEL(CA3,CA4,CO3,CO4,T3,T4)
      IF(V.LT.15..AND.V.GT.3.5)GO TO 2
      IANS=1
    2 IF(IANS.EQ.0)GO TO 11
      IF(J.GE.JQ3)GO TO 12
      CALL CCHEC(CA1,CA2,CA2,CA4,CO1,CO2,CO2,CO4,IANS)
      IF(IANS.EQ.1)GO TO 12
      FIX(J+4,2)=(FIX(J+2,2)+FIX(J+6,2))/2.
      FIX(J+4,3)=(FIX(J+2,3)+FIX(J+6,3))/2.
      GO TO 10
   11 N(IC)=K+2
      J=J+2
      GO TO 13
   12 N(IC)=K+5
      J=J+5
      GO TO 13
   14 K=K+JQ-J
      MX=5
      N(IC)=K
      M=2
      MM=1
      NO=1
      DO 500 I=1,IC
C  IC IS NUMBER OF COURSES. TAKE EACH COURSE SEPARATELY.
      WRITE(6,863)N(I)
C  WRITE OUT NUMBER OF FIXES ON COURSE.
  863 FORMAT(4H NI=I4)
      NI=N(I)
      NNO=NO+N(I)
C  LEAVE OUT COURSE IF LESS THAN 5 FIXES.
      IF(NI.LT.5)GO TO 70
C  ROTATE AXES UNTIL COURSE IS AT 45 DEGREES.
      AT1=FIX(NO,2)
      AT2=FIX(NO+NI-1,2)
      ONG1=FIX(NO,3)
      ONG2=FIX(NO+NI-1,3)
      THET=DATAN2(AT2-AT1,ONG2-ONG1)
      ALPH=THET-0.7854
      LIM=NO+NI-1
      DO 855 J=NO,LIM
      SPAR=FIX(J,3)*DCOS(ALPH)+FIX(J,2)*DSIN(ALPH)
```

```
      FIX(J,2)=FIX(J,2)*DCOS(ALPH)-FIX(J,3)*DSIN(ALPH)
      FIX(J,3)=SPAR
  855 CONTINUE
C  FACILITY IN NEXT PART TO CATER FOR ENDS OF COURSES
C  AND SHORT COURSES.
  854 IF(NI.GT.20)GO TO 17
      NNO=NO+N(I)
      IF(NI.LT.5)GO TO 70
      IS=NO
C  FIT QUADRATIC LINE THROUGH FIXES.
      CALL POLRG(NI,FIX)
      NNO=NO+N(I)
      Y1=FIX(NNO-1,2)
      Y2=FIX(NO,2)
      NNOP=NNO-1
      FIXA1=FIX(NNO-1,3)
      FIXA2=FIX(NO,3)
      DO 18 IN=NO,NNOP
      FIXA3=FIX(IN,3)
      FIXA4=FIX(IN,2)
C  DROP ORIGINAL FIXES ONTO FITTED COURSE.
      CALL DROP(FIXA1,Y1,FIXA2,Y2,FIXA3,FIXA4)
      FIX(IN,3)=FIXA3
      FIX(IN,2)=FIXA4
   18 CONTINUE
      NO=NNO
      GO TO 16
   17 NNO=NO+N(I)
      NNOP=NNO-1
      NNO6=NNO-12
      DO 190 JJ=NO,NNO6,6
      IS=JJ
      IF(JJ+19.GT.NNO-1)GO TO 20
      CALL POLRG(20,FIX)
      Y1=FIX(IS+19,2)
      Y2=FIX(IS,2)
      IF(JJ.EQ.NO)GO TO 21
      IS3=IS+7
      IS6=IS+12
      FIXA1=FIX(IS+19,3)
      FIXA2=FIX(IS,3)
      DO 22 IN=IS3,IS6
      FIXA3=FIX(IN,3)
      FIXA4=FIX(IN,2)
      CALL DROP(FIXA1,Y1,FIXA2,Y2,FIXA3,FIXA4)
      FIX(IN,3)=FIXA3
      FIX(IN,2)=FIXA4
   22 CONTINUE
      GO TO 19
   21 IS6=IS+12
      FIXA1=FIX(IS+19,3)
      FIXA2=FIX(IS,3)
      DO 23 IN=IS,IS6
      FIXA3=FIX(IN,3)
```

```
      FIXA4=FIX(IN,2)
      CALL DROP(FIXA1,Y1,FIXA2,Y2,FIXA3,FIXA4)
      FIX(IN,3)=FIXA3
      FIX(IN,2)=FIXA4
   23 CONTINUE
      GO TO 19
   20 II=NNO-IS
      IS=NNO-20
      CALL POLRG(20,FIX)
      Y1=FIX(NNO-1,2)
      Y2=FIX(IS,2)
      NNOP=NNO-1
      IS3=NNO-II+7
      FIXA1=FIX(NNO-1,3)
      FIXA2=FIX(IS,3)
      DO 24 IN=IS3,NNOP
      FIXA3=FIX(IN,3)
      FIXA4=FIX(IN,2)
      CALL DROP(FIXA1,Y1,FIXA2,Y2,FIXA3,FIXA4)
      FIX(IN,3)=FIXA3
      FIX(IN,2)=FIXA4
   24 CONTINUE
   19 NNO6=NNO-12
  190 CONTINUE
   70 NO=NNO
   16 CONTINUE
      PI=3.14159
      NI=N(I)
      NN=MM+NI-1
      IF(NI.LT.5)GO TO 632
C  ROTATE AXES BACK.
      DO 633 J=MM,NN
      SPAR=FIX(J,3)*DCOS(ALPH)-FIX(J,2)*DSIN(ALPH)
      FIX(J,2)=FIX(J,2)*DCOS(ALPH)+FIX(J,3)*DSIN(ALPH)
      FIX(J,3)=SPAR
  633 CONTINUE
  632 DO 31 J=MM,NN
      IF(NI.LE.2)GO TO 31
      IF(J.EQ.MM)GO TO 32
      IF(J.EQ.NN)GO TO 33
      T1=FIX(J-1,1)
      T2=FIX(J,1)
      T3=FIX(J+1,1)
      AT1=FIX(J-1,2)
      AT2=FIX(J,2)
      AT3=FIX(J+1,2)
      ONG1=FIX(J-1,3)
      ONG2=FIX(J,3)
      ONG3=FIX(J+1,3)
C  CALCULATE VELOCITIES BETWEEN FIXES.
      V1=VEL(AT1,AT2,ONG1,ONG2,T1,T2)
      V2=VEL(AT2,AT3,ONG2,ONG3,T2,T3)
      V=(V1+V2)/2.
      S6(J)=V
```

```
C   CALCULATE COURSES BETWEEN FIXES.
      CALL CORS(AT1,AT2,ONG1,ONG2,CO1)
      CALL CORS(AT2,AT3,ONG2,ONG3,CO2)
      CO3=DABS(CO2-CO1)
      IF(CO3.GT.2.)GO TO 34
      CO=(CO2-CO1)/2.+CO1
      GO TO 35
   34 CO=(CO2-CO1)/2.+CO1+PI
      IF(CO.LT.2.*PI)GO TO 35
      CO=CO-2.*PI
      AT21=AT2*2.*PI/360.
   35 CD3(J)=CO*360./(2.*PI)
      GO TO 31
C   FACILITY FOR END OF COURSES.
   32 T1=FIX(J,1)
      T2=FIX(J+1,1)
      T3=FIX(J+2,1)
      AT1=FIX(J,2)
      AT2=FIX(J+1,2)
      AT3=FIX(J+2,2)
      ONG1=FIX(J,3)
      ONG2=FIX(J+1,3)
      ONG3=FIX(J+2,3)
      V1=VEL(AT1,AT2,ONG1,ONG2,T1,T2)
      V2=VEL(AT2,AT3,ONG2,ONG3,T2,T3)
      V=(V1+V2)/2.
      S6(J)=V
      CALL CORS(AT1,AT2,ONG1,ONG2,CO)
      CD3(J)=CO*360./(2.*PI)
      AT11=AT1*2.*PI/360.
      GO TO 31
   33 T1=FIX(J-2,1)
      T2=FIX(J-1,1)
      T3=FIX(J,1)
      AT1=FIX(J-2,2)
      AT2=FIX(J-1,2)
      AT3=FIX(J,2)
      ONG1=FIX(J-2,3)
      ONG2=FIX(J-1,3)
      ONG3=FIX(J,3)
      V1=VEL(AT1,AT2,ONG1,ONG2,T1,T2)
      V2=VEL(AT2,AT3,ONG2,ONG3,T2,T3)
      V=(V1+V2)/2.
      S6(J)=V
      CALL CORS(AT1,AT2,ONG1,ONG2,CO)
      CD3(J)=CO*360./(2.*PI)
      AT21=AT2*2.*PI/360.
   31 CONTINUE
      DO 400 J=MM,NN
      IF(NI.LT.5)GO TO 30
      IF(J.EQ.MM)GO TO 501
      MM1=MM+1
      IF(J.EQ.MM1)GO TO 502
      NN1=NN-1
```

```
      IF(J.EQ.NN1)GO TO 503
      IF(J.EQ.NN)GO TO 504
      S7(J)=(S6(J)+S6(J-2)+S6(J+2))/3.
      GO TO 30
C  SMOOTH VELOCITIES.
  501 S7(J)=(S6(J)+S6(J+3))/2.
      GO TO 30
  502 S7(J)=(S6(J)+S6(J+2))/2.
      GO TO 30
  503 S7(J)=(S6(J)+S6(J-2))/2.
      GO TO 30
  504 S7(J)=(S6(J)+S6(J-3))/2.
   30 CONTINUE
      CO=CD3(J)*2.*PI/360.
      AT=FIX(J,2)*2.*PI/360.
      EOTCON(J)=7.487*S7(J)*DSIN(CO)*DCOS(AT)
C   OUTPUT TIMES,LATS,LONGS,EOT.CORRS,VELOCITIES,COURSES.
  300 WRITE(1,27)FIX(J,1),FIX(J,2),FIX(J,3),EOTCON(J),S7(J),CD3(J)
   27 FORMAT(5X,F10.6,5X,F9.6,5X,F9.6,5X,F10.5,5X,F5.2,5X,F7.3)
  400 CONTINUE
      MM=MM+NI
  500 CONTINUE
      GO TO 9999
      STOP
      END
      FUNCTION SCALE(B)
C   FUNCTION WITH FORMP SCALES DISTANCES AT DIFFERENT
C   LATITUDES.
      DOUBLE PRECISION A,AA,FORMP,CALE
      A=B
      AA=A-1./60.
      CALE=1./(FORMP(A)-FORMP(AA))
      SCALE=CALE
      RETURN
      END
      FUNCTION FORMP(X)
C   USED BY SCALE.
      DOUBLE PRECISION AK,THET,XX,X,X1,Y,Y1
      AK=7915.704456
      THET=(45.+X/2.)*0.01745327
      XX=X*0.01745327
      X1=DSIN(XX)
      Y=DTAN(THET)
      Y1=DLOG10(Y)
      FORMP=(AK*Y1)-23.38871*X1-0.053042*X1**3-0.000216523*X1**5
      RETURN
      END
      SUBROUTINE CORS(AT1,AT2,ONG1,ONG2,CO)
C   CALCULATES COURSE BETWEEN FIXES.
      DOUBLE PRECISION AT1,AT2,ONG1,ONG2,CO,PI,X,Y,T,AT
      PI=3.14159
      X=AT1-AT2
      Y=(ONG1-ONG2)*SCALE(AT1)
      T=DABS(Y/X)
```

```
      AT=DATAN(T)
      IF(Y.LT.0.AND.X.GT.0)GO TO 12
      IF(Y.LT.0.AND.X.LT.0)GO TO 11
      IF(Y.GT.0.AND.X.GT.0)GO TO 13
      GO TO 10
   11 AT=2.*PI-AT
      GO TO 10
   12 AT=PI+AT
      GO TO 10
   13 AT=PI-AT
   10 CO=AT
      RETURN
      END
      SUBROUTINE DROP(X1,Y1,X2,Y2,X3,Y3)
C   DROPS FIX PERPENDICULARLY ONTO COURSE.
      COMMON/DOUB/COE1,COE2,COE3
      DOUBLE PRECISION X1,X2,X3,Y1,Y2,Y3,COE1,COE2,COE3,A,B,C,
     1D,E,F,Z,X31,Y31
      IF(COE1.EQ.0.)GO TO 10
      Z=-(X2-X1)/(Y2-Y1)
      D=Y3+X3*(X2-X1)/(Y2-Y1)
      A=COE1
      B=COE2
      C=COE3
      E=(B-Z)**2-4.*A*(C-D)
      IF(E.LT.0.)GO TO 2
      X31=(-(B-Z)+DSQRT(E))/2./A
      IF(DABS(X31-X3).GT.0.5)GO TO 3
      X3=X31
      GO TO 4
    3 X3=(-(B-Z)-DSQRT(E))/2./A
    4 F=((B*Z-Z**2-2.*A*D)**2-4.*A*(A*D**2-B*D*Z+C*Z**2))/Z**4
      IF(F.LT.0.)GO TO 2
      Y31=(-(B*Z-Z**2-2.*A*D)/Z**2+DSQRT(F))/(2.*A/Z**2)
      IF(DABS(Y31-Y3).GT.0.5)GO TO 5
      Y3=Y31
      GO TO 6
    5 Y3=(-(B*Z-Z**2-2.*A*D)/Z**2-DSQRT(F))/(2.*A/Z**2)
      GO TO 6
   10 X3=(COE2*Y3+X3-COE2*COE3)/(1+COE2**2)
      Y3=COE2*X3+COE3
      GO TO 6
    2 WRITE(MX,1)
    1 FORMAT('IMAGINARY ROOT IN DROP')
    6 RETURN
      END
      SUBROUTINE CCHEC(A1,A2,A3,A4,B1,B2,B3,B4,IANS)
C   CHECKS FOR COURSE CHANGES BETWEEN 3 FIXES.
C   'EXS' MUST BE CHANGED FOR DIFFERENT TOLERANCES OF CHANGE.
      DIMENSION CO(3)
      DOUBLE PRECISION A1,A2,A3,A4,B1,B2,B3,B4,CO,PI,EXS,X,Y,
     1T,AT,EXS1,EXS2,TOL
      PI=3.14159
      EXS=30.
```

```
      X=A1-A2
      Y=((B1-B2)*SCALE(A1))
      T=DABS(Y/X)
      AT=DATAN(T)
      IF(Y.LT.0.AND.X.GT.0)GO TO 12
      IF(Y.LT.0.AND.X.LT.0)GO TO 11
      IF(Y.GT.0.AND.X.GT.0)GO TO 13
      GO TO 10
   11 AT=2.*PI-AT
      GO TO 10
   12 AT=PI+AT
      GO TO 10
   13 AT=PI-AT
   10 CO(1)=AT*360./2./PI
      X=A3-A4
      Y=((B3-B4)*SCALE(A3))
      T=DABS(Y/X)
      AT=DATAN(T)
      IF(Y.LT.0.AND.X.GT.0)GO TO 16
      IF(Y.LT.0.AND.X.LT.0)GO TO 15
      IF(Y.GT.0.AND.X.GT.0)GO TO 17
      GO TO 18
   15 AT=2.*PI-AT
      GO TO 18
   16 AT=PI+AT
      GO TO 18
   17 AT=PI-AT
   18 CO(3)=AT*360./2./PI
      EXS1=EXS/2.
      EXS2=360.-EXS1
      IF(CO(1).GT.EXS2.AND.CO(3).LT.EXS1)GO TO 20
      IF(CO(3).GT.EXS2.AND.CO(1).LT.EXS1)GO TO 20
      TOL=DABS(CO(1)-CO(3))
   72 IF(TOL.LE.EXS)GO TO 20
      IANS=1
      GO TO 21
   20 IANS=0
   21 RETURN
      END
      SUBROUTINE POLRG(N,ARRAY)
C  FITS QUADRATIC COURSE THROUGH FIXES.
      DIMENSION ARRAY(1000,3),X(70),DI(4),D(8),B(3),SB(3),T(3),E(3),XBAR
     1(4),STD(4),COE(8),SUMSQ(8),ISAVE(8),ANS(10),P(1)
      COMMON/DOUB/COE1,COE2,COE3
      DOUBLE PRECISION DI,DET,B,T,XBAR,STD,SUMSQ,DI,E,SB,ANS,X,D,ARRAY,
     1COE1,COE2,COE3
      COMMON/INT/MX,MY,M,IS,IDEGR
      L=N*M
      DO 110 I=1,N
      J=L+I
      KK=IS+I-1
      X(I)=ARRAY(KK,3)
      X(J)=ARRAY(KK,2)
  110 CONTINUE
```

```
C  GDATA, ORDER, MINV AND MULTR ARE FROM IBM SSP.
C THEY OCCUR IN LISTING CONVERTED TO DOUBLE PRECISION.
      CALL GDATA(N,M,X,XBAR,STD,D,SUMSQ)
      MM=M+1
      SUM=0.0
      NT=N-1
      DO 200 I=1,M
      ISAVE(I)=I
      CALL ORDER(MM,D,MM,I,ISAVE,DI,E)
      CALL MINV(DI,I,DET,B,T)
      CALL MULTR(N,I,XBAR,STD,SUMSQ,DI,E,ISAVE,B,SB,T,ANS)
      IF(ANS(7))240,230,230
  230 SUMIP=ANS(4)-SUM
      IF(SUMIP)240,240,250
  250 SUM=ANS(4)
  200 CONTINUE
  240 COE3=(ANS(1))
      COE2=(B(1))
      COE1=(B(2))
      WRITE(6,278)COE1,COE2,COE3
  278 FORMAT(2H  F10.2,F10.2,F10.2)
    2 RETURN
      END
      FUNCTION VEL(X1,X2,Y1,Y2,T1,T2)
C  CALCULATES VELOCITY BETWEEN TWO FIXES.
      DOUBLE PRECISION X1,X2,Y1,Y2,T1,T2,D,T,SCALE
      D=DSQRT((X1-X2)**2+((Y1-Y2)*SCALE(X1))**2)
      T=(T2-T1)*24.
      VEL=60.*D/T
      RETURN
      END
      SUBROUTINE GDATA (N,M,X,XBAR,STD,D,SUMSQ)
      DIMENSION X(1),XBAR(1),STD(1),D(1),SUMSQ(1)
      DOUBLE PRECISION X,XBAR,STD,D,SUMSQ,T1,T2
      IF(M-1) 105, 105, 90
   90 L1=0
      DO 100 I=2,M
      L1=L1+N
      DO 100 J=1,N
      L=L1+J
      K=L-N
  100 X(L)=X(K)*X(J)
  105 MM=M+1
      DF=N
      L=0
      DO 115 I=1,MM
      XBAR(I)=0.0
      DO 110 J=1,N
      L=L+1
  110 XBAR(I)=XBAR(I)+X(L)
  115 XBAR(I)=XBAR(I)/DF
      DO 130 I=1,MM
  130 STD(I)=0.0
      L=((MM+1)*MM)/2
```

```
      DO 150 I=1,L
  150 D(I)=0.0
      DO 170 K=1,N
      L=0
      DO 170 J=1,MM
      L2=N*(J-1)+K
      T2=X(L2)-XBAR(J)
      STD(J)=STD(J)+T2
      DO 170 I=1,J
      L1=N*(I-1)+K
      T1=X(L1)-XBAR(I)
      L=L+1
  170 D(L)=D(L)+T1*T2
      L=0
      DO 175 J=1,MM
      DO 175 I=1,J
      L=L+1
  175 D(L)=D(L)-STD(I)*STD(J)/DF
      L=0
      DO 180 I=1,MM
      L=L+I
      SUMSQ(I)=D(L)
  180 STD(I)= DSQRT( DABS(D(L)))
      L=0
      DO 190 J=1,MM
      DO 190 I=1,J
      L=L+1
  190 D(L)=D(L)/(STD(I)*STD(J))
      DF=SQRT(DF-1.0)
      DO 200 I=1,MM
  200 STD(I)=STD(I)/DF
      RETURN
      END
      SUBROUTINE MINV(A,N,D,L,M)
      DIMENSION A(1),L(1),M(1)
      DOUBLE PRECISION A,D,BIGA,HOLD
      D=1.0
      NK=-N
      DO 80 K=1,N
      NK=NK+N
      L(K)=K
      M(K)=K
      KK=NK+K
      BIGA=A(KK)
      DO 20 J=K,N
      IZ=N*(J-1)
      DO 20 I=K,N
      IJ=IZ+I
   10 IF( DABS(BIGA)- DABS(A(IJ))) 15,20,20
   15 BIGA=A(IJ)
      L(K)=I
      M(K)=J
   20 CONTINUE
      J=L(K)
```

```
      IF(J-K) 35,35,25
   25 KI=K-N
      DO 30 I=1,N
      KI=KI+N
      HOLD=-A(KI)
      JI=KI-K+J
      A(KI)=A(JI)
   30 A(JI) =HOLD
   35 I=M(K)
      IF(I-K) 45,45,38
   38 JP=N*(I-1)
      DO 40 J=1,N
      JK=NK+J
      JI=JP+J
      HOLD=-A(JK)
      A(JK)=A(JI)
   40 A(JI) =HOLD
   45 IF(BIGA) 48,46,48
   46 D=0.0
      RETURN
   48 DO 55 I=1,N
      IF(I-K) 50,55,50
   50 IK=NK+I
      A(IK)=A(IK)/(-BIGA)
   55 CONTINUE
      DO 65 I=1,N
      IK=NK+I
      HOLD=A(IK)
      IJ=I-N
      DO 65 J=1,N
      IJ=IJ+N
      IF(I-K) 60,65,60
   60 IF(J-K) 62,65,62
   62 KJ=IJ-I+K
      A(IJ)=HOLD*A(KJ)+A(IJ)
   65 CONTINUE
      KJ=K-N
      DO 75 J=1,N
      KJ=KJ+N
      IF(J-K) 70,75,70
   70 A(KJ)=A(KJ)/BIGA
   75 CONTINUE
      D=D*BIGA
      A(KK)=1.0/BIGA
   80 CONTINUE
      K=N
  100 K=(K-1)
      IF(K) 150,150,105
  105 I=L(K)
      IF(I-K) 120,120,108
  108 JQ=N*(K-1)
      JR=N*(I-1)
      DO 110 J=1,N
      JK=JQ+J
```

```
      HOLD=A(JK)
      JI=JR+J
      A(JK)=-A(JI)
  110 A(JI) =HOLD
  120 J=M(K)
      IF(J-K) 100,100,125
  125 KI=K-N
      DO 130  I=1,N
      KI=KI+N
      HOLD=A(KI)
      JI=KI-K+J
      A(KI)=-A(JI)
  130 A(JI) =HOLD
      GO TO 100
  150 RETURN
      END
      SUBROUTINE ORDER (M,R,NDEP,K,ISAVE,RX,RY)
      DIMENSION R(1),ISAVE(1),RX(1),RY(1)
      DOUBLE PRECISION R,RX,RY
      MM=0
      DO 130 J=1,K
      L2=ISAVE(J)
      IF(NDEP-L2) 122, 123, 123
  122 L=NDEP+(L2*L2-L2)/2
      GO TO 125
  123 L=L2+(NDEP*NDEP-NDEP)/2
  125 RY(J)=R(L)
      DO 130 I=1,K
      L1=ISAVE(I)
      IF(L1-L2) 127, 128, 128
  127 L=L1+(L2*L2-L2)/2
      GO TO 129
  128 L=L2+(L1*L1-L1)/2
  129 MM=MM+1
  130 RX(MM)=R(L)
      ISAVE(K+1)=NDEP
      RETURN
      END
      SUBROUTINE MULTR (N,K,XBAR,STD,D,RX,RY,ISAVE,B,SB,T,ANS)
      DIMENSION XBAR(1),STD(1),D(1),RX(1),RY(1),ISAVE(1),B(1),SB(1),
     1          T(1),ANS(1)
      DOUBLE PRECISION XBAR,STD,D,RX,RY,B,SB,T,ANS,RM,BO,SSAR,SSDR,SY,
     1FN,FK,SSARM,SSDRM,F
      MM=K+1
      DO 100 J=1,K
  100 B(J)=0.0
      DO 110 J=1,K
      L1=K*(J-1)
      DO 110 I=1,K
      L=L1+I
  110 B(J)=B(J)+RY(I)*RX(L)
      RM=0.0
      BO=0.0
      L1=ISAVE(MM)
```

```
      DO 120 I=1,K
      RM=RM+B(I)*RY(I)
      L=ISAVE(I)
      B(I)=B(I)*(STD(L1)/STD(L))
  120 BO=BO+B(I)*XBAR(L)
      BO=XBAR(L1)-BO
      SSAR=RM*D(L1)
  122 RM=DSQRT(DABS(RM))
      SSDR=D(L1)-SSAR
      FN=N-K-1
      SY=SSDR/FN
      DO 130 J=1,K
      L1=K*(J-1)+J
      L=ISAVE(J)
  125 SB(J)= DSQRT( DABS((RX(L1)/D(L))*SY))
  130 T(J)=B(J)/SB(J)
  135 SY=DSQRT(DABS(SY))
      FK=K
      SSARM=SSAR/FK
      SSDRM=SSDR/FN
      F=SSARM/SSDRM
      ANS(1)=BO
      ANS(2)=RM
      ANS(3)=SY
      ANS(4)=SSAR
      ANS(5)=FK
      ANS(6)=SSARM
      ANS(7)=SSDR
      ANS(8)=FN
      ANS(9)=SSDRM
      ANS(10)=F
      RETURN
      END
```

## Appendix B

## Digitisation of gravity records

The paper chart analogue records were digitised on a D-Mac Pen Follower table. The Pen-Follower produces punched paper tape which is read by an IBM 1130 computer. The computer calculates, from the data on the tape, the gravity readings at the digitised points.

The points A, B and C (Fig.58) are first digitised to define the position of the chart on the table. The times at A and B, $T_1$ and $T_2$, are also punched onto the tape. The gravimeter spring tension and the full scale reading are punched in and then the analogue trace on the record is digitised. The computer calculates the gravity values in gravimeter units and outputs them on cards together with the times of the readings and the spring tensions.

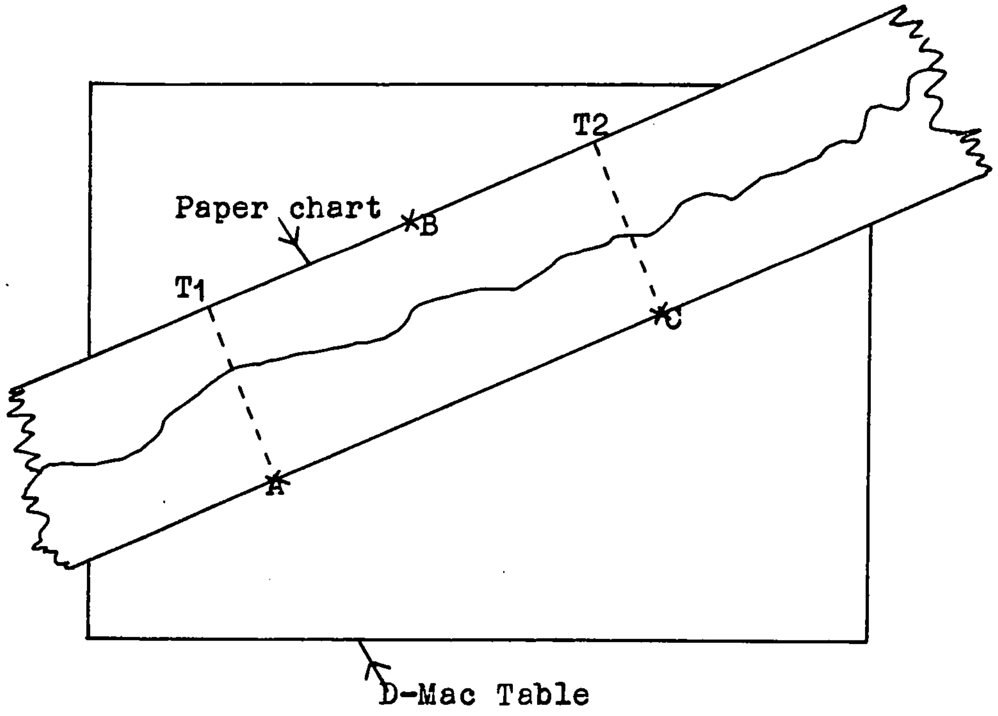


Figure 58. D-Mac Pen Follower digitisation of gravity records.

## Appendix C

## Wide-angle reflection results

The following results were calculated by A.G. McKay, University of Durham from data collected on the 1970 cruise.

The table overleaf shows the interval velocities and thicknesses obtained from arrivals interpreted as wide-angle reflections.

Station 2, near St. Kilda is the only shallow water station. Wide angle reflections were completely obscured by seabed multiples, but refracted arrivals stand out clearly, showing the usefulness of this technique for shallow refraction work.

Station 6 appears to exhibit a velocity reversal with depth, but the quoted standard errors show that this need not be so. This is one of the poorer stations, with much sea-noise on the record.

The record from station 1, to the southwest of the Anton-Dohrn Seamount is one of the clearest and allowed the determination of interval velocities to over 4 km beneath the seabed. The velocities in layers 3 and 4 are typical of consolidated sediments.

Station 3 is 24 km east of an unreversed refraction line of Ewing and Ewing (1969) where they observed a 2.48 km thickness of semi-consolidated sediments with a velocity of 2.08 km/s. At station 3 we observe a total of 2.0 km of semi-consolidated sediments with about the same velocity.

The station positions are marked on Fig.6.

## Wide Angle Reflections

| Station Number | Position of Buoy | | Velocities (km/s). | | | Water Depth | Thickness (metres). | | |
|---|---|---|---|---|---|---|---|---|---|
| | Latitude | Longitude | V1 | V2 | V3 | | T1 | T2 | T3 |
| 1 | 57°07'N | 12°12'W | 1.935±0.042 | 1.957±0.072 | 3.882±0.237 | 2008±9 | 1090±24 | 894±33 | 2281±140 |
| 2 | 57°56' | 08°48' | | | | 146±1 | | | |
| 3 | 58°13' | 10°08' | 2.120±0.077 | 2.035±0.641 | 2.045±0.235 | 1970±9 | 742±27 | 466±147 | 780± 90 |
| 4 | 59°56' | 11°36' | 1.809±0.041 | 2.032±0.056 | | 1181±6 | 480±11 | 668± 20 | |
| 5 | 59°19' | 07°52' | 2.133±0.037 | | | 1233±5 | 1730±31 | | |
| 6 | 60°50' | 03°45' | 1.830±0.211 | 1648±0.108 | | 948±4 | 434±50 | 275±18 | |
| 7 | 59°57' | 08°57' | 1.808±0.020 | | | 1299±6 | 732±9 | | |
| 8 | 58°46' | 10°27' | 1.761±0.075 | | | 1875±8 | 520±22 | | |
| 9 | 58°37' | 09°56' | 2.258±0.590 | | | 1830±8 | 550±143 | | |

## Appendix D

## Gravity interpretation program GRAVZ

This program calculates the gravity anomaly caused by a model made up of layers and individual bodies of specified densities. The calculated anomaly is compared to the observed anomaly. The station points, bathymetry and observed gravity values are read in from the standard data bank.

### Input.

The data from the data bank is read in under Logical Unit No.1.

All other data is read in under Logical Unit No.8.

Both sets of data are ended by an ENDFILE.

The data bank card format is:-

| | Time. | Distance. | Latitude. | Longitude. | Bathymetry. | Free-air gravity. | Bouguer gravity. | Magnetics. |
|---|---|---|---|---|---|---|---|---|
| | (days) | (km) | (degrees) | (degrees) | (km) | (mgal) | (mgal) | (gamma) |
| Format: | F11.5 | F9.3 | F12.6 | F12.6 | F7.4 | F9.3 | F9.3 | F11.1 |

Program is set up to use station points at 2 km intervals. Other input data is as follows:-

1st Card. Either 1.0 or -1.0. Format:- F10.0. +ve indicates that bathymetry from data is to be used. -ve indicates that it is not to be used.

2nd Card. Title. Format:- 80A1.

3rd Card. Density of first layer, spacing of body points, No. of body points. Format:- 2F10.0, I10.

4th Card. Depths of body points. First point must lie below first station point. Format:- 8F10.0. Cards continue until all body points have been read in.

Next Card. As for 3rd card but for next layer. Cards continue until all layers have been read in.

Card after last layer is ENDFILE if data is finished or 0.0 (Format:- F10.0) if individual bodies are to follow.

| | |
|---|---|
| Next Card. | Demsity contrast of individual body, No. of body points. Format:- F10, I10. |
| Next Cards. | Body point x-coord., body point z-coord. Repeat until all body points are read in. Format:- 8F10.0. |
| Next Card. | Data for next individual body or ENDFILE if data is finished. |

Output.

All the model data is printed out followed by station point values of:-

Day, Time, Distance, Bathymetry, Observed Anomaly, Calculated Anomaly, Difference, Bouyancy inequilibrium.

N.B. Bouyancy inequilibrium has no meaning if individual bodies have been used in the model.

```
   23 X1=BODX(K)
      Z1=BODZ(K)
      X2=BODX(K+1)
      Z2=BODZ(K+1)
   24 HYP=RR(X1,X2,Z1,Z2)
      SI=(Z2-Z1)/HYP
      CI=(X1-X2)/HYP
      IF(X2-P(I))31,32,31
   32 P2=PIB2
      GO TO 33
   31 P2=ATAN2(Z2,X2-P(I))
   33 IF(X1-P(I))41,42,41
   42 P1=PIB2
      GO TO 43
   41 P1=ATAN2(Z1,X1-P(I))
   43 IF(X2.EQ.P(I))X2=P(I)+0.001
      IF(X1.EQ.P(I))X1=P(I)+0.001
      R=RR(X2,P(I),Z2,0.)/RR(X1,P(I),Z1,0.)
      AP=2.*GC*RHO*(-((X1-P(I))*SI+Z1*CI)*(SI*ALOG(R)+CI*(P2-P1))+
     1 Z2*P2-Z1*P1)
      IF(BODZ(K+1).GT.BODZ(K)) ACAL(I)=ACAL(I)+AP
      IF(BODZ(K+1).LE.BODZ(K)) ACAL(I)=ACAL(I)-AP
   30 CONTINUE
      RETURN
      END
      SUBROUTINE GRAVN(P,NX,RHO,BODX,BODZ,N,ACAL)
C      THIS SUBROUTINE CALCULATES THE ANOMALY CAUSED BY AN INDIVIDUAL
C      BODY FED INTO PROGRAM AFTER THE LAYERS.
      DIMENSION P(500),ACAL(500),BODX(1000),BODZ(1000)
      RR(X,P,Z,ZD)=SQRT((X-P)**2+(Z-ZD)**2)
      DATA PIB2,GC/1.570796,6.667/
      N=N-1
   12 DO 30 I=1,NX
      ACAL(I)=0.
      DO 30 K=1,N
      IF(BODZ(K+1).EQ.BODZ(K))GOTO 30
      IF(BODZ(K+1).GT.BODZ(K))GO TO 23
      X1=BODX(K+1)
      Z1=BODZ(K+1)
      X2=BODX(K)
      Z2=BODZ(K)
      GO TO 24
   23 X1=BODX(K)
      Z1=BODZ(K)
      X2=BODX(K+1)
      Z2=BODZ(K+1)
   24 HYP=RR(X1,X2,Z1,Z2)
      SI=(Z2-Z1)/HYP
      CI=(X1-X2)/HYP
      IF(X2-P(I))31,32,31
   32 P2=PIB2
      GO TO 33
   31 P2=ATAN2(Z2,X2-P(I))
   33 IF(X1-P(I))41,42,41
```

```
   42 P1=PIB2
      GO TO 43
   41 P1=ATAN2(Z1,X1-P(I))
   43 IF(X2.EQ.P(I))X2=P(I)+0.001
      IF(X1.EQ.P(I))X1=P(I)+0.001
      R=RR(X2,P(I),Z2,0.)/RR(X1,P(I),Z1,0.)
      AP=2.*GC*RHO*(-((X1-P(I))*SI+Z1*CI)*(SI*ALOG(R)+CI*(P2-P1))+
     1 Z2*P2-Z1*P1)
      IF(BODZ(K+1).GT.BODZ(K)) ACAL(I)=ACAL(I)+AP
      IF(BODZ(K+1).LE.BODZ(K)) ACAL(I)=ACAL(I)-AP
   30 CONTINUE
      RETURN
      END
C       MAIN PROGRAM 'GRAVZ'.
C    CALCULATES ANOMALY CAUSED BY A BODY DEFINED IN LAYERS AND
C    INDIVIDUAL BODIES AND COMPARES IT TO THE OBSERVED ANOMALY.
      DIMENSION DAY(500),DIST(500),BATH(500),OBS(500),ARX(500),CMX(500),
     1 ANOMW(500),DM(500),ANOM(500),BOUY(500),NAME(20),DMZ(500)
      LAYER=1
      DENW=1.03
      BASE=40.0
      VELW=1.48
      DO 900 I=1,500
C    READ IN STATION POINT DISTANCES AND OBSERVED ANOMALY FROM
C    STANDARD DATA BANK.
      READ(1,10,END=14)DAY(I),DIST(I),BATH(I),OBS(I)
   10 FORMAT(F11.5,F9.3,24X,F7.4,F9.3,///)
  900 CONTINUE
C    READ IN 0 FOR YES IF BATHYMETRY DATA FROM DATA BANK IS NOT
C    TO BE USED IN MODEL. READ IN +VE IF IT IS.
   14 READ(8,103)YES
      IF(YES)13,12,12
   12 NX=I-1
C    CALCULATE ANOMALY OF WATER LAYER AND STORE.
      DO 400 J=1,NX
      ARX(J)=0.
      DMX(J)=BATH(J)
      BOUY(J)=DENW*BATH(J)
  400 CONTINUE
      CALL GRAVY(ARX,BATH,DIST,DENW,NX,ANOMW)
      GO TO 701
   13 NX=I-1
      DO 50 I=1,NX
      BATH(I)=0.
      DMX(I)=0.
      ANOMW(I)=0.
   50 CONTINUE
  701 READ(8,84)(NAME(I),I=1,20)
C    READ IN NAME OF PROFILE OR INTERPRETATION.
   84 FORMAT(20A4)
      WRITE(6,85)(NAME(I),I=1,20)
   85 FORMAT(5X,20A4)
C    READ IN DETAILS OF FIRST LAYER. DENSITY CONTRAST, SPACING
C    OF BODY POINTS AND NUMBER OF BODY POINTS.
```

```
C   DENSITY IS READ IN AS 0.0 IF LAST LAYER HAS BEEN READ AND
C   AN INDIVIDUAL BODY IS TO COME. ENDFILE FINISHES ALL DATA.
  700 READ(8,103,END=600)DENS,SPAC,NOM
  103 FORMAT(2F10.0,I10)
      IF(DENS.EQ.0.0)GO TO 601
C   READ IN DEPTHS OF BASE OF LAYER IN CORRECT ORDER.
      DO 500 I=1,NOM,8
      I7=I+7
      READ(8,30)(DM(II),II=I,I7)
   30 FORMAT(8F10.0)
  500 CONTINUE
      WRITE(6,81)LAYER
   81 FORMAT(///20X,'LAYER NO.'I3)
      WRITE(6,82)SPAC,DENS
   82 FORMAT(/5X,'SPACING OF POINTS=',F5.1,'KMS.   DENSITY='F5.2,
     1  'GRMS./CC.')
      WRITE(6,83)(DM(I),I=1,NOM)
   83 FORMAT(10F10.4)
      DO 102 I=1,NX
      IX=IFIX((DIST(I)-DIST(1))/SPAC)+1
      IX1=IX+1
      ARX(I)=(DIST(I)-DIST(1)-(FLCAT(IX-1)*SPAC))/
     1SPAC*(DM(IX1)-DM(IX))+DM(IX)
C   CALCULATE BOUYANCY ANOMALY OF LAYER.
      BOUY(I)=BOUY(I)+DENS*(ARX(I)-DMX(I))
  102 CONTINUE
C   CALCULATE ANOMALY OF LAYER.
      CALL GRAVY(DMX,ARX,DIST,DENS,NX,ANOM)
      DO 800 I=1,NX
      ANOMW(I)=ANOMW(I)+ANCM(I)
      DMX(I)=ARX(I)
  800 CONTINUE
      LAYER=LAYER+1
      GO TO 700
C   READ IN INDIVIDUAL BODY DATA. DENSITY CONTRAST AND NUMBER
C   OF BODY POINTS.
  601 READ(8,602,END=600)DENS,NOP
  602 FORMAT(F10.0,I10)
C   READ IN BODY POINTS. X COORD THEN Z COORD.
      READ(8,30)(DMX(I),DMZ(I),I=1,NOP)
      WRITE(6,604)DENS
  604 FORMAT(5X,'INDIVIDUAL BODY OF RELATIVE DENSITY',
     1 F5.2,'GRMS./CC.')
      WRITE(6,605)(DMX(I),DMZ(I),I=1,NOP)
  605 FORMAT(5X,'POSITIONS OF BODY POINTS ARE',/,
     1 10X,'DEPTH(KMS.)    POSITICN(KMS.)',
     2 (/,2F20.2))
C   CALCULATE ANOMALY OF BODY.
      CALL GRAVN(DIST,NX,DENS,DMX,DMZ,NOP,ANOM)
      DO 606 I=1,NX
      ANOMW(I)=ANOMW(I)+ANOM(I)
  606 CONTINUE
      GO TO 601
C   CALCULATE REGIONAL FRCM FIRST POINT.
```

```
  600 REG=ANOMW(1)-OBS(1)
      BAY=BOUY(1)
      WRITE(6,74)
   74 FORMAT(///5X,'DAY    TIME     DIST.    BATH.    OBS.ANOM.    '
     1 'CALC.ANOM.    DIFF.    ISOSTASY.')
C     SUBTRACT REGIONALS. CALCULATE DIFFERENCES BETWEEN CALCULATED
C     AND OBSERVED.
      DO 100 J=1,NX
      BOUY(J)=BOUY(J)-BAY
      ANOMW(J)=ANOMW(J)-REG
      DIFF=ANOMW(J)-OBS(J)
      IDAY=IFIX(DAY(J))
      IY1=IFIX((DAY(J)-FLOAT(IDAY))*24.+0.05)
      IY2=IFIX((DAY(J)-FLOAT(IDAY)-FLOAT(IY1)/24.)*1440.+0.5)
C     WRITE OUT RESULTS. BOUYANCY HAS NO MEANING IF IND. BODIES PRESENT.
      WRITE(6,75)IDAY,IY1,IY2,DIST(J),BATH(J),OBS(J),ANOMW(J),
     1DIFF,BOUY(J)
   75 FORMAT(/I8,I6,I2,F11.1,F9.3,F11.1,F14.1,F10.1,F11.2)
  100 CONTINUE
      STOP
      END
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