Geophysical investigations in the Faeroes to Scotland region, Northeast Atlantic

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GEOPHYSICAL INVESTIGATIONS
IN THE
FAEROES TO SCOTLAND REGION,
NORTHEAST ATLANTIC

A Thesis submitted for the Degree of
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by

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ABSTRACT

Gravity, magnetic and seismic reflection profiles from the sea area between the Faeroe Islands and Scotland were obtained on the 1967 and 1968 cruises of RRS John Murray. The submarine shelf adjacent to the Faeroe Islands is separated from the continental shelf and slope north of Scotland by the Faeroe-Shetland Channel. The purpose of the cruises was to provide geophysical evidence of the geological structure of the region.

Gravity and seismic reflection profiles across the Faeroes shelf, SE of the Faeroe Islands, indicate a substantial thickness of post-Mesozoic sediments. The gentle submarine slopes bordering the Faeroe-Shetland Channel are made up of seaward dipping sediments. Gravity profiles show that the Channel is associated with a Bouguer anomaly "high". This is interpreted as caused by a thinning of the crust beneath the Channel in close agreement with the predictions of the Airy-Heiskanen hypothesis of isostasy.

Geophysical surveys around the Hebrides, Orkneys and Shetlands represent a large area of previously uninvestigated British continental shelf and slope. The Bouguer anomaly map shows a large gravity "high" reaching 94 mgal which is continuous for 250 km and trends NNE-SSW across the shelf. This is interpreted as caused by a seaward extension of dense Precambrian basement rocks outcropping in NW Scotland. Large amplitude gravity "lows" have been outlined on the shelf and slope north of Scotland. A large amplitude "low" 70 km west of the Shetlands has been interpreted as caused by a deep sedimentary basin infilled by Mesozoic/Tertiary sediments and bounded on its SE margin by a large normal fault. A buried basement ridge has been located west of the gravity "low", near the shelf break in slope. Recent sediments form the continental slope which gently truncates the older Caledonian structures on the shelf.

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CHAPTER 1

INTRODUCTION

1-1. Geological setting.

The sea area between the Faeroe Islands, the Shetlands and northern Scotland represents about 75,000 sq.km of the NE Atlantic Ocean. The Faeroe Islands outcrop on a submarine shelf at the SE end of the Iceland-Faeroes Rise and the NE end of the Faeroe Rise (Fig. 1-1). The Faeroes shelf is separated from the continental shelf and slope north of Scotland by the NE-SW trending Faeroe-Shetland Channel, up to 1·6 km deep and 75 km wide. The only connection between the Faeroe Rise and the continental shelf north of Scotland is the narrow NW-SE trending Wyville Thompson Rise. The Wyville Thompson Rise, which reaches a depth of about 500 meters, separates the Faeroe-Shetland Channel to the NE from the Rockall Trough to the SW. The continental shelf break in slope north of Scotland occurs between 140 and 230 meters and the slope dips gently at about 2^{o} NW of the Outer Hebrides decreasing to about 1^{o} NE of the Shetlands.

The Faeroe Islands are made up of at least 3 km of Lower Tertiary plateau basalts (Walker and Davidson, 1936; Noe-Nygaard and Rasmussen, 1968; Tarling and Gale, 1968). Rockall Islet, at the SW end of the Faeroe Rise, probably represents a Lower Tertiary granite intrusive complex (Sabine, 1965; Miller and Mhor, 1965). Pre-Tertiary rocks are unknown from the two outcrops on the Faeroe Rise although metamorphic rocks have been dredged between Faeroe Bank and Rockall Bank (Carruthers et al., 1923). Unlike NW Scotland, the plateau basalts on the Faeroe Islands are not associated with any known intrusive complexes and were probably extruded from NW-SE trending sub-aerial fissures and shield volcanoes (Noe-Nygaard, 1968). The extrusion of the lavas was followed by an intrusive period of

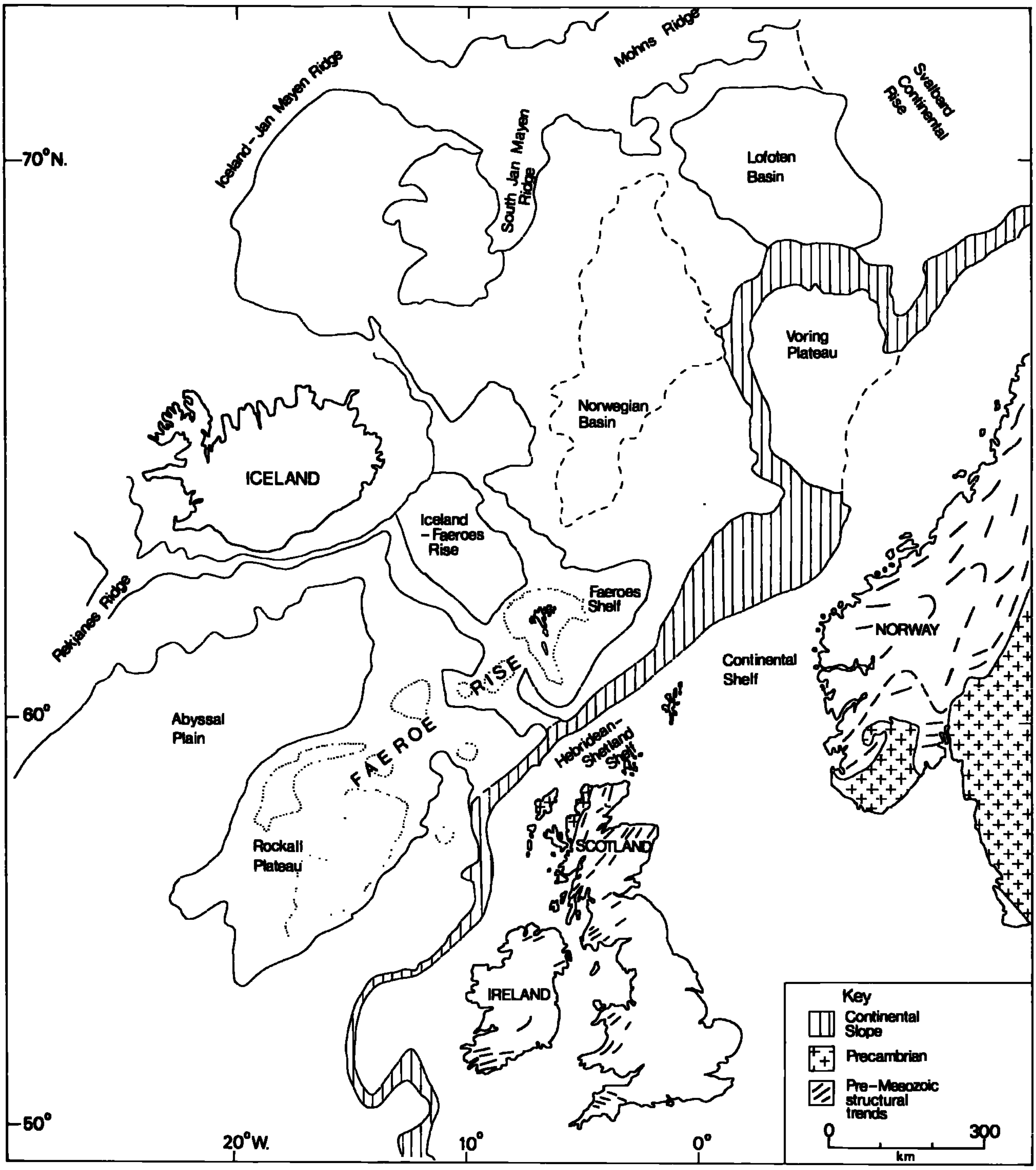


Fig. 1-1. Physiographic map of the Northeast Atlantic. Partly after Avery et al. (1968). Pre-Mesozoic structural trends after Rutten (1969).

dyke and sill emplacement. The final event in the Faeroe Islands appears to have been a gentle warping of the lavas into a NE-SW trending anticline which may have produced the present NW-SE trending pattern of "master" joints and fjords.

The land areas adjacent to the continental shelf and slope north of Scotland form a significant part of the Caledonian fold-belt. The Caledonian fold-belt in northern Scotland is divisible into three tectonic units: a Precambrian basement area to the west, a central metamorphic belt and a post-orogenic Old Red Sandstone area to the east. The Precambrian basement rocks form a broad NNE-SSW trending outcrop in West Sutherland where they include assemblages of gneisses and pyroxene granulites. Precambrian basement rocks (collectively referred to as the Lewisian) outcrop in the Outer Hebrides (Jehu and Craig, 1923), North Rona (Nisbet, 1961) and the Skerries (Geological Survey, 1957). In NW Scotland the Lewisian is overlain with marked unconformity by the Torridon Sandstones. During the late Precambrian and early Palaeozoic the Lewisian basement formed a stable foreland to a sedimentary trough to the SE (Watson, 1963). A monotonous series of sandstones and argillaceous sediments, which make up the Moine Series, were deposited in the trough at the same time as part of the Torridon Sandstone Series (Watson, 1963). The Moine Series were extensively migmatised and metamorphosed during the final Caledonian movements of late Silurian and early Devonian times (Giletti et al., 1961). Moine schists were overthrust NNW onto Lewisian basement at a shallow angle along the Moine Thrust belt, which extends from the north coast to the Sleat of Skye. The metamorphic belt is also made up of Dalradian schists and gneisses in central Scotland, SE of the Moine schists, but do not occur north of the Great Glen Fault. They may, however, be represented by the East Mainland metamorphic succession in the Shetlands (Miller and Flinn, 1966). Moine and Dalradian rocks of the metamorphic belt are overlain with widespread discordance in Caithness, Cromarty and Aberdeen by post-orogenic Old Red Sandstone sediments. It is probable that the coarse grained sediments were deposited in a deep trough within the metamorphic belt which extended from the flanks of Moray Firth to Caithness, the Orkneys and the Shetlands (Waterston, 1965). Devonian igneous activity involved the emplacement of granitic sheets and intrusives in Sutherland, Caithness and the Shetlands and the extrusion of lava in the Orkneys (Wilson et al., 1935) and the Shetlands (Flinn et al., 1968).

Mesozoic sediments outcrop in the coastal areas of Scotland and in the Shiant Islands, North Minch (Hallam, 1965). A discontinuous sequence of Trias to Kimmeridge occurs in East Sutherland at the NW margin of the Moray Firth (Bailey and Weir, 1932). The thickest Jurassic succession is observed in Skye and Raasay where the basal sediments are Lower Lias limestones (Hallam, 1965). The coarse sediments from the Middle Jurassic Great Estuarine Series in Skye and Raasay were derived mainly by erosion of metamorphic and intrusive rocks of the Scottish Highlands (Hudson, 1964). Cretaceous sediments outcrop in Mull and Morven on the west coast, and glacial erratics of Lower and Upper Cretaceous age occur in East Sutherland (Hallam, 1965). At the end of the Cretaceous the coastal areas were partly uplifted, faulted and peneplained prior to the extrusion of Lower Tertiary plateau basalts.

Tertiary igneous activity in NW Scotland formed part of the Thulean province extending to Northern Ireland, the Faeroe Rise, Iceland and Greenland. The plateau basalts in NW Scotland are frequently intruded by acid to ultrabasic complexes (Richey, 1961). The complexes are associated with the products of explosion vents and dyke swarms and examples have been described from Ardnamurchan, Skye, Rum, Mull and St. Kilda (Stewart, 1965). Tertiary sediments are confined to thin terrestrial accumulations below and within the lava sequence.

During the Quaternary Scotland was extensively glaciated. The glaciation probably extended to the Outer Hebrides, North Rona, the Orkneys and the Shetlands. The present position of the first post-glacial shoreline suggests an isostatic post-glacial recovery of Scotland (Sissons, 1965).

The dominant trend direction of the main faults in Scotland is NNE-SSW and NE-SW (Pitcher, 1969). The Great Glen Fault has been interpreted as a sinistral transcurrent fault (Kennedy, 1946). Holgate (1969) has proposed two transcurrent movements along the Fault line. The first was a sinistral movement of about 120 km, similar to that envisaged by Kennedy (1946), which occurred in late Lower or early Middle Old Red Sandstone times and the second, a dextral movement of about 29 km during the Lower Tertiary. Flinn (1961 and 1969) has suggested that the sinistral component extends beyond the Moray Firth to be represented in the Shetlands by the N-S trending Walls Boundary Fault. Further transcurrent faults have been proposed along NNE-SSW trends which displace parts of the Moine and Dalradian outcrop (Pitcher, 1969). Dearnley (1962) suggested that the Scourie assemblages of the Outer Hebrides and NW Scotland are displaced by a sinistral transcurrent fault at the NW margin of the North Minch.

1-2. Previous geophysical surveys.

There had been a limited number of geophysical investigations of the sea area between the Faeroe Islands and Scotland before the 1967 and 1968 cruises of RRS John Murray. Sea gravimeter traverses of the continental shelf and slope north of Scotland were obtained on the 1965 cruises of MV Hvidbjørnen (Geodaetisk Institut Copenhagen, personal communication) and HMS Hecla (Midford, 1965). The preliminary traverses showed that the continental shelf was associated with large gravity and magnetic anomalies. Midford (1965) interpreted the gravity "lows", on a single traverse between west of the Shetlands and the North Minch, as caused by deep sedimentary basins. The only other recorded investigations include a reversed seismic refraction profile across the SE margin of the Wyville Thompson Rise (Ewing and Ewing, 1959) and a closely spaced magnetic survey SE of Lerwick, Shetland (Wilson, 1965).

Geophysical investigations in the Faeroe Islands, the Shetlands and the Orkneys have been completed. Saxov and Abrahamsen (1964 and 1966) described the results of density measurements and gravity surveys of the basalt lavas in the Faeroe Islands. Seismic refraction profiles show that the basalts extend to depths of at least 2 to 5 km (Palmáson, 1965). Palaeomagnetic investigations by Abrahamsen (1967) were followed by isotopic age determinations of the lavas by Tarling and Gale (1968). A complex pattern of Bouguer anomalies ranging from +2 to +47 mgal have been obtained from geophysical surveys of the Shetlands (McQuillin and Brooks, 1967). Several large magnetic anomalies were discovered in Unst, Shetland. The pattern of Bouguer anomalies outlined on the Orkneys is simpler and more clearly related to the local geology (McQuillin, 1968). Geophysical data available from NW Scotland are restricted to the gravity traverses and density measurements obtained by Storry (1969) across the Ben Stack Line in West Sutherland.

Geophysical investigations of the sea area between the Faeroe Islands and Scotland have been completed since the 1967 and 1968 cruises of RRS John Murray. Stride et al. (1967) described a single seismic reflection profile from the Wyville Thompson Rise to the Faeroe Bank. A gravity traverse of the continental shelf and slope between the Pentland Firth and the Faeroe Bank was obtained on the 1968 cruise of MV Meteor (Deutches Hydrographisches Institut, personal communication). Aeromagnetic surveys of the region between the Faeroe Islands and the Shetlands north of 60°N have been completed on ESE-WNW traverses (Avery et al., 1968). The

Institute of Geological Sciences (IGS, 1968) aeromagnetic survey of Great Britain included the Shetlands, the Orkneys, the Outer Hebrides and part of the continental shelf north of Scotland. A description and qualitative interpretation of the aeromagnetic maps north of Scotland has been made by Flinn (1969). Stride et al. (1969) described the first complete seismic reflection traverse of the continental shelf and slope NW of the Pentland Firth.

1-3. Aims of this investigation.

The purpose of this thesis is to describe the reduction and interpretation of gravity, magnetic and seismic reflection profiles obtained between the Faeroe Islands and Scotland on the 1967 and 1968 cruises of RRS John Murray. Where possible data from other surveys in the region have been incorporated. Chapter 2 describes the observation and reduction of geophysical data. An account of the computer methods used to reduce the data, the observational errors and the presentation of results is given. A general description and interpretation of geophysical data obtained between the Faeroe Islands and Scotland is the subject of Chapter 3. A brief account is given of the evidence relating to the deep structure of the Faeroe-Shetland Channel and the shallow structure of the Faeroes shelf and the Channel. Chapter 4 describes in detail the geological interpretation of marine geophysical data from the continental shelf and slope north of Scotland. Evidence of the geological structure is obtained from the gravity and magnetic results, seismic reflection profiles and the geology of adjacent land areas. Interpretation of gravity and magnetic profiles have been made, where applicable, using computer techniques available at Durham. The interpretations are intended as working hypotheses which could be tested by further seismic experiments and bottom sampling. A general geological interpretation of the Faeroes to Scotland region and its regional implications are considered in the concluding remarks of Chapter 5.

CHAPTER 2

GEOPHYSICAL SURVEYS AND THEIR REDUCTION

2-1. Geophysical surveys.

The recording and reduction of marine geophysical data obtained in the Faeroes to Scotland region on RRS John Murray are discussed in the following sections. The 1967 cruise of RRS John Murray provided reconnaissance traverses north of Scotland as an extension of the Iceland-Faeroes Rise survey described by Stacey (1968). In 1968 a regional geophysical survey of the continental shelf and slope around the Outer Hebrides, the Orkneys and the Shetlands was completed. The tracks of the RRS John Murray in the Faeroes to Scotland region are shown in Figure 2-1.

Variations in the Earth's gravity field were recorded with a Graf-Askania sea gravimeter on loan from the Department of Geodesy and Geophysics, Cambridge University. The gravimeter was operated at a controlled temperature of 40°C and required manual adjustment of the main spring. A fault developed in the latter part of the 1968 cruise which allowed the gravimeter to cool down to 27°C. The meter was immediately tied into Thorshavn gravity base station where no measurable discrepancy was recorded. The gravimeter was mounted on an electrically erecting gyrostabilised platform manufactured by the Anshütz Company, Kiel. The gyro erection system was operated in the "fast" mode during the 1967 cruise and the "normal" mode during the 1968 cruise. The movements of the damped beam were recorded on an Enograph chart recorder. A cross-coupling computer on loan from the Department of Geodesy and Geophysics, Cambridge University was available on the 1968 cruise.

Variations in the Earth's total magnetic field were recorded on both cruises using a direct reading proton magnetometer supplied by the Natural Environment Research Council. Echo-soundings were made with a T.H. Gifft

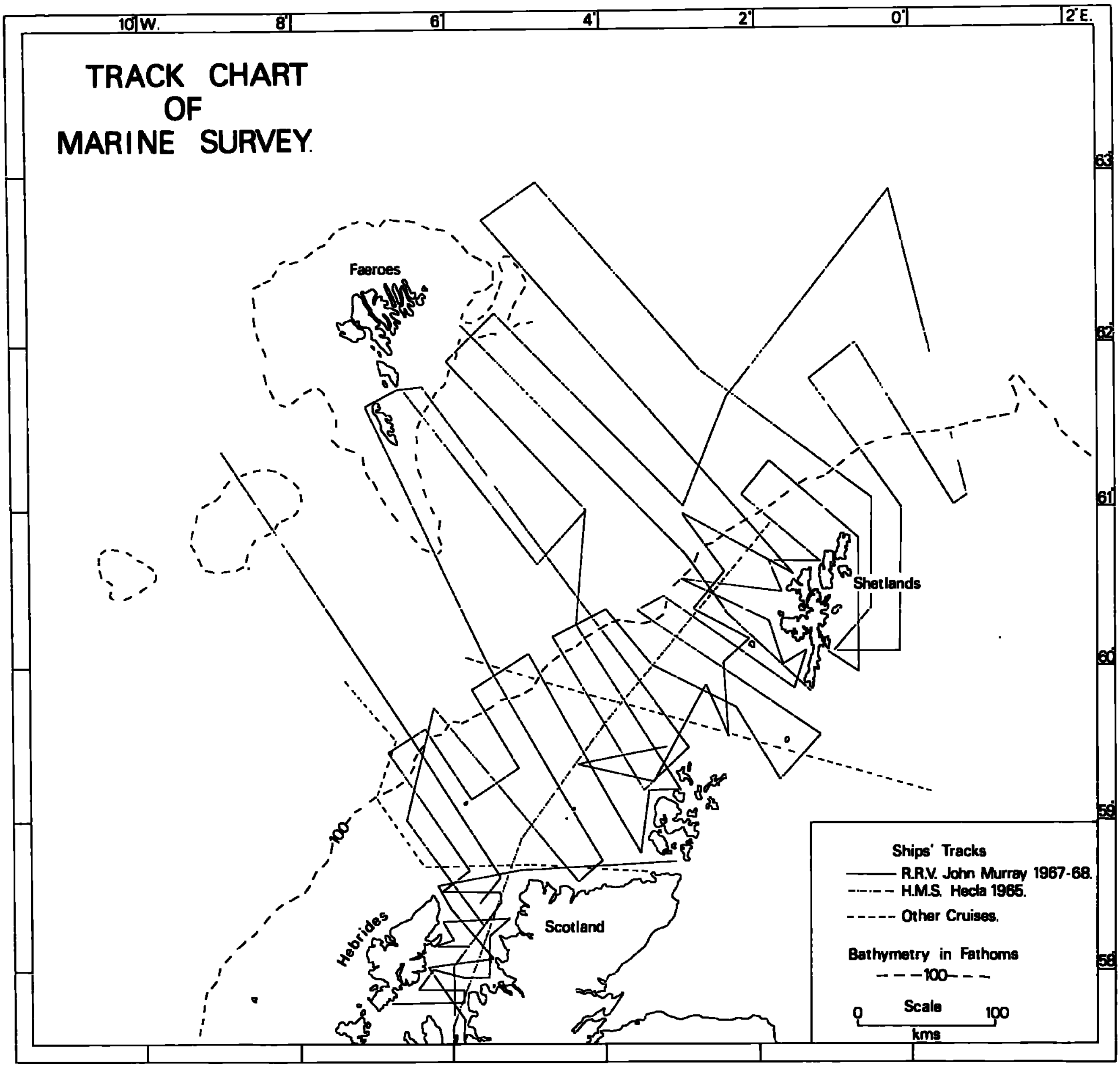


Fig. 2-1. Track chart of marine geophysical surveys in the Faeroes to Scotland region.

model GR-T recorder and a Marconi Seagraph 3.

Continuous seismic reflection profiles were obtained during the 1968 cruise with an E.G. and G. seismic profiling system supplied by the Natural Environment Research Council. The seismic reflection "sparker" system was operated at 1,000 to 2,000 joules by firing at 1 second intervals. The "sparker" array consisted of 3 electrodes mounted 2 feet apart on a sledge towed astern of the ship. The receiving system consisted of a multi-element hydrophone array and an E.G. and G. Type 254 seismic recorder. The seismic reflection system was operated for survey speeds of 5-6 knots.

Navigation in the Faeroes to Scotland region was with the Decca Navigator system operated in the North Scottish chain. A mark 12 receiver was used in both cruises. Limited use was made of a Loran A recording system near the Faeroe Islands and the Shetlands where Decca control was poor.

A common digital clock provided time marks at 10 minute intervals on the 1967 cruise simultaneously on the echo-sounder, Varian recorder and the Enograph. Due to a failure of the clock early in the 1968 cruise the time marks had to be triggered manually from an independant digital clock.

2-2. Gravity surveys and their reduction.

2-2-1. Introduction.

Since the reconnaissance gravity traverse of HMS Hecla (Midford, 1965) four cruises have added approximately 2910 gravity stations in the Faeroes to Scotland region. The cruises have been divided up into arbitrary "legs". Each "leg" corresponds to a single passage by one ship between two ports (Table 2-1). With the exception of Kirkwall the ports were locations of gravity base stations used to compute the values of gravity at sea. Gravity observations during the 10 cruise "legs" were made with a Graf-Askania GSS2 sea gravimeter mounted on a gyrostabilised platform. The results of

TABLE 2-1

SURFACE SHIP GRAVITY DATA FROM THE FAEROES TO SCOTLAND REGION

Latitude 58° 24·5'N - 63° 00·0'N
Longitude 01° 00·0'E - 10° 00·0'W

Leg Number	Ship	Dates	Ports of call	Stations	Reference
1	M.V. Hvidbjørnen	May 27-28, 1965	Copenhagen-Rekyjavik	137	Geodaetisk Institut, Copenhagen
2	H.M.S. Hecla	December 11-12, 1965	Rekyjavik-Devonport	84	Durham (Midford, 1965)
3	R.R.S. John Murray	May 28-June 5, 1967	Stornoway-Thorshavn	105	Durham
4	R.R.S. John Murray	June 23-24, 1967	Thorshavn-Lerwick	108	Durham
5	R.R.S. John Murray	June 25-28, 1967	Lerwick-Kirkwall	424	Durham
6	R.R.S. John Murray	June 30-July 4, 1967	Kirkwall-Plymouth	55	Durham
7	M.V. Meteor	July 2-6, 1968	Hamburg-Thorshavn	154	Deutches Hydrographisches Institut
8	R.R.S. John Murray	July 4-12, 1968	Stornoway-Lerwick	1040	Durham
9	R.R.S. John Murray	July 14-19, 1968	Lerwick-Thorshavn	447	Durham
10	R.R.S. John Murray	July 19-26, 1968	Thorshavn-Plymouth	440	Durham

the 10 cruise "legs" have been incorporated in a free air anomaly map of the Faeroes to Scotland region (Fig. 3-1) and a Bouguer anomaly map of the continental shelf and slope north of Scotland (Fig. 4-1).

The reduction of surface ship gravity data from "legs" 3-6 and "legs" 8-10 on RRS John Murray are discussed in the following sections. The data from "legs" 3-6 were reduced manually but data from "legs" 8-10, which contributed about 60% of all the sea gravity stations, were reduced by a computer programme written for the N.U.M.A.C. I.B.M. 360/67. The details of the computer reduction are followed by a brief account of observational errors and data presentation.

2-2-2. Gravity base stations.

Gravity stations at sea are established by computing differences from land base stations where gravity is accurately known. The IGS gravity base stations at Lerwick, Stornoway and Plymouth occupied on the RRS John Murray cruises are based on a fundamental base station at Pendulum House, Cambridge Observatory. The gravity stations established at sea therefore depend on the absolute value of gravity at Pendulum House. Bullard and Jolly (1936) obtained a value of 981265•0 mgal for gravity at Pendulum House based on the Potsdam system. This value has been used in previous gravity surveys (e.g. Midford, 1965). However, a more accurate value was obtained by Cook (1953) as 981268•5 ± 0•3 mgal.

The Cook (1953) value has been used to determine the value of gravity at the IGS base stations, occupied during the marine surveys. The gravity base station at Thorshavn I (Saxov and Spellauge, 1967) occupied during the cruise "legs" (Table 2-1) is based on an absolute gravity value at Copenhagen Buddinge. The determination at Thorshavn I was readjusted to be based on Pendulum House using observed gravity differences between Pendulum House and Europe (Solaini et al., 1963; Winter et al., 1961; Cook, 1952). The results have been tabulated (Table 2-2).

TABLE 2-2

GRAVITY BASE STATIONS OCCUPIED DURING THE MARINE SURVEYS ADJUSTED TO THE FUNDAMENTAL STATION AT PENDULUM HOUSE, CAMBRIDGE OBSERVATORY ($g = 981268 \cdot 5$ mgal).

Base Station Name	Reference	Gravity (mgal)
Millbay Dock	IGS	981130•5
Stornoway Town	IGS	981830•4
Lerwick Town	IGS	981963•4
Thorshavn I	Saxov and Spellauge, 1967	982108•6

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 for gravity at sea.

2-2-3. Free air anomaly reduction.

An important problem in the reduction of marine gravity data is the correct computation of the Eötvös correction (Harrison, 1960). This is caused by the change in centripetal acceleration experienced on a gravimeter when a ship travels relative to the rotating spherical Earth. The Eötvös correction (E) is given by Worzel (1959):

$$E = 7 \cdot 487 \times \mathrm{Sin}C\mathrm{Cos}A \times S + S^2/R$$

where C = ship's heading

A = latitude of ship

S = speed of ship (knots)

R = radius of the earth

In the Faeroes to Scotland region the maximum value of E for a ship travelling at 9 knots is approximately 33 mgal. Most of the ship's tracks for "legs"

3-6 and "legs" 8-10 trend NW-SE (Fig. 2-1). For a ship travelling on this course at 8 knots a change or determination error in the heading by 1 degree causes a change in E of 0·4 mgal but a change or error in the speed of the ship of 1 knot causes a change of 2·7 mgal. It is therefore of some importance to establish as accurately as possible the true heading and speed over the ground. This ultimately depends on the accuracy of the navigation system used.

A Decca navigator system was used during the 1967 and 1968 cruises of RRS John Murray. During "legs" 3-6 the positions were recorded at half hour intervals and plotted on a 1:1,000,000 plotting sheet. The positions were then manually adjusted to give a smoothed ship's track which was used to compute the Eötvös correction averaged for approximately one hour. The smoothed value was then assigned to each ten minute gravity reading. During "legs" 8-10 the positions were obtained at ten minute intervals and the amount of heading changes and speed variations between each pair of positions computed. It was clear that significant speed and heading changes occurred in regions far from the Decca transmitter stations. Variable errors, particularly at night, occur in the Deccometer readings due to skywave interference. In regions where two Decca patterns cross each other at shallow angles a "diamond of error" occurs around the correct receiver position. A marine gravity reduction programme (MGRED, Appendix A) was written to compute the smoothed ship's tracks from the observed positions by assuming each latitude and longitude to be in error.

The first computation stage of MGRED reads the gravity header cards (Appendix A-1) containing information on the gravity at sea-level at the ports, Enograph and gravimeter calibration factors and the programme storage requirements. Following a short computation for the drift of the gravimeter the navigation cards (Appendix A-1) are read and stored. Each card has a time identification, latitude and longitude value obtained as punched card output from a programme written by the Decca Navigator Company to convert Deccometer readings to geographical co-ordinates. MGRED sorts the computed positions into a number of courses. A change in the ship's course is defined when the heading change between two pairs of positions exceeds a specified value. The programme checks that the course has not been triggered incorrectly by a position in error. The main computation begins by operating on each stored course sequentially. A regression line is fitted to the positions defined for each course. The observed positions are then brought perpendicularly onto the regression line and re-defined as the "smoothed" position. The distance and speed are computed between pairs of "smoothed" positions and stored. Gravity cards (Appendix A-1) are then read for each "smoothed" position. Free air anomalies are computed from the 1930 International Gravity formula from the "smoothed" positions. The results are punched on cards in a similar format (Appendix A-1) to that proposed by Talwani (1966a). If the last gravity anomaly has been computed for the course, computation is returned to the main loop and a new course begun.

The method depends for success on the correct determinations of course changes as specified by the heading tolerance. A problem occurs if a change in course is not detected. This could occur if a ship was affected by a gradual drift causing an undetected change in course between two pairs of observations. The traverses of the shelf and slope north of Scotland were generally less than 100 km. A heading tolerance of 5^o to 9^o was used for "legs" 8-10 so the traverses of the shelf and slope were divided into a large number of courses, the longest not exceeding twelve hours. It is probable that serious errors have not resulted from drifting of the ship for these time intervals. This is generally confirmed by the continuity of "smoothed" tracks plotted on the shelf. It is possible that for long courses such as occurred between the Faeroe Islands and Scotland a systematic error in the Eötvös correction of up to 8 mgal could occur. The general inaccuracies in the navigation data adjacent to the Faeroe Islands caused a sufficient number of course changes to reduce the errors due to drift.

2-2-4. Bouguer anomaly reduction.

The Bouguer anomaly is obtained by correcting the computed free air anomaly for the mass deficiency of the water. The mass deficiency can be computed for each depth observation from the horizontal infinite slab formula. Errors in the application of the slab formula will occur if the sea bottom topography changes rapidly around a station. In the Faeroes to Scotland region the maximum submarine slopes do not exceed 3° which would cause a maximum likely error of 1-2 mgal for deep water stations. The Bouguer anomaly profiles used in interpretations, or in the computation of isostatic anomalies, incorporate a Bouguer correction computed by GRAVN (Bott, 1969a).

A common practise in the choice of topography density for the computation of the Bouguer correction is to use an average crustal density of 2·67 g/cm^3 (Woollard and Strange, 1961). The method of Nettleton (1939) chooses a density which shows the least correlation with topography. A meaningful approach is to use the mean density of the crystalline basement in the region, if it is known. The thick Lower Tertiary basalt lavas on the Faeroe Islands (Palmason, 1965) probably extend SE to underlie large thicknesses of recent sediments on the Faeroes shelf (Section 3-5). The basalt lavas have a mean density of 2·86 g/cm^3 (Saxov and Abrahamsen, 1966). North of Scotland, islands of Lewisian basement rocks outcrop on the shelf. 254 samples of Lewisian gneiss from the Outer Hebrides have a mean density of 2·80 g/cm^3 (R. McQuillin, personal communication). Although the geological structure of the Faeroe-Shetland Channel is unknown the mean density of crystalline basement in the region was determined between the Faeroe Islands lavas and the Outer Hebrides gneisses as 2•83 g/cm^3. An error in the assumed density of ± 0•03 g/cm^3 would cause a maximum error of ± 0•2 mgal for the continental shelf north of Scotland and ± 2•0 mgal for the Faeroe-Shetland Channel.

2-2-5. Errors of observation.

Important sources of error occur in a gravity reading at sea which are independent of the navigation system used. A problem of a gravimeter mounted on an electrically erecting gyrotable is platform off-levelling. Errors due to off-levelling occur if the platform is subjected to a tilt in the presence of horizontal accelerations of a similar frequency (Harrison, 1960). The level of the platform can be corrected at sea by manually applying error signals. Checks of platform levelling were made during scientific watches and corrections were not applied unless the levelling bubbles deviated more than 5 divisions from level. Calibration of the off-levelling error on the pitch and roll axis of the platform showed that for a table off-levelling error of 5 divisions the corresponding reduction in the gravity reading was 1 mgal.

For a sea gravimeter with heavy damping and small deflection of the beam Lacoste and Harrison (1960) have shown that errors due to cross-coupling can occur. Cross-coupling errors occur if horizontal accelerations act in the direction of the beam with the same period as the vertical motions of the beam. The magnitude of these errors can be quite significant and they appear to depend on the sea state and the angle of approach of the swell to the ship (Wall et al., 1966; Talwani et al., 1966). The magnitude of the cross-coupling errors for "legs" 1-7 of the Faeroes to Scotland gravity surveys are unknown. Prior to the 1968 cruise the only published account of cross-coupling errors on RRS John Murray were seven determinations by Day (1967). A continuous recording cross-coupling computer was available for "legs" 8-10 of the 1968 cruise. The computer determines an instantaneous cross-coupling error from an output of the beam motion and the horizontal accelerations it experiences (Haworth,1967). The instantaneous error is then filtered by two low-pass filters to enable a direct comparison with the gravity reading recorded by the Enograph. The filtered cross-coupling errors sampled at half hour intervals for a period of three weeks on RRS John Murray are shown in Figure 2-2-2. The resulting histogram shows that although the error is normally ± 2 mgal, errors of up to ± 22 mgal can occur. Less than 10% of the sampled errors exceed 6•5 mgal (Fig. 2-2-2). Figure 2-2-1 shows the relation of the filtered cross-coupling error to changes of the relative angle of approach of the sea and swell measured anticlockwise from the direction of the ship's heading (Angle K, Fig. 2-2-1). There is a relation between the magnitude and polarity of the filtered cross-coupling error and the angle K. For the Graf-Askania sea gravimeter on RRS John Murray, which is mounted with its front plate facing forward and the beam pivot along the aft direction of the ship, the errors are generally positive for head seas and negative for following seas (Fig. 2-2-1). These results are in agreement with Wall et al. (1966), Bower (1966) and Day (1967). The magnitude of the errors even for average sea states suggest that corrections should be applied to the computed gravity anomalies. Cross-coupling errors have not, however, been applied to the data from "legs" 8-10 since it would not significantly improve the overall accuracy of the gravity anomaly maps.

The Graf-Askania sea gravimeter incorporates heavy magnetic damping to reduce the response of the beam to large vertical accelerations (Graf and Schulze, 1961). It has been shown that heavy damping can result in an amplitude reduction and an indication lag of a gravity anomaly (Graf and Schulze, 1961). Steep gravity gradients of up to 9 mgal/km have been recorded on the continental shelf north of Scotland. A particularly sharp change in gravity occurs on the NW margin of gravity "high" A (Fig. 4-10).

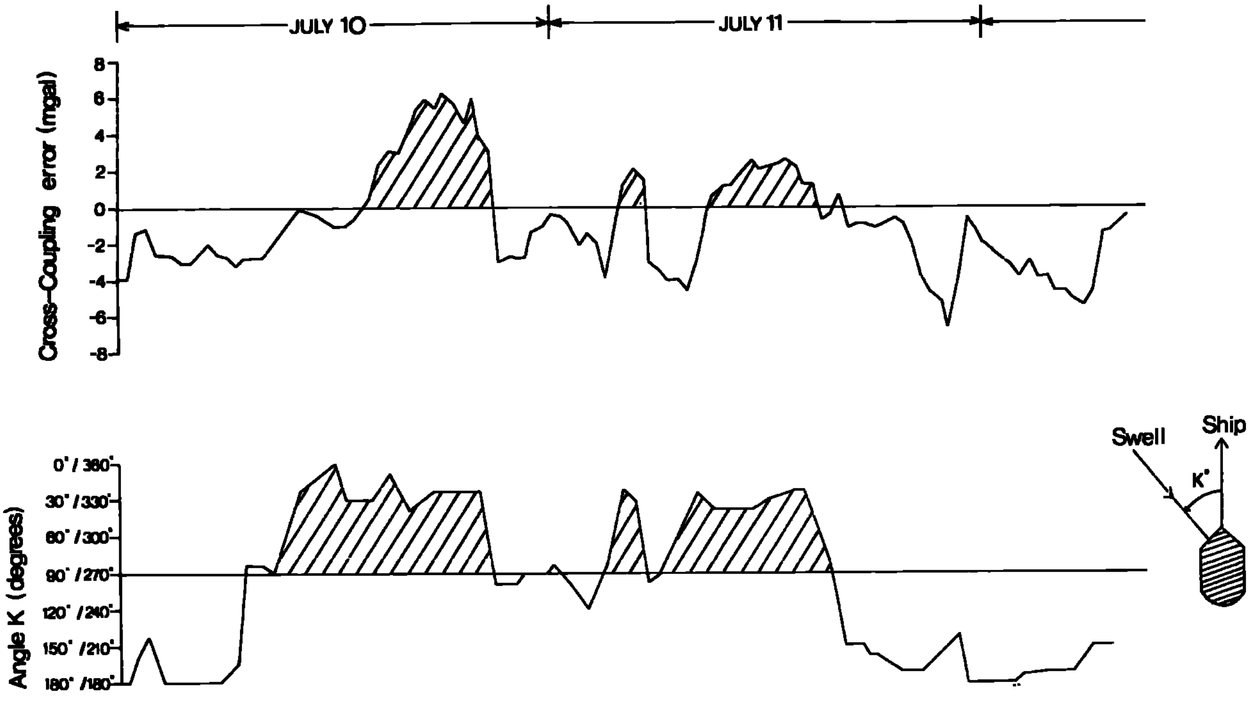


Fig. 2-2-1. Cross-coupling errors (read every ten minutes) versus K, the angle of approach of the swell.

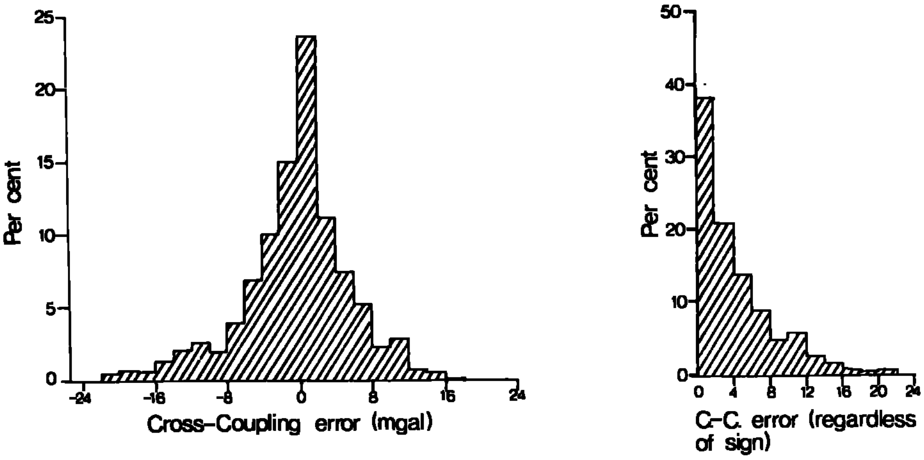


Fig. 2-2-2. Left. Histogram of cross-coupling errors for three weeks on RRS John Murray in the Faeroes to Scotland region. Right. Accumulative percentage of cross-coupling errors smaller than values indicated on the abcissa.

The anomalies were traversed at survey speeds of 5 to 6 knots and it is considered unlikely that response errors are generally significant for the observed gradients north of Scotland. Response errors may occur on the NW margin of gravity "high" A. A damping setting of 0•5 was used during the surveys which caused a data presentation delay of 4 minutes.

Drift of the gravimeter has been computed between gravity base stations and applied to each reading by assuming a linear increase in drift between ports. The drift rates for "legs" 3-6 and "legs" 8-10 on RRS John Murray are shown in Table 2-3.

TABLE 2-3

DRIFT RATES OF GRAF-ASKANIA SEA GRAVIMETER ON RRS JOHN MURRAY

"Leg" number	Drift rate (mgal/day)	"Leg" number	Drift rate (mgal/day)
3	-0•3	8	-1•7
4	-1•5	9	-0•6
5/6	-0•4	10	-0•7

An estimate of the overall accuracy of the gravity survey can be made from track intersections. A value of the free air gravity anomaly at a cross-over point was determined by linear interpolation between two observations. Track intersections in regions of steep gravity gradients and for distances between observations exceeding 3 km were ignored. The mean cross-over error was determined from 46 observations as 5.1 mgal.

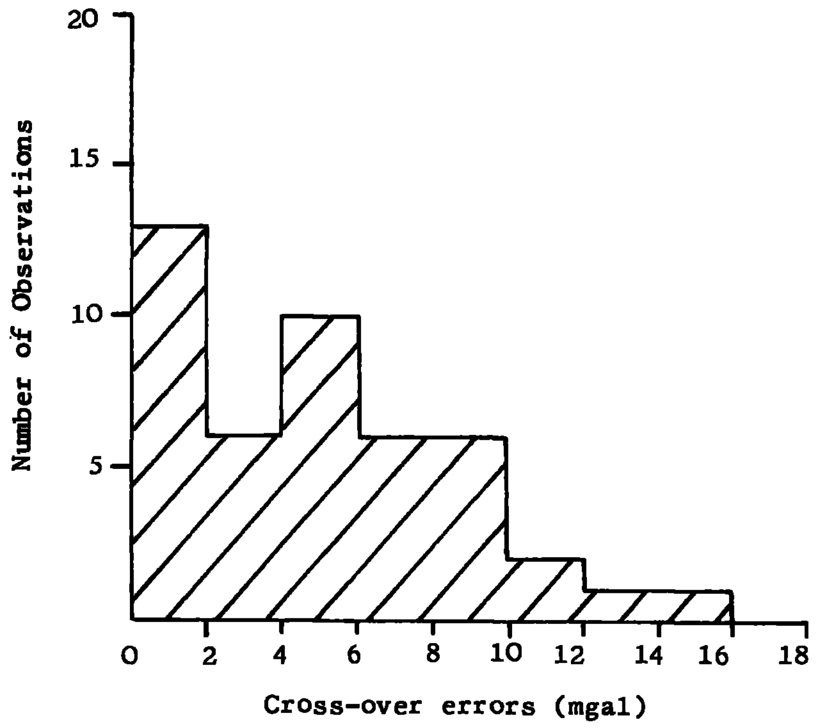
The distribution is shown in Table 2-4.

2-2-6. Results.

The advantage of an automated gravity reduction system is that the punched card output can be inputted to data display programmes. A "mapping"

TABLE 2-4

HISTOGRAM OF CROSS-OVER ERRORS FOR SURFACE SHIP GRAVITY DATA BETWEEN FAEROES AND SCOTLAND



programme was written for the Durham I.B.M. 1130 system in Fortran II to plot the computed free air or Bouguer gravity anomalies on Transverse Mercator or National Grid projections on the on-line Calcomp X-Y plotter. A "profiling" programme was written to plot bathymetry and gravity anomaly profiles for a specified horizontal scale. The display of both programmes are based on descriptions by Talwani (1966b).

The marine gravity data from the 10 cruise "legs" (Table 2-1) have been combined into a free air anomaly map of the Faeroes to Scotland region plotted on a Transverse Mercator projection at a scale of 1:1,000,000 at 65^{o}N (Fig. 3-1). The free air anomaly results in the Faeroes to Scotland region have also been combined with the results of Stacey (1968) north of the Faeroes in a free air anomaly map of the Iceland to Scotland region

(Bott and Watts, 1970c). A Bouguer anomaly map of the continental shelf and slope north of Scotland has been plotted on a National Grid projection at a scale of approximately 1:445,000 (Fig. 4-1). This enabled a direct comparison with the IGS (1968) aeromagnetic survey and land gravity maps of the Shetlands (McQuillin and Brooks, 1967) and the Orkneys (McQuillin, 1968). The gravity maps have been contoured at 10 mgal. intervals which is outside the estimated overall accuracy of the surveys (Section 2-2-5).

2-3. Magnetic surveys and their reduction.

2-3-1. Introduction.

Variations in the Earth's total magnetic field were recorded on the 1967 and 1968 cruises of RRS John Murray. The marine magnetic data have been supplemented by single traverses of the continental shelf north of Scotland by HMS Hecla in 1965 and MV Moray Firth in 1969. Aeromagnetic surveys of the Faeroes to Scotland region have been completed north of 60°N on ESE-WNW trending tracks approximately 10 km apart (Avery et al., 1968). The continental shelf south of 60°N has been completed by aeromagnetic survey on closely spaced tracks (IGS, 1968, Sheets 12, 13, 15 and 16). The marine magnetic data has been used in interpretation of individual gravity and seismic reflection profiles and to map a small area of the continental shelf break in slope north of Scotland not covered by previous surveys.

2-3-2. Magnetic anomaly reduction.

Variations in the total magnetic field were recorded as analogue traces on a Varian chart recorder. The first part of the reduction was to convert the analogue traces to punched cards containing information on time, position and total magnetic field. The chart records were manually digitised on to punched paper tape using a D-Mac Pencil Follower.

The paper tape was then inputted to the Paper Tape Reader, on-line to the I.B.M. 1130, and converted to punched cards using a computer programme written by A. Dobinson (personal communication). Each card contained two sets of time identification and total magnetic field in gamma. The punched cards were then read into a programme written for the I.B.M. 1130 with the appropriate number of punched cards from MGRED (Appendix A-1) containing information on time and position. Each time identification and total magnetic field in gamma card was converted into a punched card with time identification, position in National Grid co-ordinates and total magnetic field in gamma by linear interpolation between positions. The observed marine magnetic data was then ready for further processing.

Observations of the geomagnetic field show it is subject to variations with time. A significant part of the time component is the diurnal variation which at the Lerwick Observatory, Shetland can vary by 20 to 40 gamma (IGS, personal communication). Another time component is the secular variation which at the Observatory increases by about 36 gamma each year. The geomagnetic field also varies in intensity and direction with latitude and longitude. It is important to make these corrections before variations of the Earth's magnetic field can be interpreted as caused by underlying geological structures.

A particular problem in the reduction of magnetic data is the choice of an expression to account for the main geomagnetic field. Two methods are currently in use (Bullard, 1967):

1. An estimate is made from the results of an individual survey.
2. The value is determined from a World Wide Reference Field based on world wide observations of the geomagnetic field.

The first method has been used in closely spaced local magnetic surveys (IGS, 1968). The second method is most applicable to widely spaced surveys (Avery et al., 1970). An advantage is that adjacent and future magnetic data can be easily combined.

The background field used in the magnetic anomaly reduction is the International Geomagnetic Reference Field (IGRF) which expresses the main field as a spherical harmonic expansion up to the 8th order (Anonymous, 1969). The computer programme, obtained from the Department of Geodesy and Geophysics, Cambridge University, incorporated coefficient data agreed on at the 1968 IGRF meeting in Washington. It is possible to compute the required spherical harmonic coefficients and secular variation for epochs from 1955 to 1972. At 60^{o}N and 04^{o}W the IGRF increases northwards about 2•2 gamma/km and eastwards about -0•2 gamma/km. These gradients are similar to those used in the reduction of the IGS (1968) aeromagnetic survey.

To determine magnetic anomalies from the observed total magnetic field the output cards from MGRED (Appendix A-1) were inputted into the IGRF programme. Values of the IGRF for the Faeroes to Scotland region were obtained on punched cards at ten minute intervals. The cards were then combined with an appropriate number of total magnetic field cards in a programme written for the I.B.M. 1130 to compute residual magnetic anomalies by linear interpolation. The resulting anomalies have therefore been corrected for secular variation and variation of the geomagnetic field with latitude and longitude. The remaining correction is for diurnal variation. Diurnal variation data was obtained from the Lerwick Observatory, Shetland and applied to two profiles used in interpretation at the shelf break in slope west of the Shetlands.

2-3-3. Errors of observation.

The observed total magnetic field may be in error due to the magnetic effect of the ship at the towed sensor head (Bullard and Mason, 1961; Barrett, 1967). The effect varies with distance of the sensor head from the ship, the field in which the ship is travelling and the ship's magnetic heading. The magnetic effect of a ship 40 meters long at a sensor head 80 meters astern is less than 10 gamma for magnetic headings of 80° or 270° (Bullard and Mason, 1961). For a distance astern of 200 meters and similar headings, the magnetic effect may be as small as 2-3 gamma (Barrett, 1967). The comparable distance towed astern and the size of the ship suggests a similar magnetic effect of the RRS John Murray at the sensor head. For large distances towed astern a correction should be made for the position of the sensor head relative to the observed ship's position.

The reduced magnetic anomalies may be in error due to the corrections applied to the observed total magnetic field. Secular variation corrections have been computed by the IGRF computer programme. The computed secular variation for the epochs 1966 to 1969 agree to within ± 1 gamma with observed differences of yearly means of the geomagnetic field at Lerwick Observatory, Shetland. Diurnal variation corrections are determined as a variation from the first observed total magnetic field of the magnetogram. The corrections have been applied to magnetic data 90 km from the Observatory. It is probable this is an acceptable correlation although errors would occur if distances from the Observatory exceeded 100 km. There may also be an increase in the amplitude of the correction at the shelf break in slope (Hill and Mason, 1962).

Magnetic anomalies, uncorrected for diurnal variation, have been mapped in sufficient detail at the shelf break in slope for 10 track intersections to be computed. The mean value obtained by linear interpolation between observations not exceeding 0·8 km was 24·3 gamma.

The instrumental error on the Varian direct reading proton magnetometer is given by the manufacturer as ± 1 gamma. It is most likely therefore that the main source of error is due to diurnal variation and to position errors.

2-3-4. Results.

Magnetic anomalies deduced from the IGRF have been obtained for all traverses of cruise "legs" 3-6 and "legs" 8-10. Magnetic anomaly profiles have been plotted to enable direct comparison with gravity and seismic reflection profiles. A magnetic anomaly map contoured at 100 gamma interval has been prepared of the shelf break in slope west of the Shetlands. The map has been combined with the IGS (1968, Sheets 15, 16) aeromagnetic map of the continental shelf north of Scotland (Fig. 4-2). No corrections have been made for the height above sea-level of the IGS (1968) survey.

2-4. Seismic reflection profiles.

2-4-1. Equipment characteristics.

An E.G. and G. seismic reflection profiling system was used on "legs" 8-10 to obtain 15 profiles in the Faeroes to Scotland region. A "sparker" sound source was generated by discharging electrical energy from electrodes mounted on a sledge towed astern of the ship. The discharge produces a "bubble-pulse" in sea-water with a frequency depending on the energy of the condenser banks, the electrode configuration and the depth of the electrode below the sea-surface. Greater sub-bottom penetration is generally obtained from low frequency sources and greater resolution of reflectors from higher frequencies (Hoskins, 1965). The "bubble-pulse" frequency depends inversely on the third root of the stored energy so that increasing the size of the condenser bank will lower the emission frequency and increase penetration. During "legs" 8-10 14,000 joules were available but 1,000 joules were sufficient to define the sub-bottom reflectors of shallow shelves (40-300 meters) before they were obscured by sea-bottom and sub-bottom reflector multiples. For traverses across deeper water slopes (300-500 meters) the energy was increased to 2,000 joules and the penetration increased to about 0·4 seconds two-way travel time. The later arrival of the first sea-bottom multiple did not obscure the seismic record of the slopes.

The "sparker" sound source was triggered by an E.G. and G. Type 254 Seismic Recorder. The receiving system consisted of a 16 element hydrophone array with 8 pre-amplifiers connected as a long eel and streamed astern of the ship. Output from the pre-amplifiers was filtered at the recorder to remove unwanted noise. A bandpass of 80-200 Hz provided the most satisfactory signal to noise level during the survey. The filtered seismic signals were recorded on electro-chemical sensitive recorder paper. A strip of paper passed between a rotating fine-wire helix and a confronting electrically grounded stainless steel blade. The blade acted as a current carrying electrode causing a variation in darkness on the sensitive paper depending on the signal current flow. The common contact point between blade and rotating helix repeatedly sweeps across the recorder paper. The sweep rate is synchronous with the firing rate and was set to scan the recorder paper at about 30 cm/sec. A firing interval of 1 second was selected so that the "sparker" shot instant was recorded at the chart leading edge followed by 1 second of seismic record to the far edge. By using a chart drive speed of 2·4 cm/minute a continuous seismic reflection profile was obtained.

2-4-2. Results.

The problems of presentation and analysis of continuous seismic reflection profiles have been discussed by Stride et al. (1969). Only one of the recorded profiles was stored on magnetic tape so that processing of the seismic profiles could only be made from the analogue records. Seismic reflection profiles are usually presented either as line drawings of selected reflectors or as photographs of the original record. Although the first method is subjective, long profiles can be easily displayed.

The second method is useful for the display of unconformities, attitude of sediments and the nature of the seismic basement over short distances.

An attempt has been made to automate the method of line drawing reflectors. The purpose of the processing is to convert the analogue record into digital form so that the records could be plotted on any scale to assist comparison with gravity and magnetic data, allow an estimate of the apparent sedimentary dip for assumed ranges of sedimentary velocities and to provide a method of storing analogue seismic reflection data. The method outlined is similar to the early stage in the reduction of magnetic data (Section 2-3-2).

1. Selected reflectors were converted to punched paper tape using the D-Mac Pencil Follower.
2. The paper tape was inputted to the I.B.M. 1130 and converted to cards with two sets of horizontal time and two-way travel time to individual reflectors in seconds on each card.
3. The punched cards were then read into a programme written for the I.B.M. 1130 with the appropriate number of punched cards from MGRED (Appendix A). Each digitised point along a reflector was assigned a position by linear interpolation. The output was plotted on the on-line X-Y plotter by computing the distance between each point along a reflector for a specified horizontal distance scale.

To obtain quantitative results from continuous seismic reflection profiles various corrections need to be considered. A significant source of error in the computation of apparent sediment dips along a profile is caused by the wide range of possible sediment velocities. The error in the calculated depth to a reflector, required to compute its apparent dip, is approximately proportional to the error in the assumed velocity. For shallow water sediments, the velocity ranges between 1·7 km/sec and 2·3 km/sec (Morgan, 1969), the depth to a reflector observed on the shelf could be in error by up to 15%. Corrections also need to be applied for the wave paths from source through water and sub-bottom sediments to receiver (Curry et al., 1965). It is unlikely, however, that these corrections constitute a significant source of error compared to that caused by the wide range of possible velocities. The depth to a sub-bottom reflector was estimated from the profiles by subtracting the one-way travel time to the sea bottom from the one-way time to the reflector and multiplying it by an assumed range of sediment velocities. It is likely that the resulting depth is an underestimate of the true value for a particular velocity. If a range of possible apparent dips has been obtained it is not possible to compare them with true geological dips unless it is known the profiles traverse the strike of the sediments approximately at right angles.

The continuous seismic reflection profiles are presented either as line drawings or as photographic reproductions. For both presentations an estimate of the vertical exaggeration has been made for velocities applicable to shallow water sediments. The exaggeration probably increases for buried sediments and the relief of sub-bottom, high velocity, seismic basement.

CHAPTER 3

DESCRIPTION AND INTERPRETATION OF GEOPHYSICAL DATA FROM THE FAEROES TO SCOTLAND REGION

3-1. Introduction.

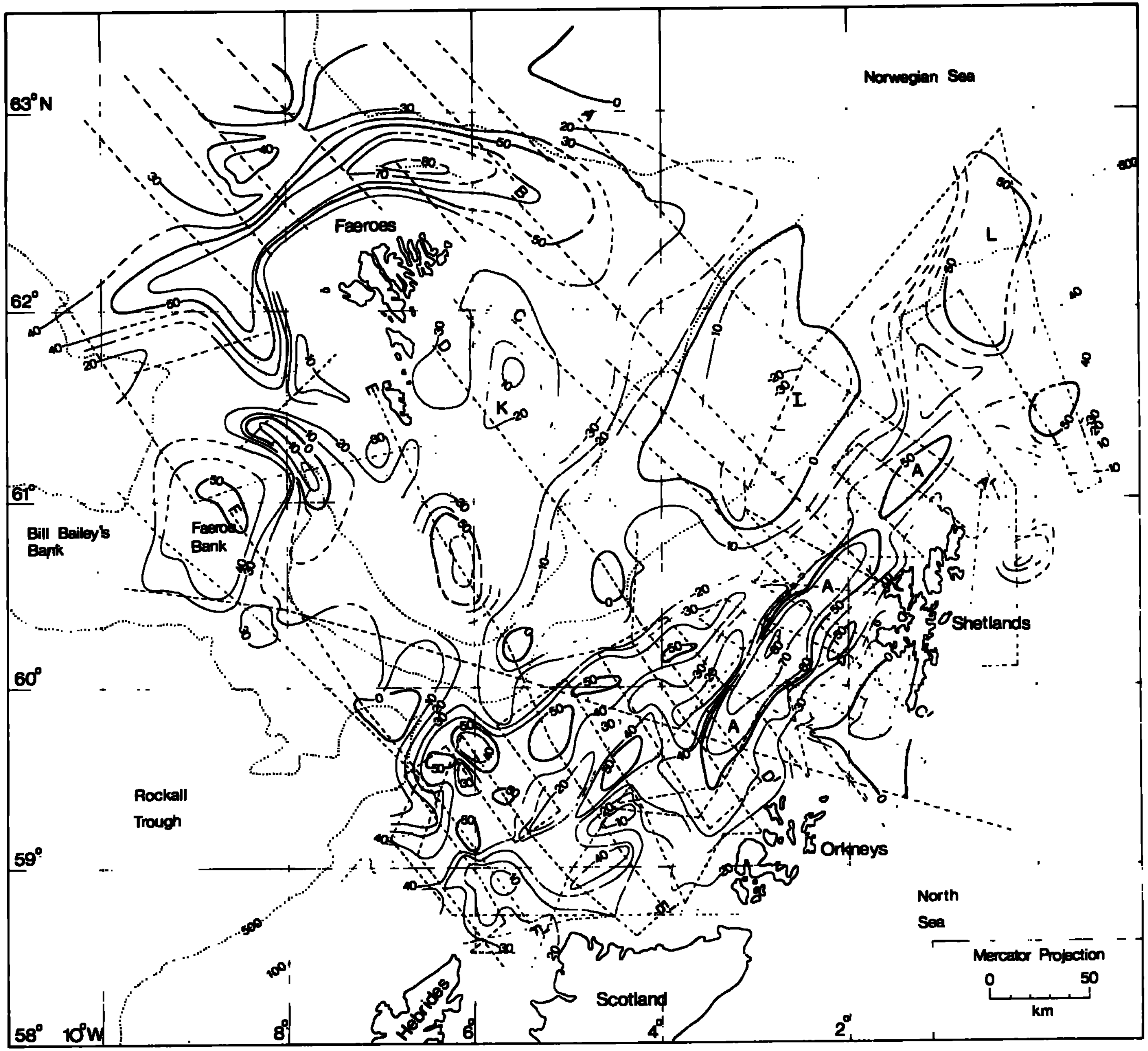
There had been little geophysical investigation of the crustal structure of the sea area between the Faeroe Islands, the Shetlands and northern Scotland before the 1967 and 1968 cruises of RRS John Murray. This chapter is a description and general interpretation of gravity, magnetic and seismic reflection profiles obtained in the Faeroes to Scotland region. The observed gravity and magnetic field in the region is briefly described. The Faeroe-Shetland Channel is associated with a Bouguer anomaly "high" which is interpreted as caused by crustal thinning towards the Channel from beneath adjacent shelves. Evidence relating to the shallow structure of the Faeroes shelf and the Channel is then discussed. The shallow structure of the continental shelf and slope north of Scotland is referred to Chapter 4.

3-2. Description of the gravity anomaly field.

There is a general correlation between changes in the free air gravity anomaly and bathymetry across the Faeroe-Shetland Channel (Fig. 3-1). The free air anomalies are negative for water depths exceeding 1•2 km reaching a minimum of -42 mgal north of the Shetlands. The shelf areas around the Faeroe Islands and north of Scotland are generally associated with positive free air anomalies (Fig. 3-1).

The large amplitude free air anomaly "high" which occurs NW of the Faeroe Islands adjacent to the Iceland-Faeroes Rise (Stacey, 1968) extends to the northern part of the Faeroes shelf adjacent to the Norwegian Basin. The Bouguer anomalies observed on the Faeroe Islands range from +22 to +39

Fig. 3-1. Free air gravity anomaly map of the Faeroes to Scotland region. Data NW of the Faeroe Islands after Stacey (1968). Bathymetry indicated in in fathoms as coarse and fine dots.


Norwegian Sea
Faeroes
Faeroe Bank
Bill Bailey's Bank
Rockall Trough
Shetlands
Orkneys
North Sea
Scotland
Hebrides
Mercator Projection
0
50
km
63° N
62°
61°
60°
59°
58°
10°W
8°
6°
4°
2°
A
B
C
D
E
F
I
K
L

mgal (Saxov and Abrahamsen, 1964) reaching a maximum on the east coast. The free air anomaly decreases SE of the Islands to a minimum of +5 mgal (Region K, Fig. 3-1). A maximum free air anomaly of +71 mgal is associated with a bathymetric rise extending SSE from Suduroy across the south part of the Faeroes shelf.

The Faeroe Bank Channel is associated with negative free air anomalies (Bott and Stacey, 1967). A maximum observed free air anomaly of +53 mgal has been recorded across the Faeroe Bank. A single gravity traverse across Bill Bailey's Bank shows a maximum free air anomaly of +55 mgal. The free air anomalies observed on the Faeroe Bank and Hebridean-Shetland shelf (Fig. 1-1) decrease to a maximum of 39 mgal on the NW margin of the Wyville Thompson Rise.

The continental slope north of Scotland is associated with a decrease in the free air anomaly. The correlation is interrupted north of Lewis, where the Wyville Thompson Rise meets the Hebridean-Shetland shelf, and north of the Shetlands, where the continental slope decreases in gradient to about 1^{o}. The continental shelf break in slope is associated with positive free air anomalies in the range 50 to 55 mgal west of the Shetlands. A striking NNE-SSW trending gravity "high" has been outlined on the shelf west of the Shetlands which reaches a maximum free air anomaly of +87 mgal. Other NNE-SSW trends occur on the shelf.

The observed free air gravity anomaly is the combined effect of the mass deficiency of the water, and sub-bottom density distributions. The relationship of free air anomaly to depth of water between the Faeroes and the Shetlands is shown in Figure 3-2. Results have been plotted for about 700 observations and for water depths exceeding 180 meters. The Bouguer anomaly is also shown which includes a correction for the mass deficiency of the water assuming the density of the topography to be $2{\cdot}83$ g/cm^3. If the change in observed free air anomaly was caused only by

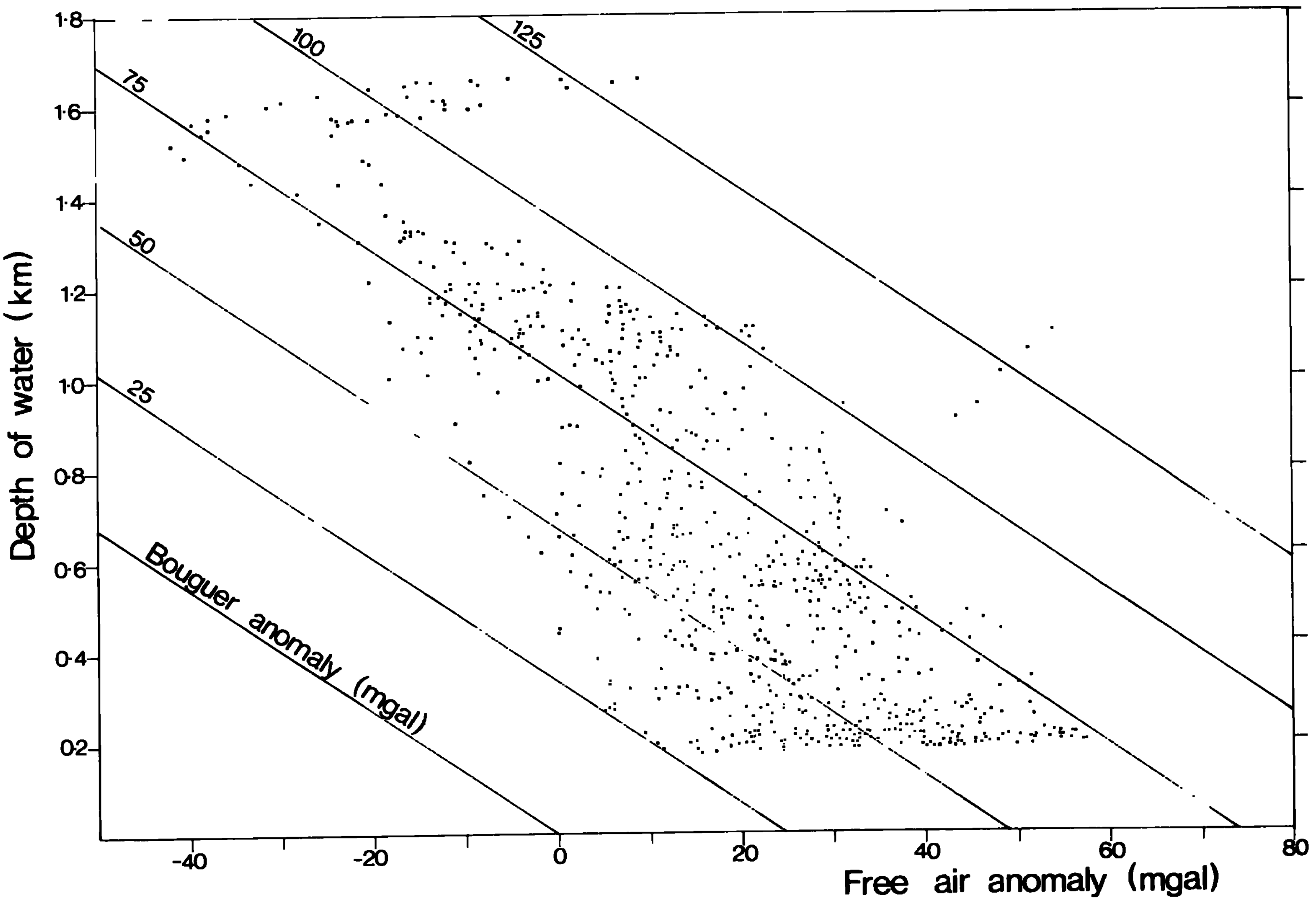


Fig. 3-2. Relationship of free air gravity anomaly to depth of water greater than 180 meters in the Faeroes to Scotland region.

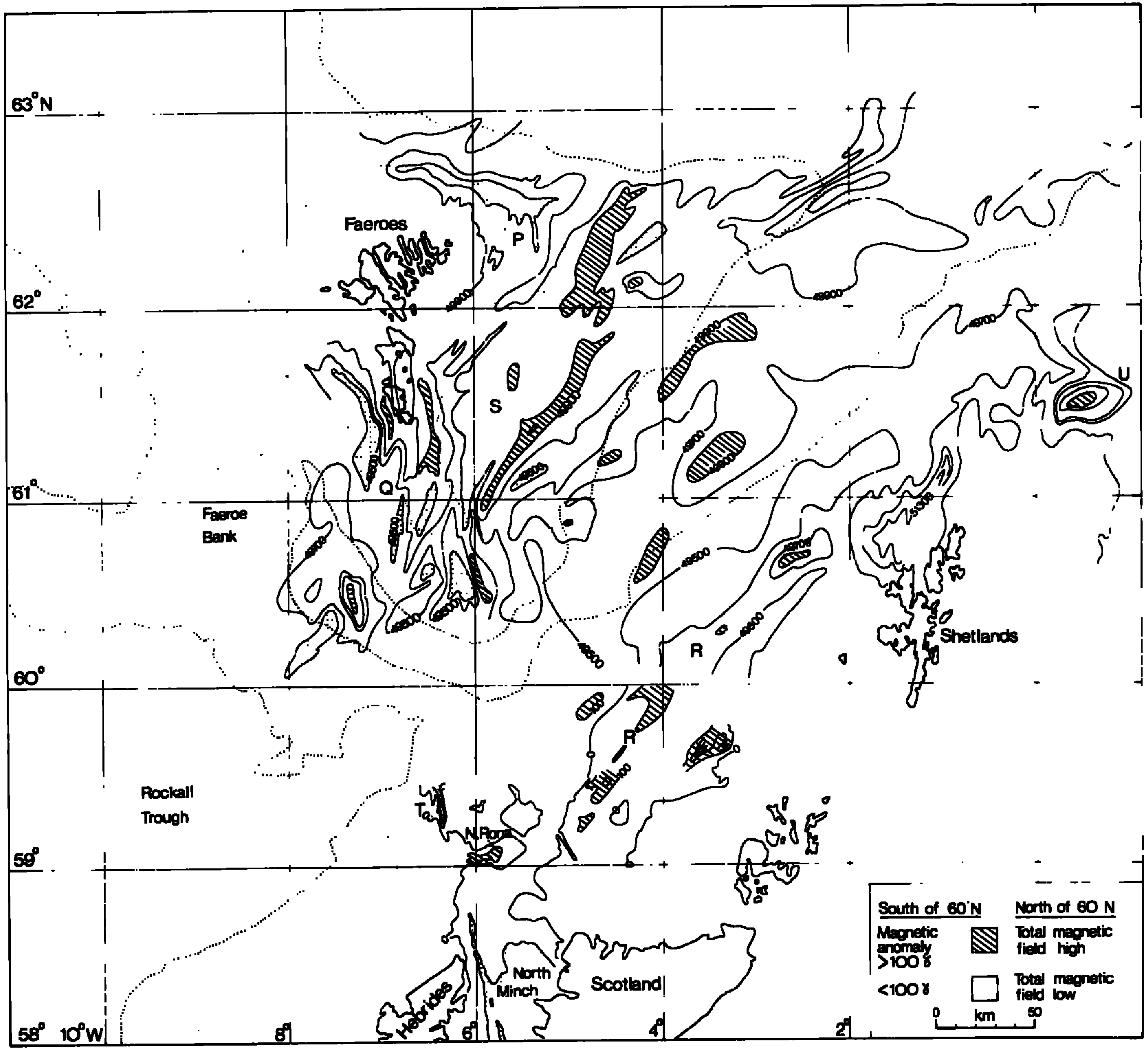
the gravity effect of the topography it would be expected that the scatter of points would generally follow lines of equal Bouguer anomaly. The observed distribution is probably due partly to the low density of the slope forming sediments and partly to sub-sediment density distributions.

3-3. Description of the magnetic field.

Magnetic data available in the Faeroes to Scotland region have been combined in a magnetic trend map (Fig. 3-3). A total field aeromagnetic survey north of 60°N (Avery et al., 1968) contoured at 200 gamma intervals has been combined with the IGS aeromagnetic survey south of 60°N (IGS, 1968 Sheets 12, 15). The results of the marine surveys of "legs" 8-10, contoured at 100 gamma, have also been combined. The aeromagnetic pattern associated with the Faeroe-Shetland Channel confirms the marine magnetic evidence of NNE-SSW trending magnetic "highs" and "lows" (Fig. 3-4, Profiles CC' and DD'). The "highs" and "lows" are not observed to extend into the south part of the Norwegian Basin. A magnetic "high" of about 400 gamma amplitude and 60 km wavelength is associated with the central part of the Faeroe-Shetland Channel (Fig. 3-4, Profiles BB' and CC'). The trend of the magnetic "highs" associated with the Faeroe-Shetland Channel is similar to reduced wavelength "highs" occuring on the Faeroes and Hebridean-Shetland shelves.

The Tertiary basalt lavas of the Faeroe Islands are associated with a complex short wavelength and high amplitude magnetic pattern. The Faeroes shelf east of the Islands is associated with a short wavelength magnetic pattern which increase towards the Faeroe-Shetland Channel (Region P, Fig. 3-3). SW of Region P is a broad magnetic "low" (Region S, Fig. 3-3) which is coincident with gravity "low" K (Region K, Fig. 3-1) and an increase in water depth on the Faeroes shelf. Located within the magnetic "low" is a NNE-SSW trending, short wavelength, magnetic "high"

Fig. 3-3. Magnetic trend map of the Faeroes to Scotland region. North of 60°N after Avery et al. (1968), south of 60°N partly after IGS (1968 Sheet 12). Bathymetry as in Fig. 3-1.


63°N
62°
61°
60°
59°
58°
10°W
8°
6°
4°
2°
Faeroes
P
S
Q
Faeroe Bank
R
R
U
Shetlands
Rockall Trough
Ta
N Rona
North Minch
Scotland
Hebrides
South of 60°N
North of 60 N
Magnetic anomaly >100 γ
Total magnetic field high
<100 γ
Total magnetic field low
0
km
50

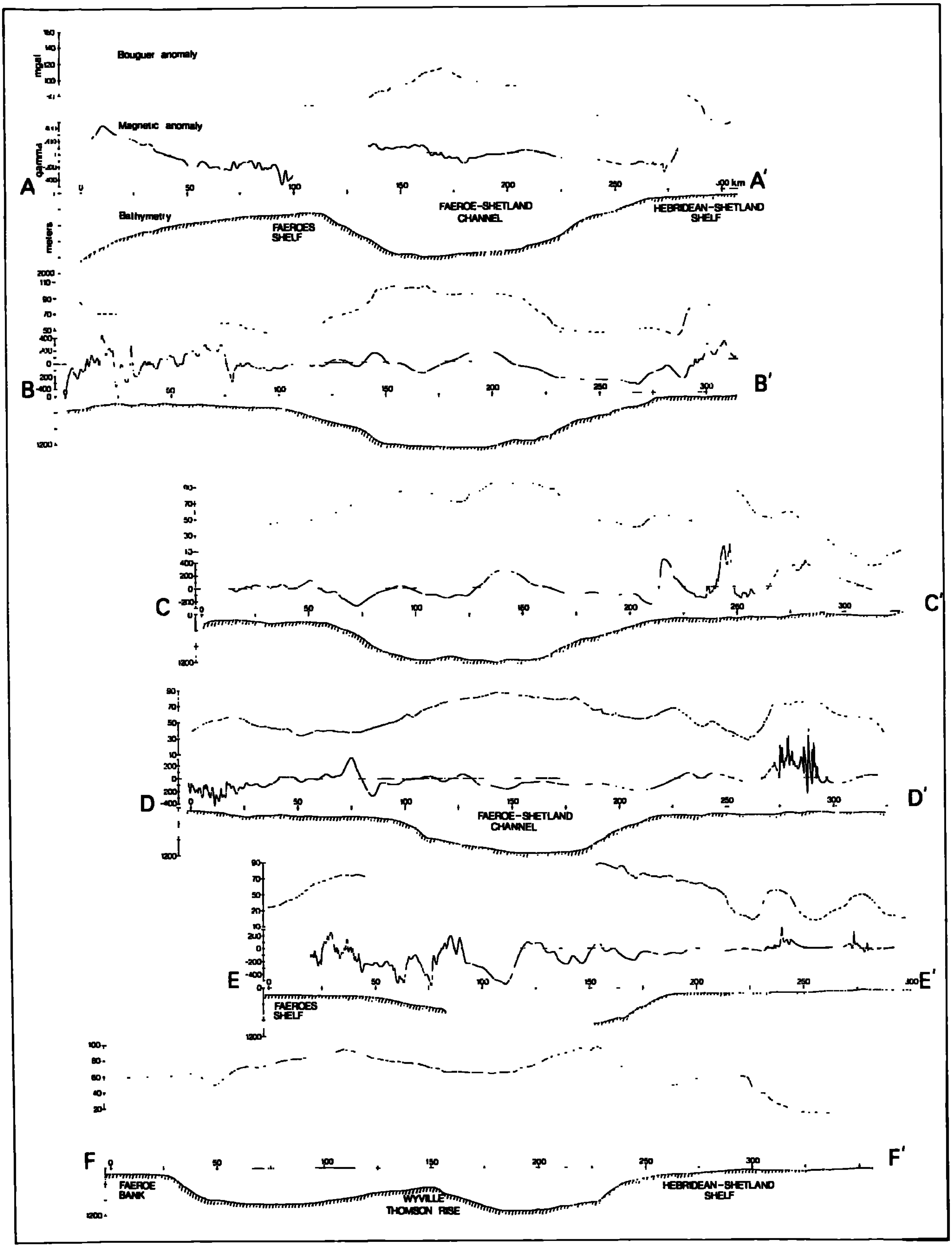


Fig. 3-4. Bouguer anomaly, magnetic anomaly and bathymetric profiles between the Faeroes and Hebridean-Shetland shelves.

which is terminated to the SSW by a complex N-S trending magnetic pattern extending south from Suduroy across the south part of the Faeroes shelf (Region Q, Fig. 3-3). Short wavelength magnetic patterns have been observed on traverses of the Wyville Thompson Rise during "leg" 3 and by Avery (1963). The N-S magnetic trend also make up a complex magnetic pattern associated with the Faeroe Bank (Avery et al., 1968; A. Dobinson, personal communication) and occur as isolated anomalies on the Hebridean-Shetland shelf (IGS, 1968 Sheet 12; Region T, Fig. 3-3).

Marine magnetic surveys of the continental shelf break in slope west of the Shetlands during "legs" 8-10 show that the magnetic "high" observed by Avery et al. (1968) and IGS (1968 Sheet 15) NW of the Shetlands extends SSW across the continental shelf to form magnetic anomaly R (Fig. 3-3). The magnetic anomaly R is discordant to the NE-SW trending continental slope.

3-4. Interpretation of the regional gravity field.

To investigate the sub-bottom crustal structure of the region a two-dimensional Bouguer correction was subtracted from the observed free air anomaly to allow for the mass deficiency of the water. Bouguer anomaly profiles have been plotted for six traverses between the Faeroes and Scotland (Fig. 3-4). The Faeroe-Shetland Channel is associated with a Bouguer anomaly "high" which increases towards the NE. The maximum Bouguer anomaly of +120 mgal is observed on the most northerly traverse where the Faeroe-Shetland Channel is 1·6 km deep. The regional Bouguer anomaly increases NW across the Hebridean-Shetland shelf and SE across the Faeroes shelf towards the Faeroe-Shetland Channel (Fig. 3-4).

The observed Bouguer anomaly "high" could be caused by:

1. A thickening of the lower crustal layer or a lateral change in its density with no change in the relief of the crust/mantle boundary beneath the Faeroe-Shetland Channel.

2. A lateral increase in the density of the mantle beneath a crust of uniform thickness and density.
3. A thin crust.
4. A combination of 1 to 3.

No seismic evidence is available which could distinguish between these possibilities. If gravity interpretation is relied on a wide range of physical properties for the crust and mantle will give a wide range of models for each hypothesis. Each model could fit the observed anomaly equally well. It is therefore necessary to consider other geological or geophysical evidence which could indicate a likely hypothesis to test. Seismic reflection profiles across the slopes bordering the Faeroe-Shetland Channel show they are made up of thick sequences of seaward dipping sediments. This is in accord with observations across the continental rise bordering the East Atlantic (Stride et al., 1969) and Eastern North America (Emery et al., 1970). Seismic refraction studies show that the continental crust thins beneath the continental slope and rise to abut against oceanic crust (summarized in Worzel, 1968). In continental areas it is also observed that thick sediments are associated with thinner crust than adjacent areas (e.g. North Sea Basin, Collette, 1968). It therefore seems likely that the continental slopes are underlain by thin crust whether the crust underlying the Faeroe-Shetland Channel is oceanic or continental. The amount of crustal thinning beneath continental slopes and rises generally compares well with the predictions of the Airy-Heiskanen hypothesis of isostatic compensation of topography (Worzel, 1968).

The formula for T_s, the thickness of crust beneath a sea area, according to the Airy-Heiskanen hypothesis is given by Heiskanen and Vening Meinesz (1958) as:

$$T_s = (T-t) \times (p_c-p_s)/(p_m-p_c)$$

where T = normal crustal thickness

t = depth of water

p_s = density of sea-water

p_c = density of crust

p_m = density of mantle

There have been no seismic refraction experiments in the Faeroes to Scotland region to determine the required crustal parameters. Approximations can, however, be made which do not significantly alter the conclusions. A normal crustal thickness of 27 km was assumed which is in general agreement to estimates from Eskdalemuir (Agger and Carpenter, 1964) and Rockall Bank (Whitmarsh, 1970). The mean density of sea-water is given by Worzel and Shurbet (1955) as 1•03 g/cm^3. An assumed crustal density of 2•83 g/cm^3 is in close agreement to the value used to compute the Bouguer correction (Section 2-2-4) and to values used by Worzel and Shurbet (1955). An assumed mantle density of 3•21 g/cm^3 is slightly lower than the 3•27 g/cm^3 used by Worzel and Shurbet (1955) and the 3•40 g/cm^3 used by Worzel (1968). The assumed crustal parameters were used to compute values of T_s for different values of t across the Faeroe-Shetland Channel. The gravity effect of the computed crust/mantle boundary (the isostatic correction) was determined assuming a two-dimensional structure with GRAVN (Bott, 1969a) and compared with the observed Bouguer anomaly. For complete isostatic compensation according to the Airy-Heiskanen hypothesis the isostatic correction should not significantly deviate from the observed Bouguer anomaly. Profile DD' shows that a large discrepancy of 40-55 mgal is associated with the Faeroes and Hebridean-Shetland shelves and 30-40 mgal with the Faeroe-Shetland Channel. Profiles

EE', CC' and BB' (Fig. 3-4) were also examined and the discrepancies expressed by subtracting the isostatic correction from the observed Bouguer anomaly and computing the mean resulting isostatic anomaly (Table 3-1). The results indicate that the region apparently shows

TABLE 3-1

MEAN GRAVITY ANOMALIES ASSOCIATED WITH THE FAEROE-SHETLAND CHANNEL

Gravity Anomaly	No. of Observations	Mean (mgal)	Standard Deviation
Free air	190	+16•8	17•0
Bouguer	190	+62•7	16•8
Isostatic	144	+25•4	11•0

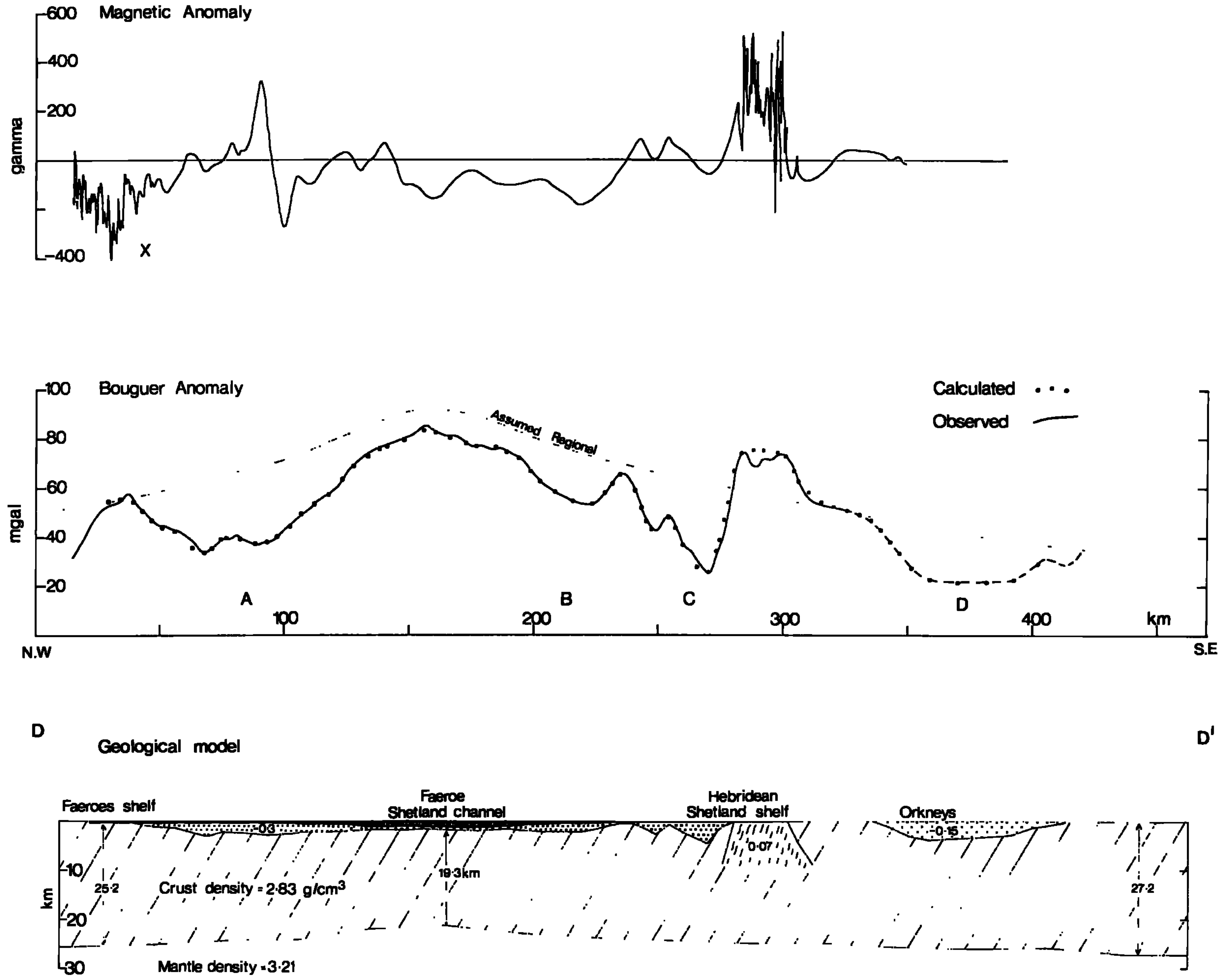
significant deviations from the predictions of the Airy-Heiskanen hypothesis. Preliminary satellite gravity measurements between Greenland and NW Britain show that a broad gravity "high" is located SW of the Faeroes to Scotland region. The effect of the "high" would be to increase the observed Bouguer anomaly (and hence the isostatic anomaly) and give an erroneous indication of the degree of compensation.

Satellite perturbations can be used to determine the long wavelength components of the Earth's gravity field (King Hele, 1967). Results, which have been referred to a spherical harmonic coefficient expression of the hydrostatic equilibrium figure of the Earth to the 8th degree, show that the North Atlantic is associated with a gravity "high" of +19 mgal (Moberly and Khan, 1969). It is generally agreed that the source of the long wavelength components arise below the lithosphere. Kaula (1969) indicates there is a close correlation between positive gravity anomalies such as the North Atlantic and Tertiary/Quaternary volcanic provinces. The Faeroes to Scotland region is therefore likely to be associated with a high background gravity anomaly of about +17 mgal (Moberly and Khan, 1969). This value may be in error when compared with the observed free air anomalies because the hydrostatic equilibrium figure of the Earth deviates from the international ellipsoid.

An interpretation has been made of a Bouguer anomaly profile between the Faeroes and Scotland (Profile DD', Fig. 3-5). A regional background field has been assumed which most completely satisfies magnetic and seismic reflection profile evidence of the shallow geological structure. To allow for the satellite perturbation evidence of a gravity "high" for the NE Atlantic a background field of 20 mgal was subtracted from the observed Bouguer anomaly. The assumed regional field (Fig. 3-5) reaches a maximum of +71 mgal for the central part of the Faeroe-Shetland Channel decreasing by about 0•4 mgal/km across the adjacent shelves. Assuming the crustal thinning hypothesis and a uniform density contrast of -0•38 g/cm^3 between crust and mantle the crust/mantle boundary was computed using a matrix inversion programme developed by Tanner (1967) and adapted for use on the I.B.M. 360/67 by G.J. Laving (personal communication). The top surfaces of the models were varied until the bottom surface corresponded to the normal crustal thickness used in the computations for the isostatic correction. The model is represented as a series of rectangular blocks which were approximated to a regular surface by connecting the mid-points of each block.

The interpreted Bouguer anomaly profile shows that the regional Bouguer anomaly "high" associated with the Faeroe-Shetland Channel can be explained if the crust thins beneath the Channel by about 6 km (Fig. 3-5). The depth to the crust/mantle boundary is determined as 21•1 km which is in agreement with the computed value of 21•9 km assuming the Airy-Heiskanen hypothesis of isotasy and a water depth of 1•1 km. These results indicate that by allowing for the satellite gravity "high" the region shows a

Fig. 3-5. Interpretation of Bouguer anomaly profile DD' (Fig. 3-1) between the Faeroe Islands and the Orkneys. The model has been deduced for an assumed regional, an assumed 2-dimensional structure and the density distribution shown.


Magnetic Anomaly
gamma
600
400
200
-400
X
Bouguer Anomaly
mgal
100
80
60
40
20
Calculated
Observed
Assumed Regional
A
B
C
D
100
200
300
400
km
N.W
S.E
D
D'
Geological model
Faeroes shelf
Faeroe Shetland channel
Hebridean Shetland shelf
Orkneys
0·3
0·07
0·15
25·2
19·3km
27·2
Crust density = 2·83 g/cm³
Mantle density = 3·21
km
10
20
30

closer approximation to isostasy. The crust/mantle boundary shown in Figure 3-5 differs only slightly from isostasy by thickening more gradually from beneath the channel to adjacent shelves. Although the assumed regional used to compute the model may be in error it is clear that the regional increase in the Bouguer anomaly "high" occurs on the landward side of the continental shelf break in slope. This may indicate that the crust beneath the Faeroe-Shetland Channel is not locally compensated according to the Airy-Heiskanen hypothesis but shows a closer approximation to regional compensation (Vening Meinesz, 1931).

3-5. The shelf east of the Faeroe Islands.

Three seismic reflection profiles have been obtained across the shelf east of the Faeroe Islands which show the onset of seaward dipping sediments 40 km SE of Thorshavn. The onset of the sediments coincides with the change from short to long wavelength magnetic anomalies at X (Profile DD', Fig. 3-5) and a decrease in the observed free air anomaly to form gravity "low" K (Fig. 3-1). The seismic basement dips gently SE (Fig. 3-6) and is overlain by at least 1 km of seaward dipping sediments.

Gravity interpretations confirm the seismic evidence of a broad sedimentary trough beneath the shelf SE of the Faeroe Islands. The assumed regional field (Fig. 3-5), which had been used to deduce an acceptable crustal model beneath the Faeroe-Shetland Channel, was subtracted from the observed Bouguer anomaly profile across the Faeroes shelf. The resulting negative residual gravity anomalies (Region A, Fig. 3-5) were then interpreted as caused by low density sediments. The basement configuration was computed for varying density contrasts between sediments and basement using the sedimentary basin programme, NTRAP (Allerton, 1968). For an assumed regional field the computations indicate a depth to the basement of 2·7 km for an assumed uniform density contrast of $-0{\cdot}3$ g/cm^3 (Fig. 3-5)

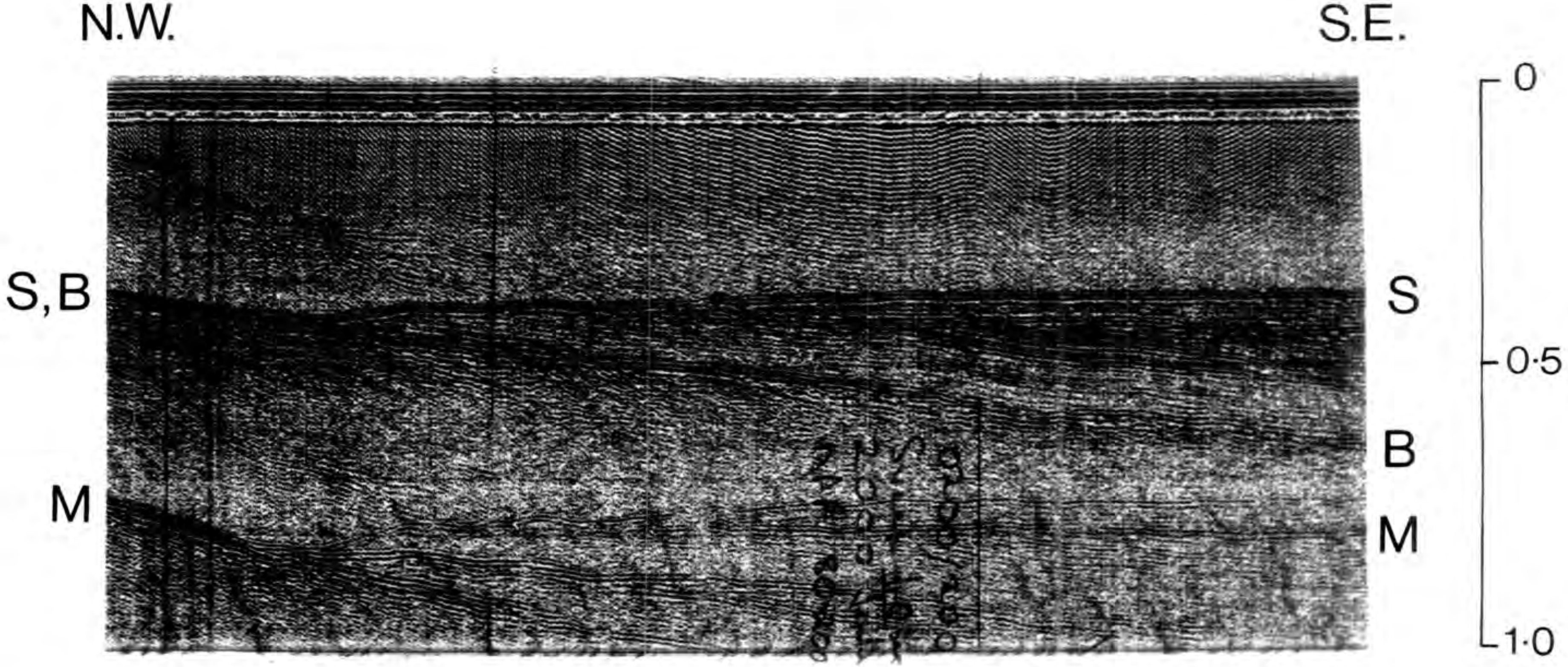


Fig. 3-6. Original seismic reflection profile at 61° 50'N and 5° 50'W 48 km SE of Thorshavn. Two-way travel time in seconds. S = Sea bottom, B = Seismic basement and M = First multiple of sea bottom. Assuming a velocity in shallow water sediments of 2 km/sec the vertical exaggeration is about three times.

or 1·8 km for a contrast of $-0·5$ g/cm^3.

It is most likely that the basement determined from the gravity interpretations and the seismic reflection profiles is a south-easterly extension of the basalt lavas in the Faeroe Islands. The SE dip of the basement may be related to the general structure of the Faeroe Islands. The lavas have been warped into a weak anticline and the Upper Basalt Series on the eastern coast dip gently to the SE (Noe-Nygaard, 1962). There may also be significance in the apparent SE dip of a refractor 3 km beneath Kollafjordur (Palmãson, 1965). The attitude of the sediments on the seismic reflection profiles (Fig. 3-6) suggest they are younger than the underlying basaltic basement which has been dated on the Faeroe Islands by Tarling and Gale (1968) as 55-60 m.y. There is evidence, therefore, on the Faeroes shelf SE of the Faeroe Islands of a broad region of seaward dipping sediments at least 1 km thick, which in part are probably post-Mesozoic.

North of the sedimentary trough the Faeroes shelf is associated with short wavelength magnetic "highs" and "lows" which increase in wavelength towards the Faeroe-Shetland Channel (Region P, Fig. 3-3). The gravity "high" outlined NW of the Faeroe Islands by Stacey (1968) extends approximately E-W across the northern part of the Faeroes shelf. The "high" NW of the Faeroe Islands has been interpreted by Stacey (1968) and Bott and Watts (1970c). The evidence suggests that at least part of the gravity "high" is caused by a lateral variation in crustal density beneath the Iceland-Faeroes Rise and the Faeroes shelf, with the Faeroes shelf possessing the lower density crust. The eastward extension of the anomaly suggests that it is also caused by a major crustal change. It is possible this is due to a crustal change between the Faeroes shelf and the thin oceanic crust of the south part of the Norwegian Basin. The gradual decrease of the gravity "high" eastwards across the Faeroes shelf, and the long wavelength magnetic anomalies, suggests that the basement dips gently towards the Faeroe-Shetland Channel to be obscured by an extension of the sediments causing the gravity and magnetic "low" SE of the Faeroe Islands.

A N-S trending region of short wavelength magnetic "highs" and "lows" extends from Sandoy and Suduroy in the Faeroe Islands to the southern slope of the Faeroes shelf (Region Q, Fig. 3-3). A similar trending magnetic pattern coincides with the Faeroe Bank and the SE part of the Iceland-Faeroes Rise (Avery et al., 1968). Avery (1963) has suggested that the magnetic pattern on the south Faeroes shelf extends south to the Wyville Thompson Rise. The cause of the N-S trends has been briefly discussed by Avery et al. (1968) who attributes them to an extension of the fissure system deduced in the Faeroe Islands.

The fissure system, which produced the extensive plateau basalts on the Faeroe Islands, probably trended NW-SE (Noe-Nygaard, 1962). Extrusion of the basalts was followed by an intrusive period during which several hundred dykes were emplaced mainly in the northern islands along WSW-ENE trends. Sill-like bodies have been outlined in West Vagar and Suduroy which generally trend NW-SE. It is possible therefore that the broad belts of short wavelength magnetic "highs" and "lows" associated with the Faeroe Bank and the south part of the Faeroes shelf are related to either the early fissure system or to the later intrusive period. The magnetic evidence cannot clearly distinguish between these two possibilities.

The N-S trending magnetic pattern south of the Faeroe Islands is repeated on the continental shelf and slope north of Scotland. An isolated short wavelength negative magnetic anomaly occurs at the shelf break in slope north of Lewis (Region T, Fig. 3-3) which may be related to the NNE-SSW trending negative anomaly extending from Loch Ewe to the North Minch (IGS, 1968 Sheet 12). Interpretations of this anomaly suggest it is caused by a reversely magnetised dyke-like body (Butler, 1968).

The close proximity to similar trending dykes in Lewis and NW Scotland suggest it is of Tertiary age. There is a close coincidence south of the Faeroe Islands between the N-S trending complex magnetic pattern and a region of high free air gravity anomaly (Figs. 3-1 and 3-3). In NW Scotland there is a close correlation between regions of high gravity anomaly and intrusive complexes with their associated dyke swarms (McQuillin and Tuson, 1963; Richey, 1935). This might tentatively suggest that the N-S trending complex magnetic pattern south of the Faeroe Islands is caused by a Tertiary dyke swarm. The Minch dyke could then be regarded as an isolated dyke between two intrusive complexes.

3-6. The Faeroe-Shetland Channel.

The interpretation of a Bouguer anomaly profile across the Faeroe-Shetland Channel for an assumed regional field shows that the Bouguer anomaly "high" could be explained by a crustal thinning of about 6 km beneath the channel (Fig. 3-5). The model obtained is approximately in isostatic equilibrium. Preliminary seismic reflection profiles and long wavelength magnetic anomalies indicate the presence of sediments beneath the Faeroe-Shetland Channel. For an assumed regional field of +71 mgal and a uniform density contrast of $-0{\cdot}3$ g/cm^3 between sediments and basement rocks the interpretation of Bouguer anomaly profile DD' (Fig. 3-5) indicates about 0•8 km of sediments beneath the Channel. The regional field associated with the Channel is unknown and it could be significantly higher than that shown in Figure 3-5. A higher regional field would increase the amount of crustal thinning and the sediment thickness. For example, a regional higher by 20 mgal than that indicated in Figure 3-5 would correspond to a crustal thinning of about 7 km and a sediment thickness of 2•7 km beneath the Channel.

The observed Bouguer anomaly increases for greater water depths along the axis of the Faeroe-Shetland Channel towards the Norwegian Basin. If there was no change in the underlying crustal structure the Bouguer anomaly would be expected to remain constant. The observed axial increase could be due either to an increase in crustal thinning or a decrease in the sediment thickness. An increase in crustal thinning would be expected according to the Airy-Heiskanen hypothesis of isostasy to compensate for the increased water depths. The presence of gravity "low" I NNW of the Shetlands (Fig. 3-1), reaching a minimum of -42 mgal, suggests that substantial thicknesses of sediment occur beneath part of the Faeroe-Shetland Channel. The NNE-SSW trending magnetic "highs" associated with the Faeroe-Shetland Channel appear to be caused partly by basement relief and partly by lateral changes in the magnetic properties of the basement (B.J. Bidston, personal communication). It is probable that the long wavelength magnetic pattern observed NNE of Shetland is due to a large sedimentary thickness at the NE end of the Faeroe-Shetland Channel.

3-7. Summary.

A broad sedimentary trough has been outlined beneath the outer part of the Faeroes shelf SE of the Faeroe Islands. It is probable that the sediments are post-Mesozoic. South of the sedimentary trough a region of shallow magnetic basement occurs. The associated N-S trending short wavelength magnetic "highs" and "lows" have been interpreted as caused by a Tertiary dyke swarm. The gravity evidence tentatively suggests an associated intrusive complex. The SE margin of the Faeroes shelf is made up of a thick sequence of seaward dipping sediments. The seaward dipping sediments are unconformably overlain by beds of negligible dip (Fig. 3-6).

The Faeroe-Shetland Channel is probably underlain by a crust about 6 km thinner than underlies the Hebridean-Shetland continental shelf. According to this model the Channel is approximately in isostatic equilibrium. The Faeroe-Shetland Channel is probably underlain by sediments which in part are an extension of the seaward dipping sediments occuring on the slopes bordering the Faeroes and Hebridean-Shetland shelves. The Channel appears to be a sedimentary trough with the thickest sediments occuring to the NE. Sediment cover is probably thin beneath the Channel where basement relief significantly contributes to the observed magnetic "highs".

CHAPTER 4

GEOLOGICAL INTERPRETATION OF GEOPHYSICAL DATA FROM THE HEBRIDEAN-SHETLAND CONTINENTAL SHELF AND SLOPE

4-1. Introduction.

The sea area around the Orkneys, Shetlands and Outer Hebrides represents a large area of previously uninvestigated British continental shelf and slope. Part of the area is of particular geological interest as it represents the seaward extension of the North Scottish Caledonian fold-belt. Lewisian basement rocks outcrop in North Rona, 73 km NNE of the Butt of Lewis, and in the Skerries, 55 km NNE of Cape Wrath. The Shetlands are made up mainly of metamorphic rocks similar to the Dalradian from the metamorphic belt of the Caledonian fold-belt in Scotland. Geophysical investigations elsewhere of the sea areas adjacent to pre-Mesozoic fold-belts show they are truncated or terminated at or near the present continental margin. It is of interest to consider the evidence for Caledonian structures on the shelf north of Scotland and to consider their relation to the present continental slope.

Geophysical investigations of the continental shelf adjacent to other areas of Britain have led to the discovery of deep sedimentary basins containing substantial thicknesses of post-Palaeozoic sediments. Deep sedimentary basins have been outlined from the Irish Sea (Bott, 1965), the Western Approaches to the English Channel (Hill and King, 1953) and the North Sea (Hinz, 1968). The present outcrop of Mesozoic sediments in Scotland is restricted to the coastal areas which may be due to their deposition in subsiding troughs bordering regions of pre-Mesozoic rocks acting as areas of positive relief (Arkell, 1933). The North Minch has been interpreted as a deep sedimentary basin (Allerton, 1968) and Donovan (1963) and Flinn (1969) have suggested that the most satisfactory explanation of a large negative gravity anomaly centred over the Moray Firth (Collette, 1960) is due to a fault bounded Mesozoic basin.

A geological interpretation of geophysical data from the continental shelf and slope around the Orkneys, Shetlands and Outer Hebrides, obtained mainly on the 1967 and 1968 cruises of RRS John Murray, is the subject of this chapter. The gravity data have been combined to construct a Bouguer anomaly map of the continental shelf and slope (Fig. 4-1). The magnetic anomaly map of the shelf and slope (Fig. 4-2) has been compiled from marine magnetic data and the IGS (1968 Sheets 12, 13, 15 and 16) aeromagnetic survey. A geological interpretation is attempted on the basis of gravity and magnetic results, seismic reflection profiles and the geology of adjacent land areas. The interpretations could be tested by seismic reflection or refraction experiments and detailed bottom sampling.

4-2. Gravity "high" A.

The most striking feature of the Bouguer gravity anomaly map (Fig. 4-1) is the NNE-SSW trending gravity "high" A. The "high" is associated with steep marginal gradients of up to 9 mgal/km on the seaward side and 3 mgal/km on the landward side. The maximum Bouguer anomaly of 94 mgal is observed 35 km WNW of Foula, Shetland at HT592521. Seismic reflection profiles show that the basement is at shallow depths west of the main gravity "high" (Fig. 4-3). When traced eastwards the strongly reflecting seismic basement outcrops on the sea floor where it is associated with the highest gravity anomalies. There is an excellent correlation at the NW margin of gravity "high" A between the disappearance of the seismic basement observed on the reflection profiles and an abrupt decrease in the Bouguer anomaly (Fig. 4-4). The seismic basement associated with gravity "high" A occurs at shallow depth as far north as Profile 5 (Fig. 4-4), 50 km north of Yell, Shetland at HP313471.

Fig. 4-1. Bouguer gravity anomaly map of the continental shelf and slope north of Scotland.

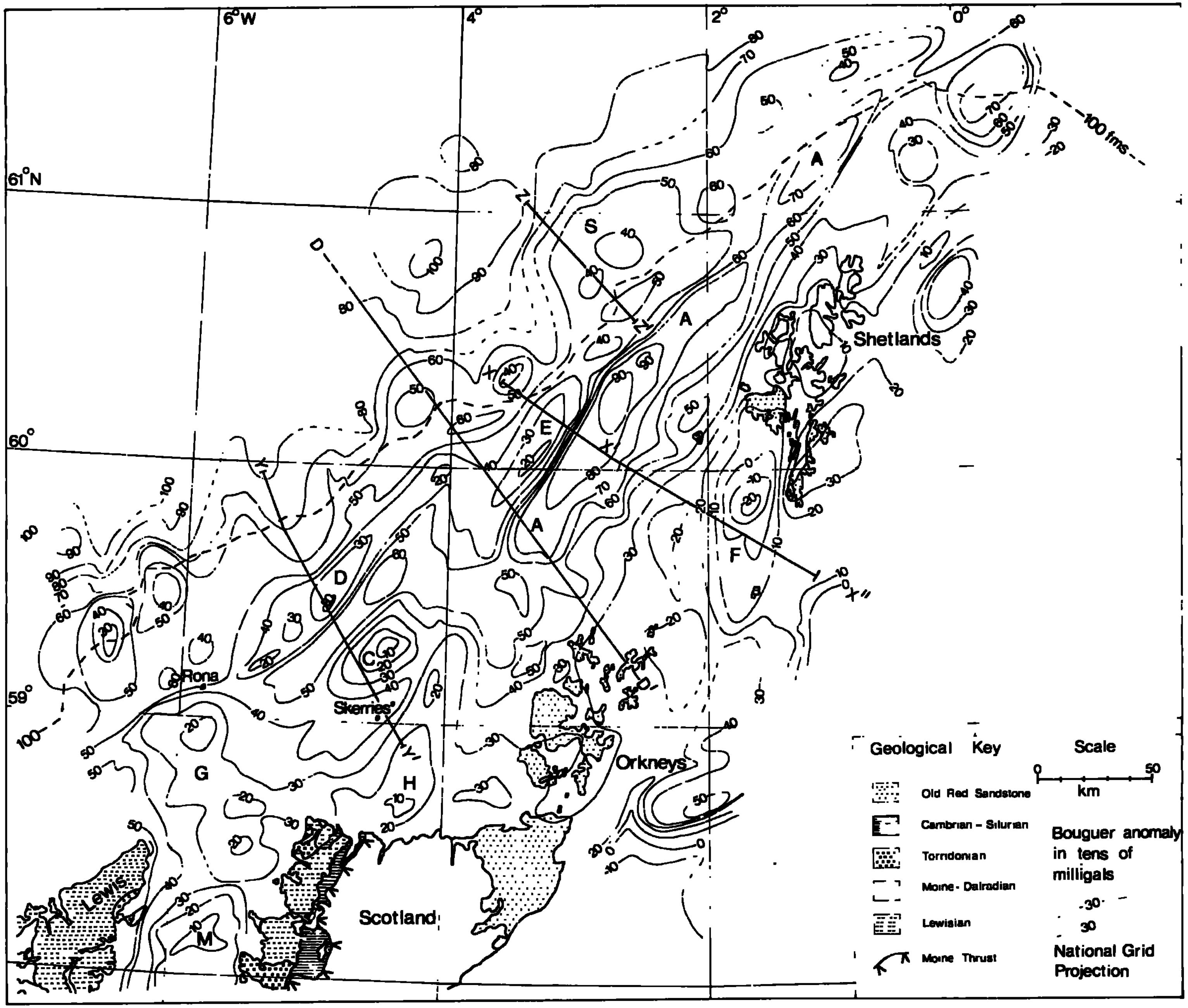
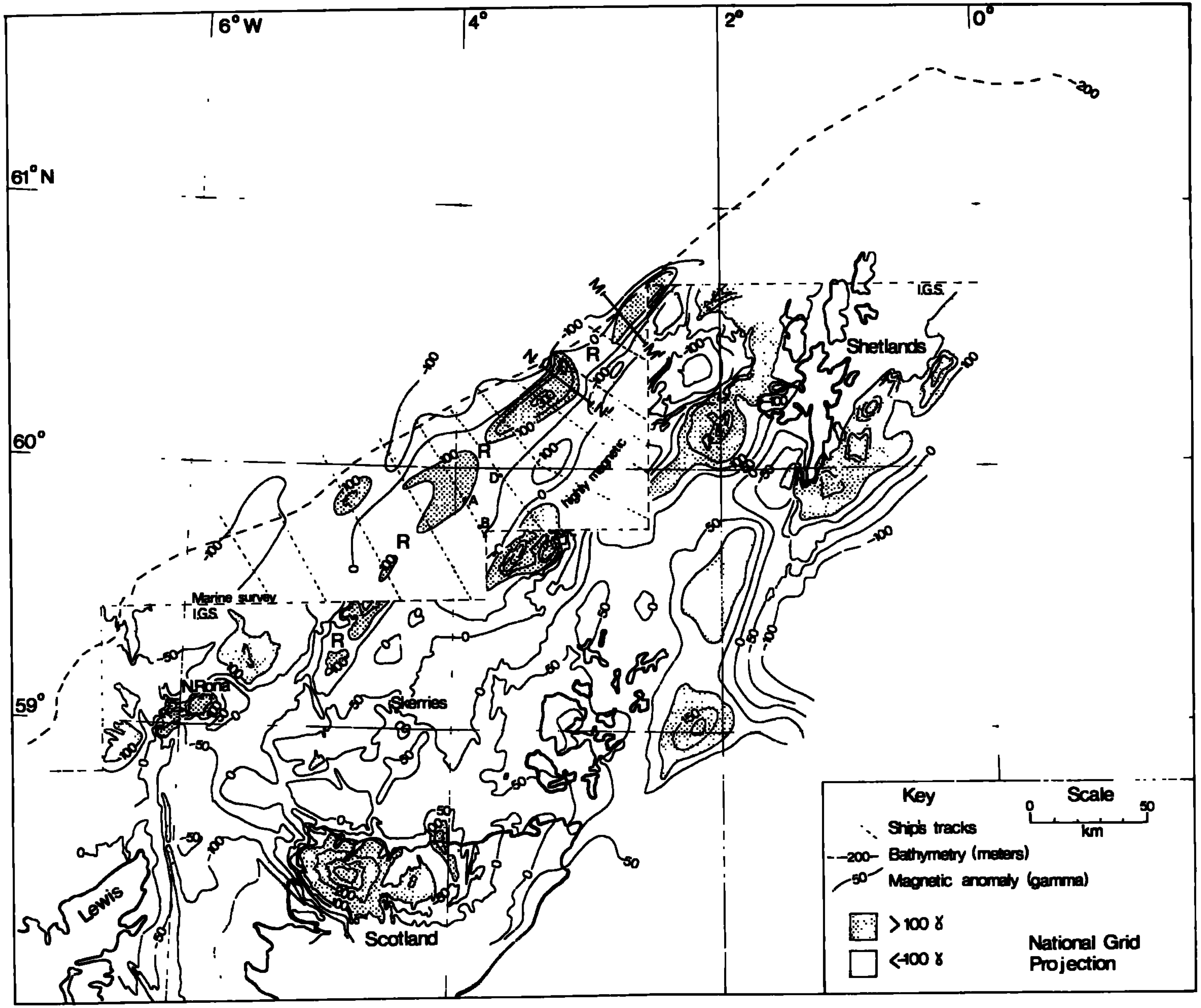
6°W
4°
2°
0°
61°N
60°
59°
100 fms
Shetlands
Orkneys
Scotland
Lewis
Rona
Skerries
A
S
E
D
C
F
G
H
M
Z
Z'
X
X'
X''
Y
Y'
D
D'
Geological Key
Old Red Sandstone
Cambrian - Silurian
Torridonian
Moine - Dalradian
Lewisian
Moine Thrust
Scale
0
50
km
Bouguer anomaly in tens of milligals
-30
30
National Grid Projection

Fig. 4-2. Magnetic anomaly map of the continental shelf and slope north of Scotland. Partly after IGS (1968 Sheets 12, 13, 15 and 16).


6° W
4°
2°
0°
61° N
60°
59°
Shetlands
Scotland
Lewis
N.Rona
Skerries
Marine survey
I.G.S.
I.G.S.
highly magnetic
R
M
N
A
B
D
-200
-100
-50
0
50
100
Key
Ships tracks
-200- Bathymetry (meters)
-50- Magnetic anomaly (gamma)
> 100 γ
<-100 γ
Scale
0
50
km
National Grid Projection

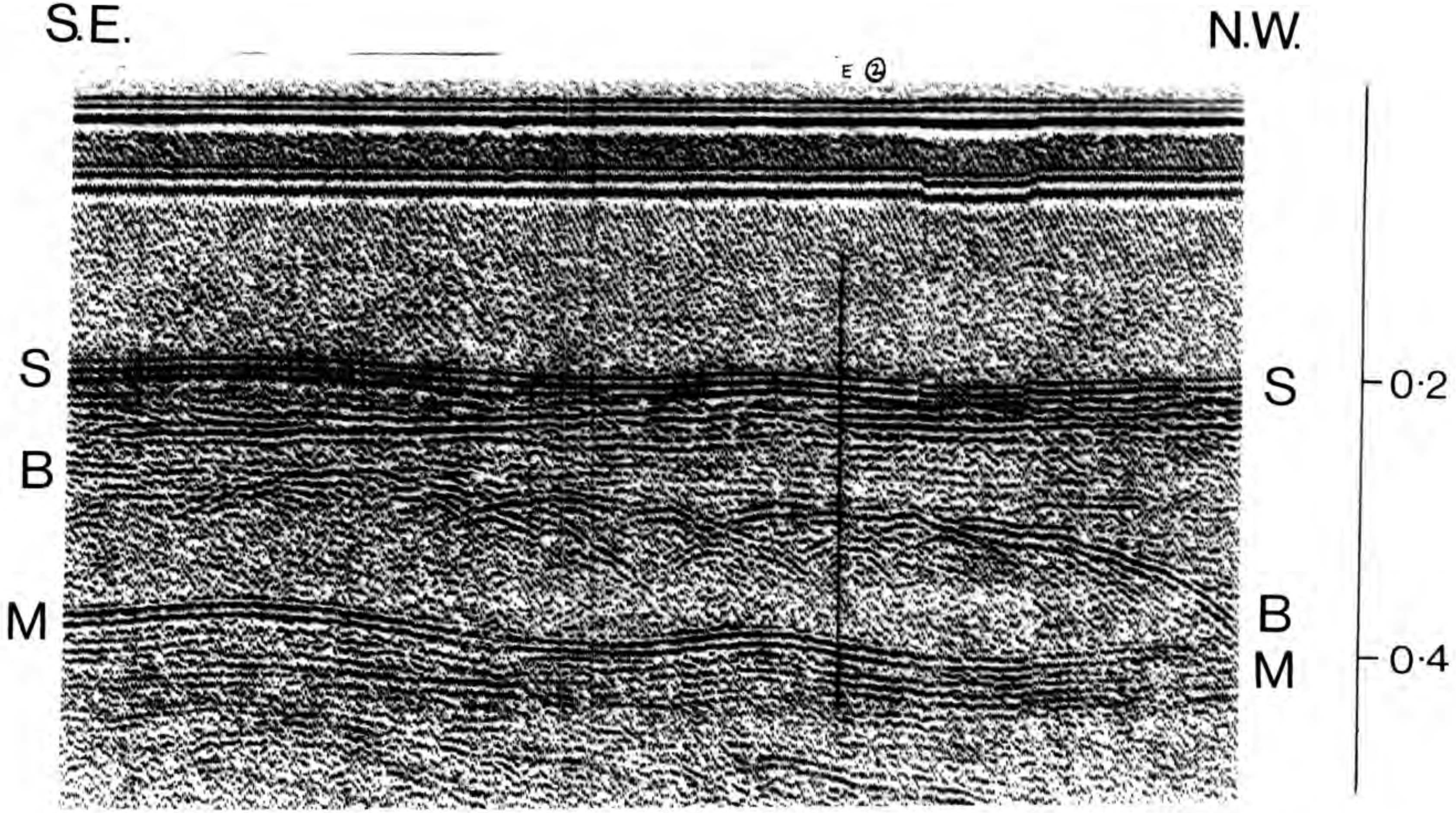
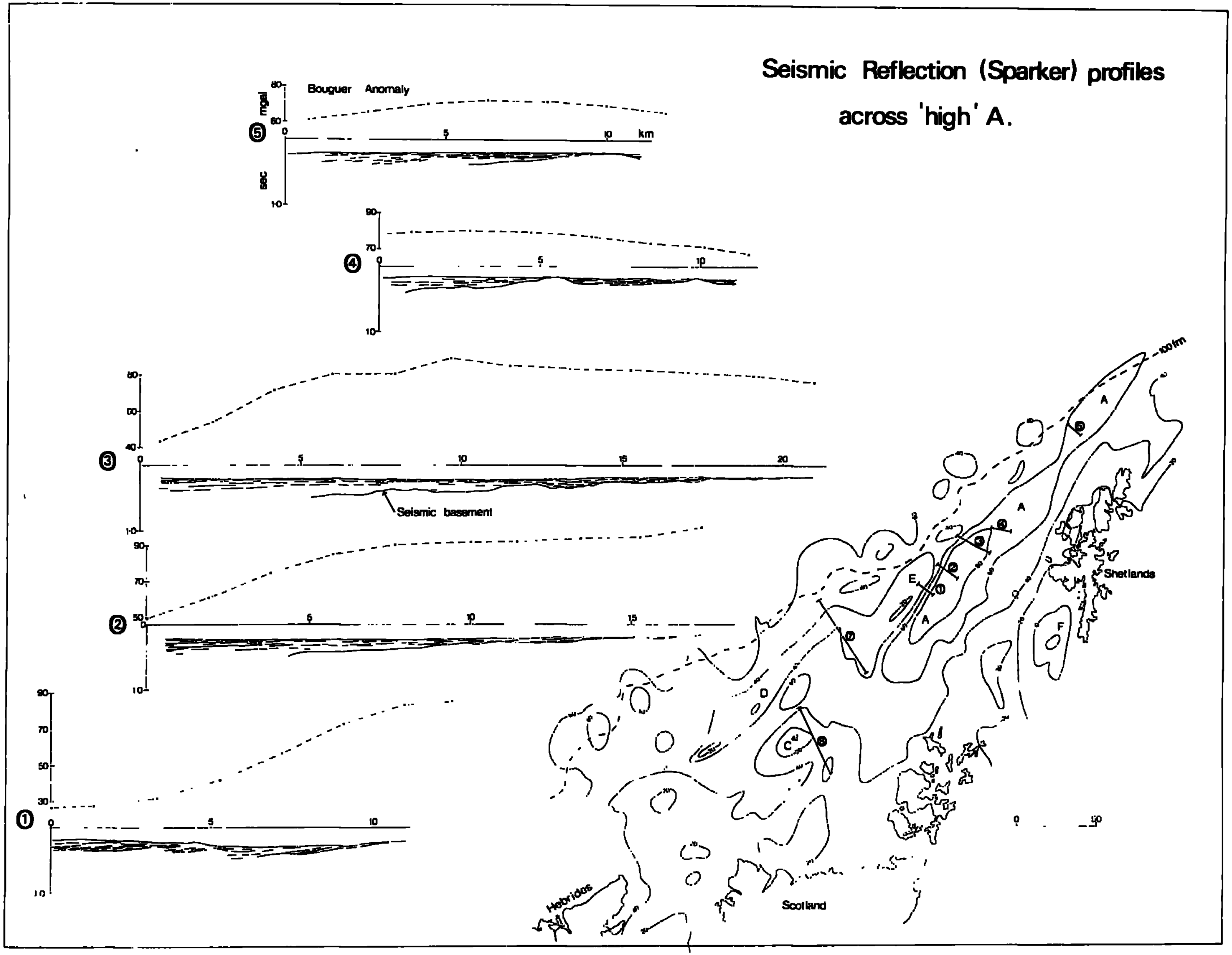


Fig. 4-3. Original seismic reflection profile at HT713693 west of gravity "high" A (Fig. 4-1). Two-way travel time in seconds. S = Sea bottom, B = Seismic basement and M = First multiple of sea bottom. Assuming a velocity in shallow water sediments of 2 km/sec the vertical exaggeration is about three times.

Fig. 4-4. Line drawings of NW-SE trending seismic reflection and Bouguer anomaly profiles across gravity "high" A (Fig. 4-1).



Marine magnetic profiles across gravity "high" A show it is associated with short wavelength anomalies reaching a peak amplitude of +4540 gamma at HT596518 (Fig. 4-5). Similar amplitude magnetic anomalies are unknown from magnetic surveys of basement rocks in the Shetlands, the Outer Hebrides or NW Scotland.

A study of the Bouguer anomaly map shows that a gentle increase in the regional gravity field occurs approximately NW across the continental shelf and slope (Fig. 4-1). This is probably due at least in part to crustal thinning beneath the Faeroe-Shetland Channel (Section 3-4). The density used in the computation of the Bouguer correction is 2•83 g/cm^3 which is the estimated mean density of basement rocks in the Faeroes to Scotland region. It would therefore be expected that the observed gravity anomaly on Lewisian basement rocks should approach the regional gravity field. The gravity field observed on Lewisian basement rocks north of Scotland are tabulated (Table 4-1) in relation to the distance from the shelf break in slope. Table 4-1 shows that an increase in the observed

TABLE 4-1

RELATIONSHIP OF THE MEAN OBSERVED BOUGUER ANOMALY OVER LEWISIAN ROCKS TO DISTANCE FROM THE SHELF BREAK IN SLOPE NORTH OF SCOTLAND

Locality	Lewisian Type	Bouguer anomaly (mgal)	Distance from shelf edge (km)	Reference
Scourie	Pyroxene granulite	+34	140	Storry (1969)
Laxford	Grey gneiss	+25	140	Storry (1969)
Sule Skerry	Hornblende gneiss	+47	100	McQuillin (1968)
Lewis	Grey gneiss	+50	70	R. McQuillin (personal communication)
North Rona	Amphibolite	+60	40	R. McQuillin (personal communication)

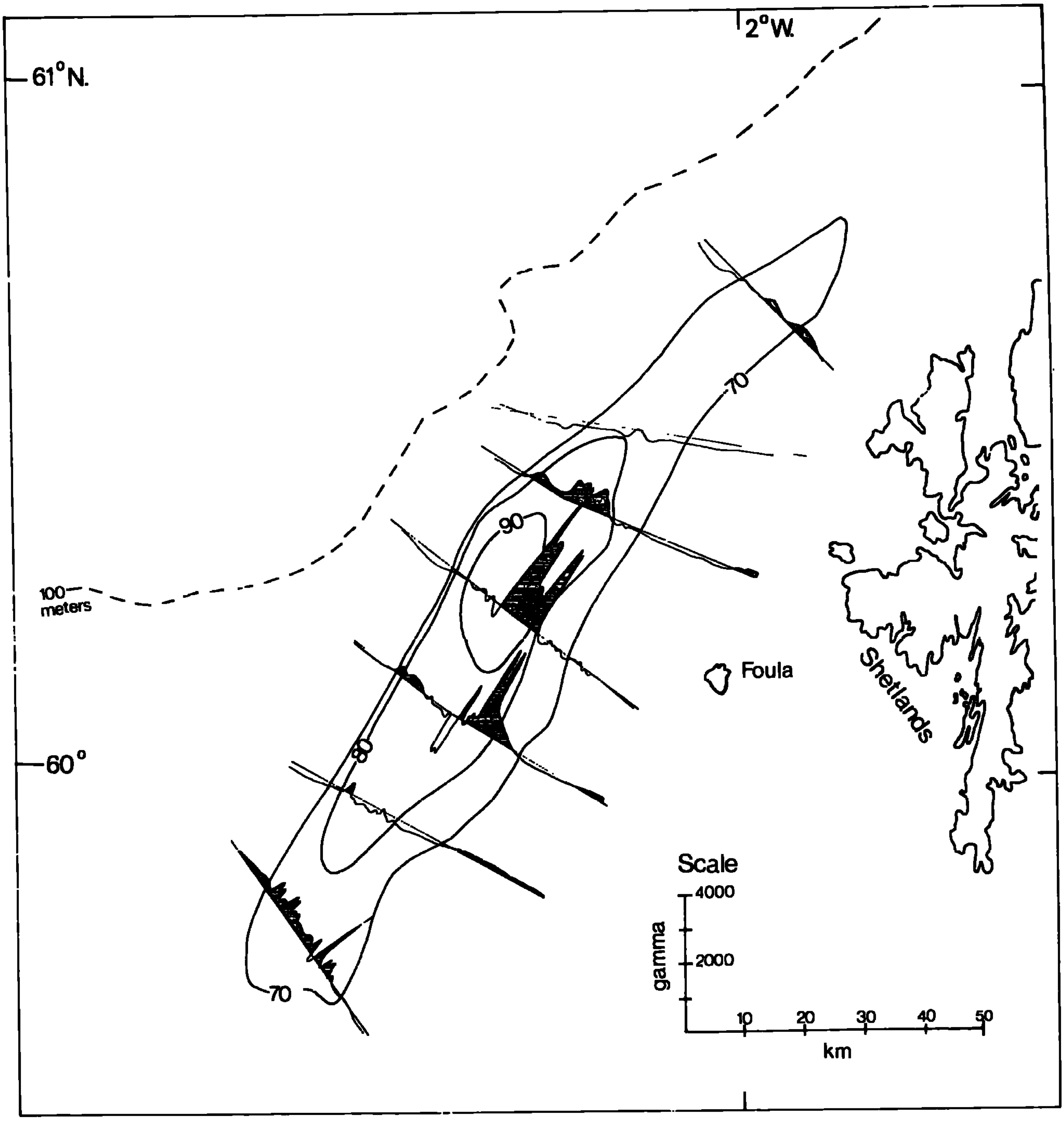


Fig. 4-5. Marine magnetic anomaly profiles across gravity "high" A (Fig. 4-1). Bouguer anomaly in mgal and bathymetry in meters.

Bouguer anomaly occurs on Lewisian basement rocks as the continental shelf break in slope is approached. The northern end of gravity "high" A is only 15 km from the shelf break in slope where it is estimated the regional field is of the order of 60-70 mgal. The southern end is 50 km from the shelf break in slope where it is estimated the regional field is 50-60 mgal. This leaves a positive residual gravity anomaly of 20-30 mgal for "high" A. The "high" could be explained in part by crustal thinning or by an exceptionally large volume of igneous rocks but the most satisfactory explanation is in terms of a belt of higher than average density metamorphic rocks (Bott and Watts, 1970a). If the NNE-SSW trend of gravity "high" A is extended SSW it continues into the Lewisian outcrop in NW Scotland where it is observed that Lewisian basement rocks are generally more dense than their metamorphic or sedimentary cover (Tuson, 1959; Storry, 1969).

The geophysical observations confirm the interpretation of Flinn (1969) that a NNE-SSW trending belt of high density rocks of variable magnetic properties, similar to the Lewisian of NW Scotland, occurs on the shelf north of Scotland. The average density of 54 samples of Lewisian grey gneiss and pyroxene granulite from the Skerricha district and the area between Loch Inver and Scourie has been determined as 2•76 g/cm^3 and 2•84 g/cm^3 respectively (Storry, 1969). Additional density measurements have been obtained from the Old Red Sandstone of the Walls Peninsula, Shetland and the East Mainland Succession of metamorphic rocks (McQuillin and Brooks, 1967). These values have been used to interpret a NW-SE Bouguer anomaly profile (Profile XX'X", Fig. 4-1) across the shelf west of the Shetlands (Fig. 4-6). For the assumed regional field and density distribution shown Figure 4-6 shows that gravity "high" A could be explained by Lewisian basement rocks similar in properties to the pyroxene granulites of the Scourie assemblage in NW Scotland. The deep structure of the Scourie

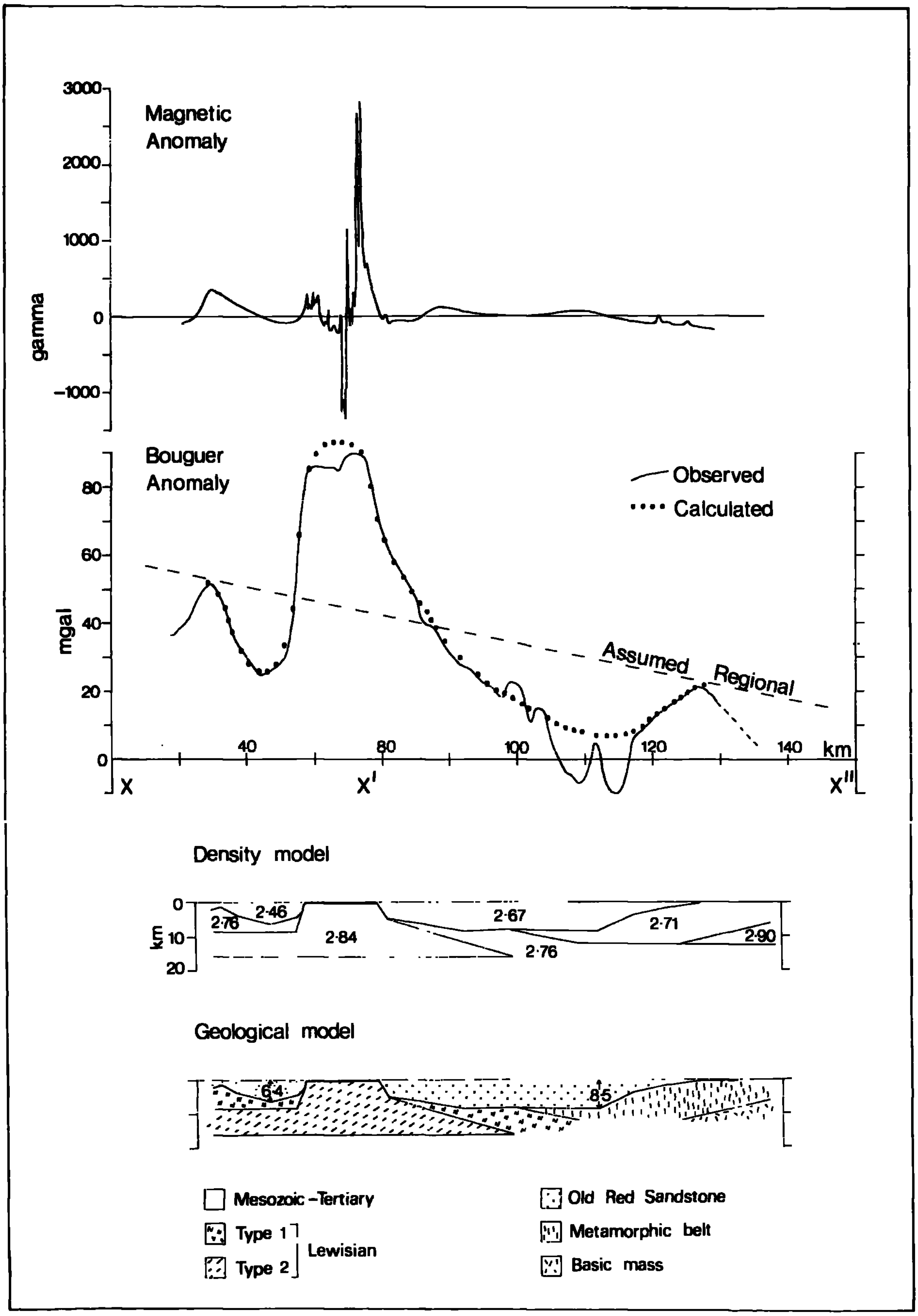


Fig. 4-6. Interpretation of Bouguer anomaly profile XX'X" (Fig. 4-1) across gravity "high" A. The model has been deduced for an assumed regional, an assumed 2-dimensional structure and the density distribution shown (see page 44).

assemblage in NW Scotland is unknown so the regional field assumed could be significantly different from that shown in Figure 4-6. If basement rocks of the Scourie assemblage causing gravity "high" A extend to great depths in the crust it would be expected that the regional field would be higher than that shown. A further problem in the interpretation is that the distribution of "Type 2" Lewisian (Fig. 4-6) with similar properties to the Laxford assemblage in NW Scotland cannot be uniquely determined in relation to "Type 1" Lewisian. The model determined (Fig. 4-6) is intended as a working hypothesis which could be tested by seismic refraction experiments and bottom sampling.

4-3. Gravity "low" E.

Gravity "low" E is a large amplitude NNE-SSW trending anomaly located west of gravity "high" A and adjacent to it. Seismic reflection profiles across the southern end of the gravity "low" show an unconformity between seaward dipping sediments above and south-easterly dipping sediments below (Fig. 4-7). The seaward dipping sediments thicken towards the continental slope (Fig. 4-8). The south-easterly dipping sediments appear at HS886171 (Profile A, Fig. 4-9) where they coincide with the main gravity "low". The south-easterly dips occur as far east as Profile C (Fig. 4-9) at HY050883, at the SE margin of gravity "low" E. Since the seismic reflection profiles indicate that basement rocks outcrop on the sea floor SE of Profile C (Fig. 4-9) at HY059867, the south-easterly sediment dips are probably cut off by a normal fault bounding the NW margin of gravity "high" A. The NW margin of gravity "low" E is associated with an increase in the observed Bouguer and magnetic anomaly near Profile A (Fig. 4-9) suggesting a rise in the basement to form a buried ridge near the shelf break in slope. The seismic reflection profiles suggest that

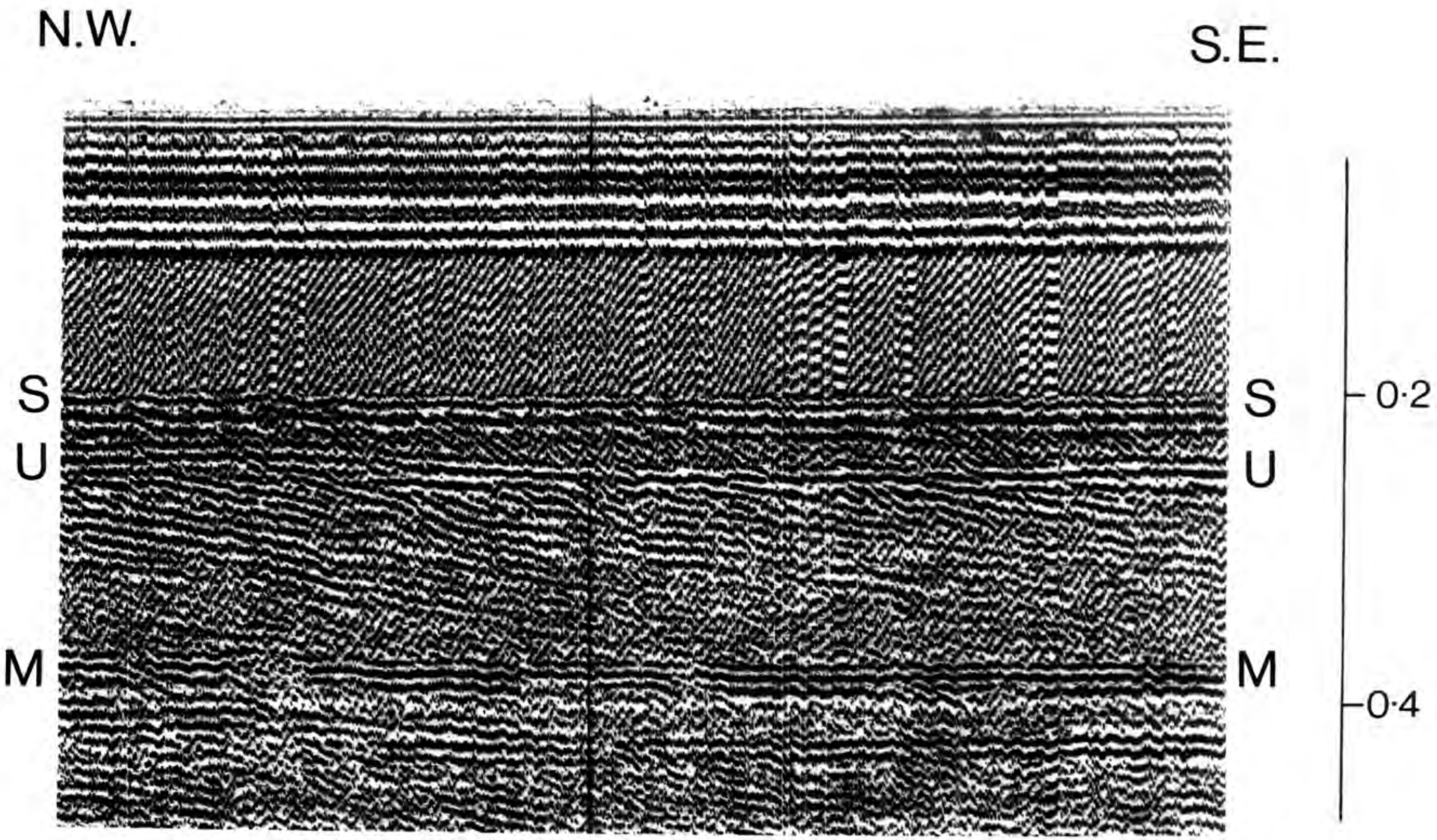


Fig. 4-7. Original seismic reflection profile at HS969021 across the southern end of gravity "low" E (Fig. 4-1) showing the shelf unconformity. U = Unconformity, other symbols and scales as in Figure 4-3.

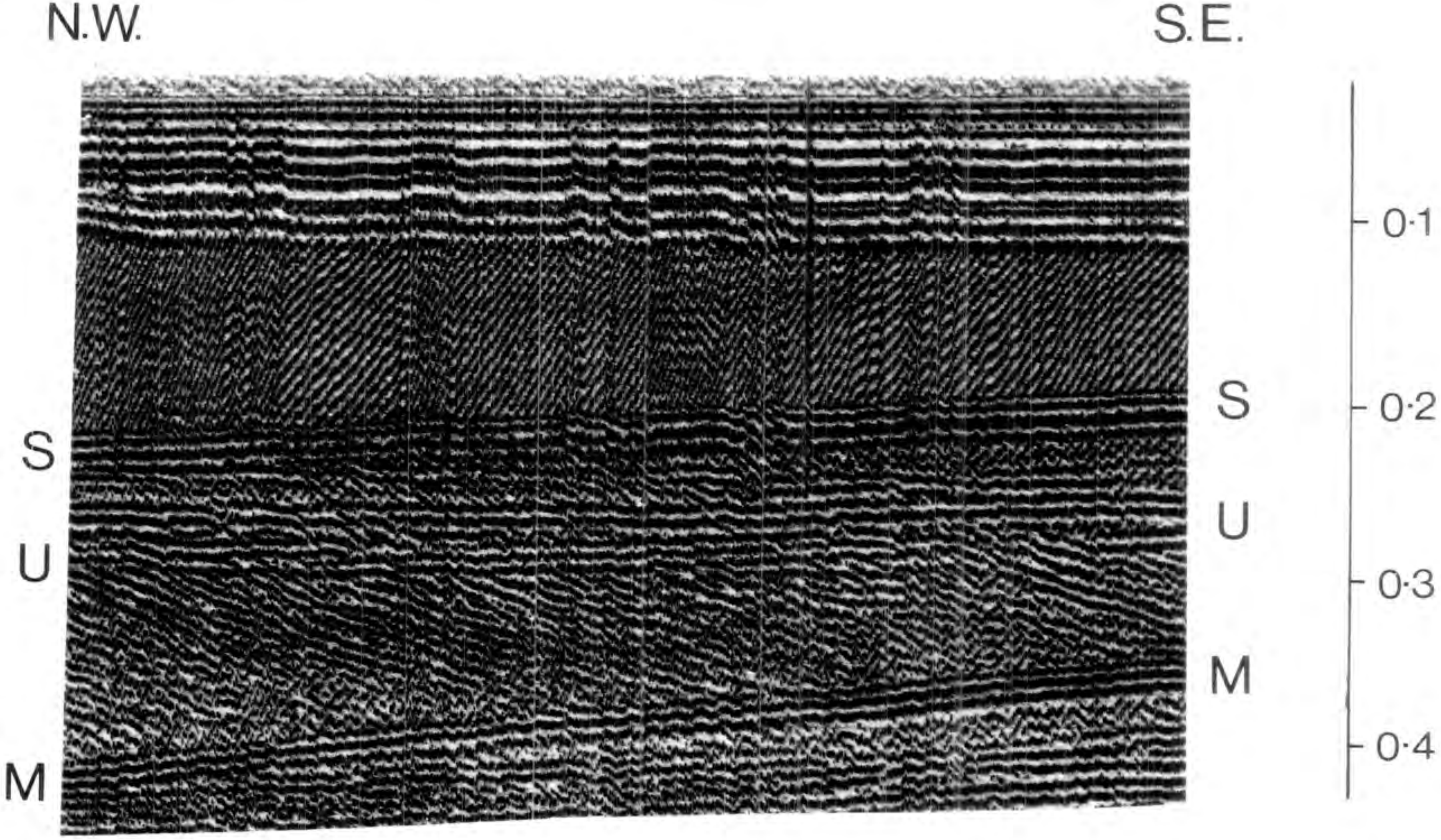
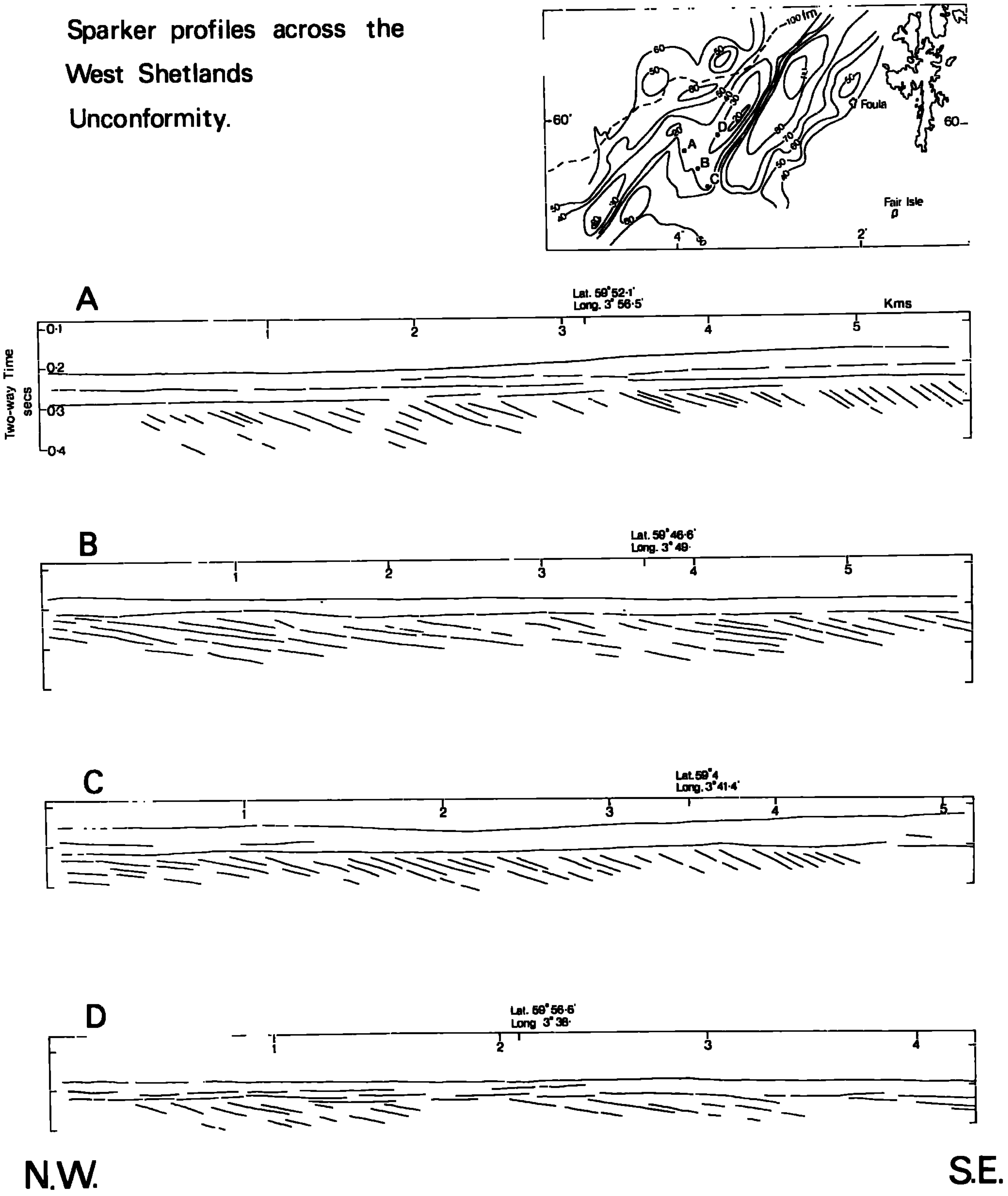


Fig. 4-8. Original seismic reflection profile at HS896139 30 km from the continental shelf break in slope. Symbols and scales as in Figures 4-7 and 4-3.



Sparker profiles across the West Shetlands Unconformity.

Fig. 4-9. Line drawings of seismic reflection profiles across the SSW end of gravity "low" E. Vertical exaggeration as in Figure 4-3.

gravity "low" E is caused by a narrow NNE-SSW trending sedimentary basin bounded on its SE margin by a normal fault. The bulk of sediments causing the gravity "low" appear to dip south-easterly. Assuming a minimum likely sediment velocity of 2·5 km/sec and that the shallow south-easterly dips extend at depth the seismic reflection profiles across the SW end of gravity "low" E indicate at least 3·7 km of sediments. If the profiles are perpendicular to the strike of the sediments a velocity of 2·5 km/sec indicates a "true" sediment dip of 8^{o} to the SE.

Gravity interpretations of "low" E confirm the seismic evidence of a normal fault bounding the SE margin of the sedimentary basin and suggest that a density contrast of at least -0·4 g/cm^3 is required to satisfy the steep marginal gradient (Bott and Watts, 1970a). A preliminary interpretation of gravity "low" E was obtained using the sedimentary basin programme NTRAP (Allerton, 1968). The sub-sediment basement configuration was obtained at each observation point for an assumed constant regional field of 91 mgal and for uniform density contrasts of -0·4 g/cm^3 and -0·5 g/cm^3 between sediments and basement rocks (Bott and Watts, 1970a). The basement configuration obtained was rather irregular although the residuals (observed - calculated anomaly) were small over the basin. A maximum residual of +5·6 mgal was obtained at the steep marginal gradient. A more satisfactory basement configuration was determined from the sedimentary basin programme TRAPPIT (G.J. Laving, personal communication) based on a matrix inversion technique described by Tanner (1967). The solution is by least squares allowing more observation points than body co-ordinates. For an assumed constant regional field of +96 mgal the sub-sediment basement configuration was computed by TRAPPIT for uniform density contrasts of -0·4 g/cm^3 to -0·6 g/cm^3 (Fig. 4-10). TRAPPIT incorporates a "smoothing technique" (G.J. Laving, personal communication) enabling a

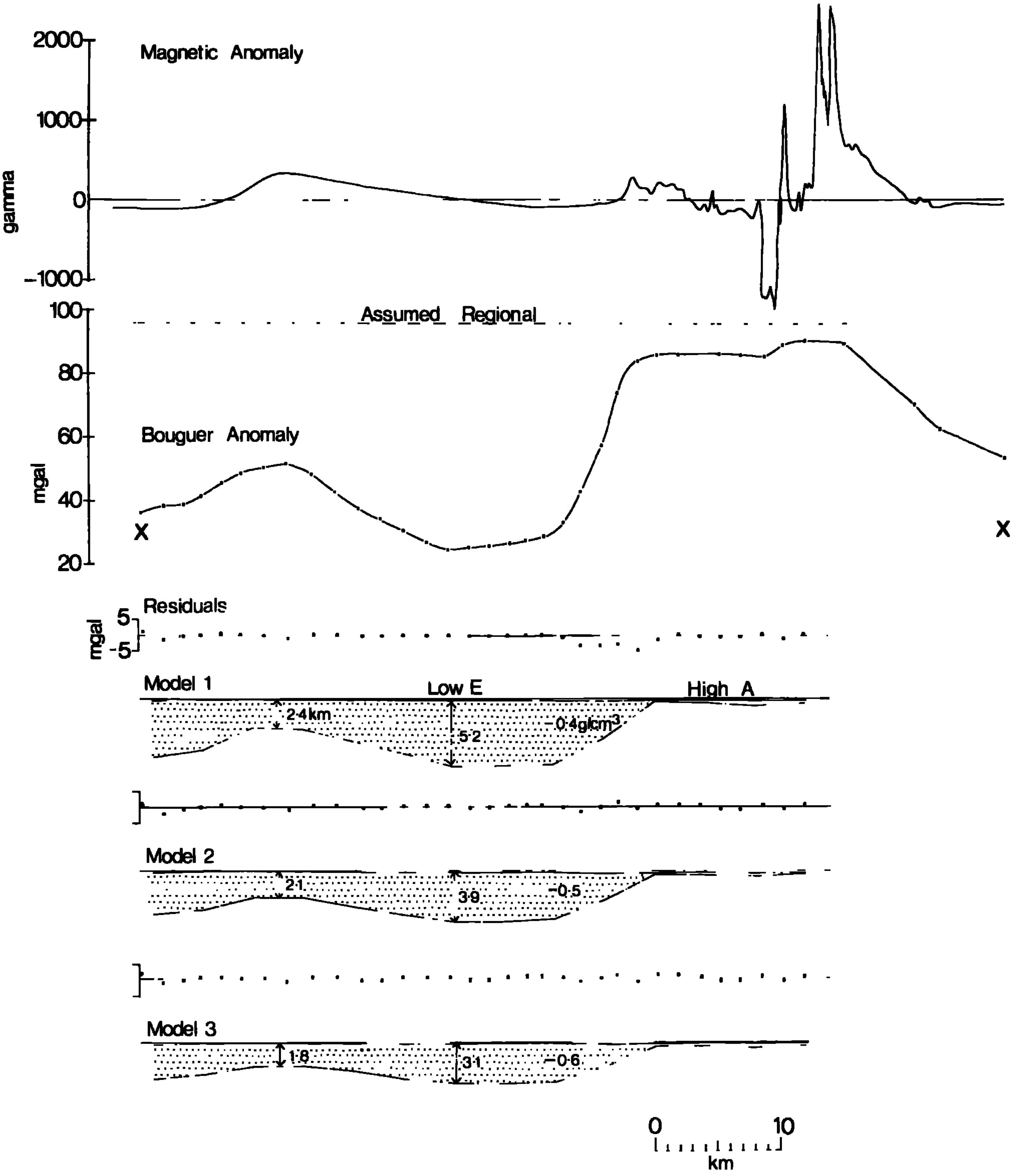


Fig. 4-10. Interpretation of Bouguer anomaly profile XX' (Fig. 4-1) across gravity "low" E. The models have been deduced for the assumed regional shown and for uniform density contrasts of -0•4 g/cm^3 to -0•6 g/cm^3.

smooth basement configuration to be obtained. The residuals for a uniform density contrast of $-0{\cdot}4$ g/cm^3 are within the range ± 2 mgal, although residuals of up to $-5{\cdot}1$ mgal occur at the steep marginal gradient (Model 1, Fig. 4-10). The residuals obtained for Models 1 to 3 (Fig. 4-10) are within the estimated overall error of the gravity surveys (Section 2-2-5). The choice of the assumed regional field is critical to the estimation of depths of the sedimentary basin. The deep structure of the dense basement rocks causing gravity "high" A is unknown so that the regional field cannot be accurately estimated at the steep marginal gradient. Due to the lack of other evidence a constant regional field about 3 mgal above the peak Bouguer anomaly of gravity "high" A was chosen. Because the dense basement rocks causing gravity "high" A outcrop on the sea floor it is unlikely that the regional field is higher than that shown (Fig. 4-10). The depth estimates for the uniform density contrasts specified in Models 1 to 3 (Fig. 4-10) are, therefore, maximum likely values.

An important unconformity has been recognised on the continental slope west of Britain (Stride et al., 1969). The "main" unconformity has been interpreted as representing a hiatus between the deposition of Upper Cretaceous and Lower Tertiary sediments which on land was accompanied by widespread uplift and normal faulting. It seems most likely that the shelf north of Scotland is covered by a thin veneer of Quaternary sediments and that the observed shelf unconformity (Figs. 4-7, 4-8 and 4-9) is a result of a later erosional phase than the "main" unconformity. If Mesozoic-Tertiary sediments form the continental slope west of the Shetlands (Section 4-7) it is possible the "main" unconformity is present north of Scotland but is obscured from the seismic reflection profiles by thick slope forming Quaternary sediments. The evidence suggests that the south-easterly dipping sediments occuring below the shelf unconformity and causing gravity "low" E are at least pre-Quaternary and may be pre-Tertiary.

Gravity interpretations of the steep marginal gradient to "low" E and "high" A suggest that a uniform density contrast of at least $-0{\cdot}4$ g/cm^3 is required. A possible pre-Tertiary age for the sediments and the high density contrasts suggest that Mesozoic sediments form at least part of the sedimentary infill causing gravity "low" E. If the basement rocks causing gravity "high" A are as dense as the pyroxene granulites from the Scourie assemblage in NW Scotland (Storry, 1969), density measurements from the Orkneys (McQuillin, 1968) suggest a likely contrast of $-0{\cdot}17$ g/cm^3 between normal density Old Red Sandstone and high density Lewisian. It is therefore unlikely that Palaeozoic rocks could provide a sufficiently large density contrast with the basement although they may be present beneath a thick Mesozoic-Tertiary succession.

Mesozoic sediments outcrop in East Sutherland and west of the Moine Thrust belt, where they reach a maximum thickness of 1 km in Skye and Raasay (Hallam, 1965). In Skye, Lower Lias limestones unconformably overlie Torridonian and Cambrian sediments. Lias limestones also outcrop in the Shiant Islands where they probably owe their preservation to normal faulting with Lewisian gneiss of the Outer Hebrides to the west (Hallam, 1965). Arkell (1933) suggested that the Scottish Highlands were a positive area during the Mesozoic complementary with areas of subsidence in the Moray Firth and the North Minch. Petrographic studies of the Middle Jurassic Great Estuarine Series show them to be derived mainly from igneous and metamorphic rocks of the Scottish mainland to the east (Hudson, 1964). The Mesozoic sediments in East Sutherland are bounded by a normal fault which moved contemporaneous with sedimentation in the Upper Jurassic (Bailey and Weir, 1932). The interpretation that the steep marginal gravity gradient to "low" E and "high" A is caused in part by the density contrast between Mesozoic-Tertiary sediments downfaulted against Lewisian basement rocks is therefore consistent with the known structural history of Scotland during the Mesozoic.

The suggested line of normal faulting between gravity "low" E and "high" A is closely followed, in part, by a steep submarine scarp. The scarp is associated with an abrupt change in the observed Bouguer anomaly separating the strongly reflecting irregular basement rock outcrops associated with "high" A from the flat sea floor of the sediments causing "low" E (Fig. 4-11). Adjacent bathymetric profiles show that the scarp bounds a narrow depression of the shelf coincident with the main gravity "low" E. This suggests that the sedimentary basin causing "low" E is bounded by a normal fault which has moved recently enough to disrupt the thin veneer of sediments (Quaternary ?) overlying the shelf.

4-4. Gravity "lows" C, D and H.

A region of relatively low gravity occurs west of the Orkneys and north of the Scottish mainland (Region H, Fig. 4-1) merging westwards into the North Minch gravity "low" and north-westwards into the large amplitude gravity "low" C. The observed Bouguer anomaly increases NW of gravity "low" C to a maximum of +66 mgal at HX623741 where it is associated with shallow seismic basement and short wavelength magnetic anomalies. The gravity "high" trends NNE-SSW and separates "low" C from the large amplitude "low" D (Fig. 4-1). Seismic reflection profiles across the NW end of gravity "low" C, west of the Orkneys, show an unconformity on the shelf separating sediments of negligible dip above from sediments with an apparent north-westerly dip below (Fig. 4-12). This is confirmed on an earlier traverse by Stride et al. (1969) NW across the shelf from the Pentland Firth. The apparent dip of the sediments increases at Profile C (Fig. 4-12) to coincide with the main gravity "low". NW

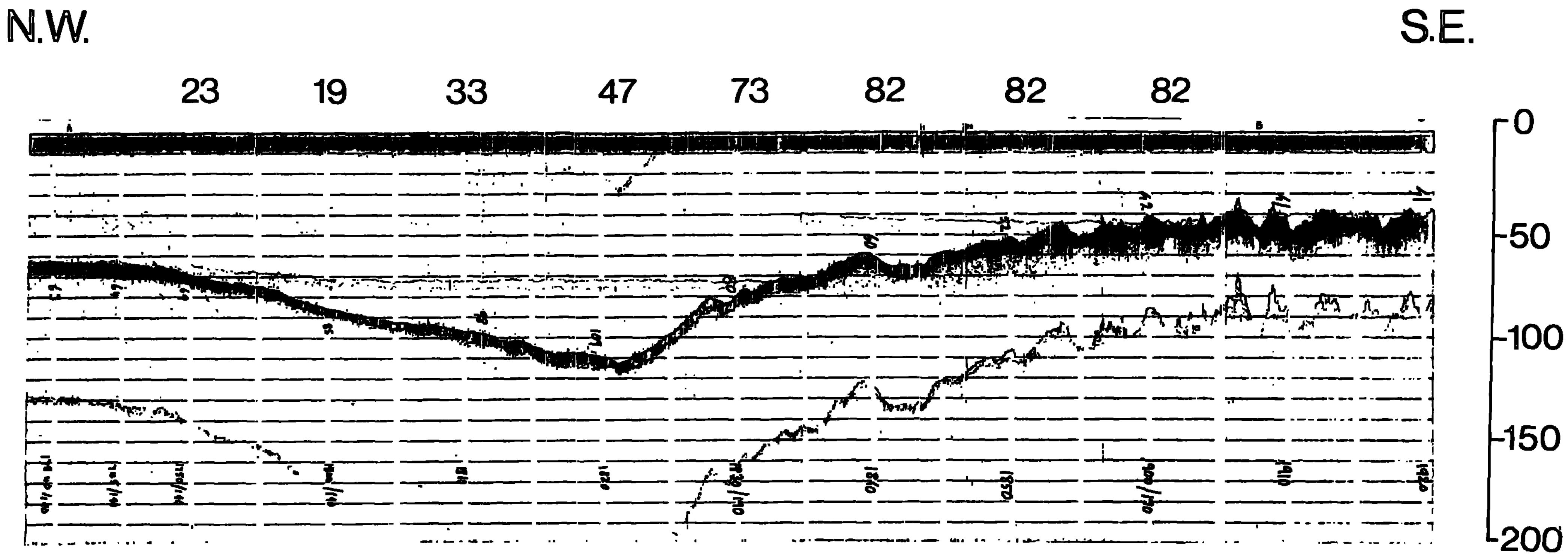


Fig. 4-11. Original bathymetric profile between gravity "high" A and "low" E west of the Shetlands. Bouguer anomaly in mgal indicated above the profile and Bathymetry in fathoms on the right.

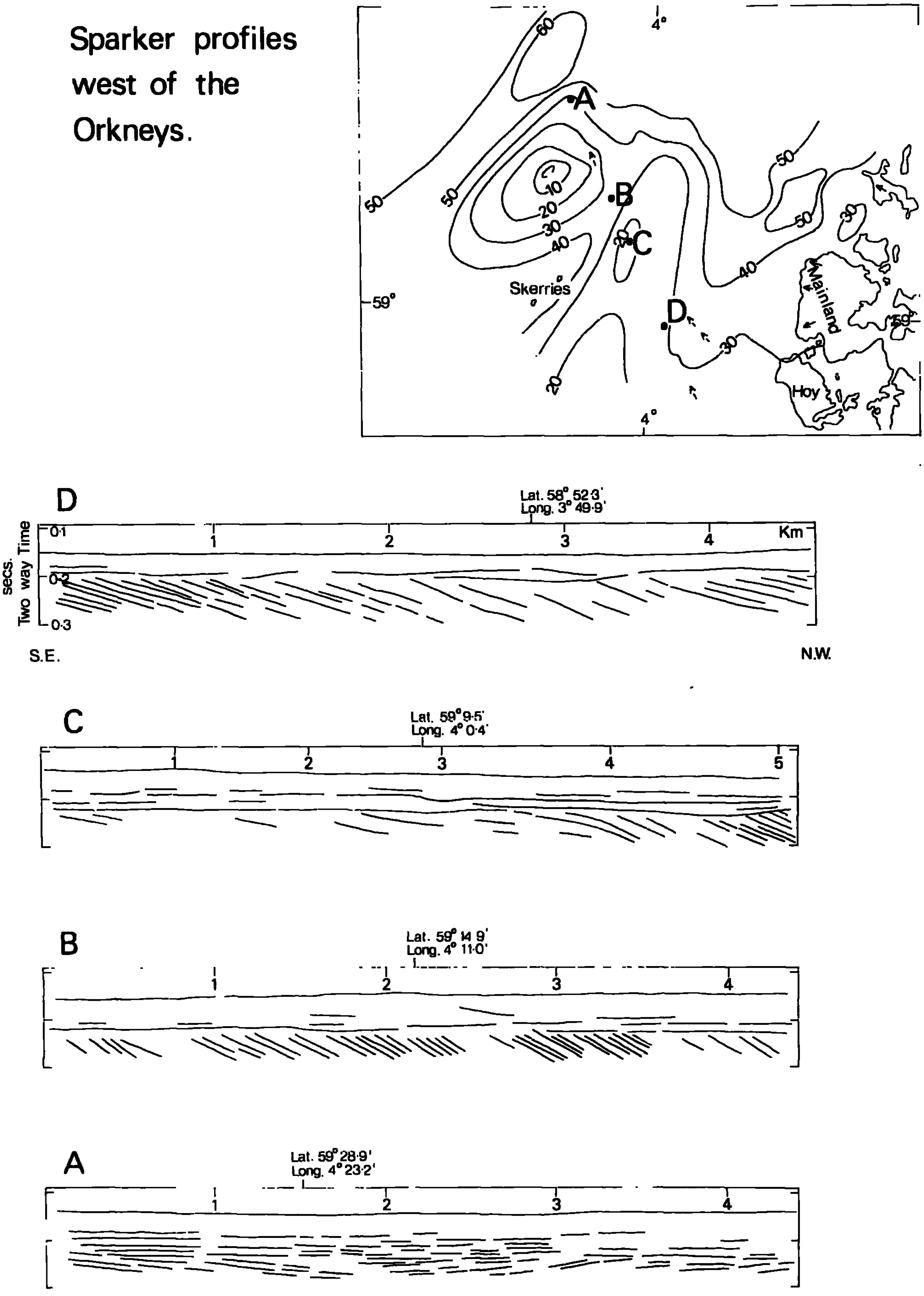


Fig. 4-12. Line drawings of seismic reflection profiles west of the Orkneys. Broken arrows in sea areas away from profiles A-D indicate apparent dip directions along other available profiles. Vertical exaggeration as in Figure 4-3.

apparent dips are observed as far west as Profile A (Fig. 4-12) where a sub-unconformity synclinal structure is observed adjacent to a steep increase in the Bouguer anomaly. The seismic reflection profiles suggest that gravity "low" C is caused by an assymetrical sedimentary basin bounded on its NW margin by a NNE-SSW trending normal fault. Assuming a minimum likely sediment velocity of 2•5 km/sec and that the observed shallow structure extends at depth the sedimentary infill is at least about 3 km. The sedimentary structure of the basin causing gravity "low" D is obscured by seaward dipping sediments which thicken towards the continental slope.

A Bouguer anomaly profile across gravity "lows" C and D (Profile YY', Fig. 4-1) has been interpreted in Figure 4-13. The models have been determined for the assumed regional shown and for uniform density contrasts of -0•4 g/cm^3 and -0•5 g/cm^3 between sediments and basement rocks. Gravity "low" C can be interpreted as a sedimentary basin 3•6 km deep for a uniform density contrast of -0•4 g/cm^3 (Fig. 4-13) or 4•6 km deep for -0•3 g/cm^3. There is an excellent correlation between short wavelength magnetic anomalies and the occurrence of shallow or outcropping basement for Models 1 and 2 (Fig. 4-13).

The NW apparent dips observed west of the Orkneys (Fig. 4-12) may represent a stratigraphic continuation of dips observed from the Old Red Sandstone in the Orkneys. Upper Stromness Flags (Middle Old Red Sandstone) dip gently west in West Mainland, Orkney and Hoy Sandstones (Upper Old Red Sandstone) dip gently NW in Hoy, Orkney (Wilson et al., 1935). NW apparent dips are observed as far west as Profile A (Fig. 4-12) at HX673627 and at HX650495 (Stride et al., 1969). On thickness grounds Stride et al. (1969) suggested that post-Devonian sediments probably occur in the region now outlined as gravity "low" C. The seismic evidence cannot satisfactorily indicate the extent of Devonian sediments on the

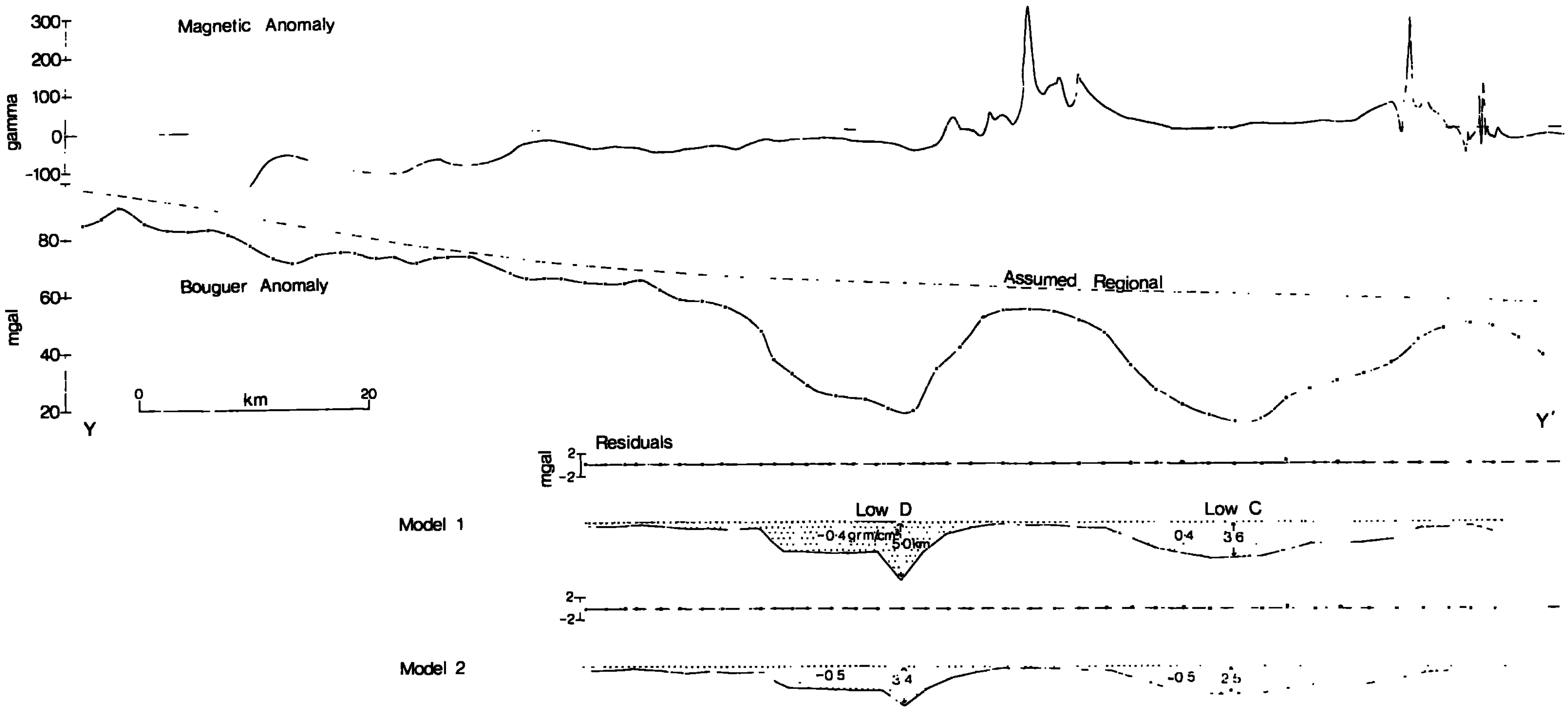


Fig. 4-13. Interpretation of Bouguer anomaly profile YY'. The models have been deduced for an assumed regional, an assumed 2-dimensional structure and for uniform density contrasts of -0·4 g/cm^3 and -0·5 g/cm^3.

shelf. The stratigraphy of the shelf Devonian sediments may have been complicated by the same normal and reversed fault patterns and simple folds which affected the Orkneys (Wilson et al., 1935). The succession has been further complicated by a pre-Upper Old Red Sandstone period of uplift and erosion preceeding deposition of the Hoy Sandstones and their associated lavas.

The narrow region of low gravity (Region H, Fig. 4-1) between the Skerries and the mainland of Scotland is associated with the seaward extension of the Moine outcrop in North Scotland. A minimum Bouguer anomaly of +6 mgal occurs at NC646813, 27 km NNE of the Kyle of Tongue. The region is also associated with long wavelength magnetic anomalies (Fig. 4-2) suggesting that the seaward extension of the magnetic Moine (and Lewisian) basement is obscured by younger sediments. A broad region of sediments north of Scotland, lower in density than the Old Red Sandstone, would account for the observed easterly increase in the Bouguer anomaly between Hoy, Orkney and the Kyle of Tongue, Sutherland.

The minimum estimate from the seismic reflection profiles of the thickness of sediments causing gravity "low" C is in close agreement with the gravity interpretations for an assumed uniform density contrast of $-0{\cdot}4$ g/cm^3 or $-0{\cdot}3$ g/cm^3. The high density contrasts indicated and the likelihood of post-Devonian sediments NW of the Skerries suggest that Mesozoic-Tertiary sediments form at least part of the sedimentary infill causing "low" C. It is possible the sediments extend into Region H (Fig. 4-1) west of the Orkneys and north of Cape Wrath into the North Minch.

4-5. Magnetic anomaly R.

Gravity "lows" C and D are separated by a region of high Bouguer gravity anomaly, shallow seismic basement and short wavelength magnetic anomalies (Figs. 4-1, 4-2 and 4-13). The magnetic anomaly pattern forms a NNE-SSW belt of positive anomalies extending to about 60 km. north of Cape Wrath (IGS, 1968 Sheet 15; Fig. 4-2). Marine magnetic surveys show that the positive anomalies extend NNE to intersect the continental shelf break in slope at HT367691 WNW of the Shetlands. Magnetic anomaly R (Fig. 4-2) forms a NNE-SSW trending belt of positive anomalies of amplitude reaching 350 gamma and approximately 225 km in length. Magnetic anomaly R, west of the Shetlands, is bounded by magnetic and gravity "lows" and trends parallel to gravity "high" A. The general association of shallow seismic basement and high gravity with magnetic anomaly R suggest it is caused at least in part by a rise of magnetic basement rocks.

Marine magnetic anomaly profiles across anomaly R have been interpreted assuming it is caused by variation in relief of a uniformly magnetised basement. Two profiles were selected WNW of the Shetlands near the shelf break in slope. The profiles were interpreted using non-linear optimisation techniques which are numerical iterative methods minimising a certain function in terms of its variable parameters (M.Al-Chalabi, personal communication). The function in this case is the sums of the squares of the residuals between observed and calculated magnetic anomalies. The magnetic anomaly was obtained from output of the magnetic reduction programmes (Section 2-3) and represents the total magnetic field in gamma with the IGRF subtracted. The two profiles traverse magnetic anomaly R approximately at right angles and are located 40 km apart. Assuming the IGRF as the regional background field, magnetic anomaly R can be explained by a change of 2•5 km to 4•5 km in the relief of a magnetic basement with a uniform total magnetisation of $2{\cdot}1 \times 10^{-3}$ emu/cm^3 in a plane perpendicular to the strike of the

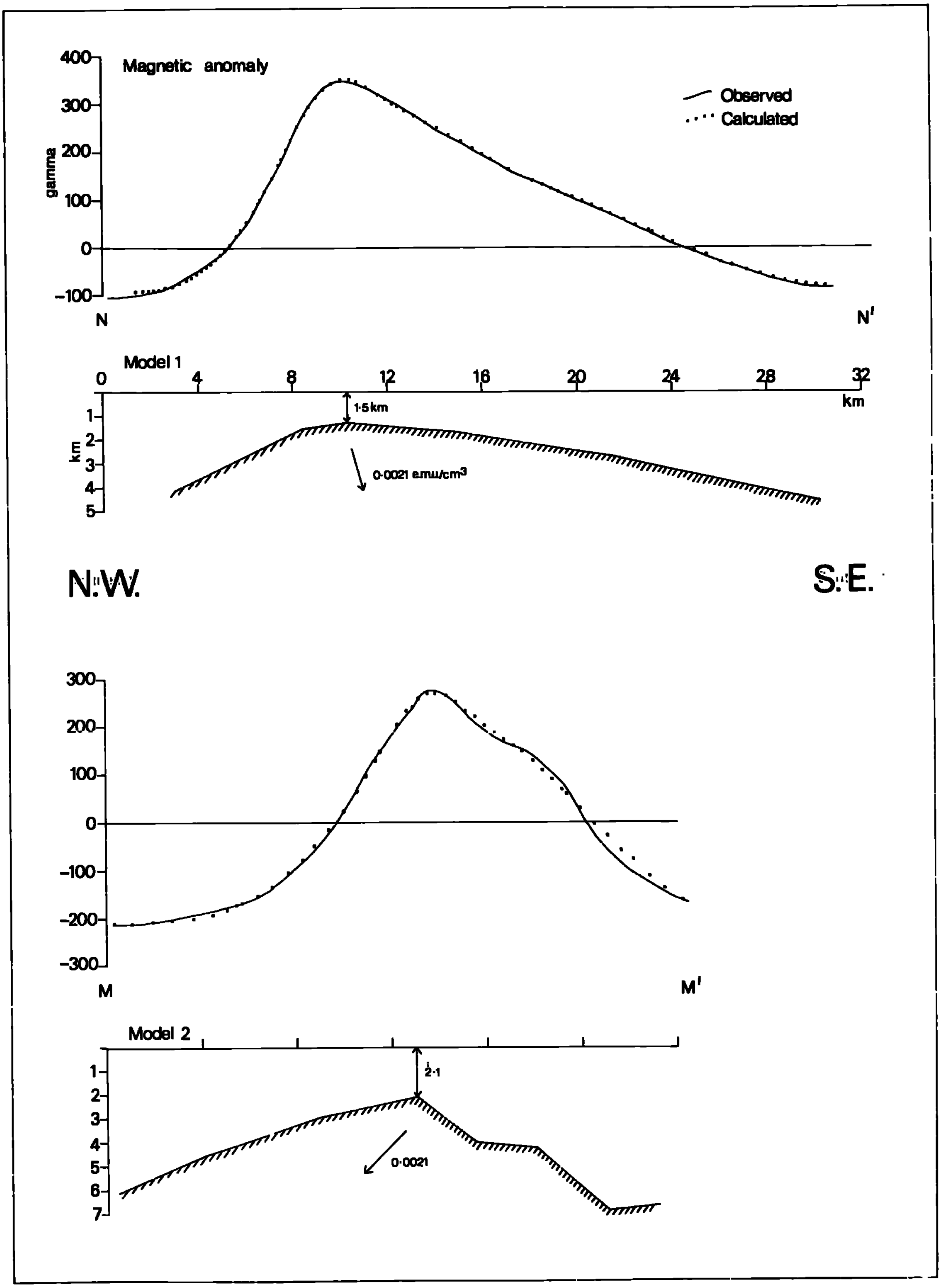


Fig. 4-14. Interpretation of magnetic anomaly profiles NN' and MM' (Fig. 4-2) across magnetic anomaly R.

basement rise (Fig. 4-14). The top surface of the basement rise occurs at a depth of 1•5 km in Model 1 and 2•1 km in Model 2 (Fig. 4-14). There is an excellent correlation between the top surface of the models and the region of highest observed Bouguer anomaly.

The basement relief of the feature causing magnetic anomaly R could not be traced on the seismic reflection profiles west of the Shetlands. The onset of south-easterly dipping sediments at Profile A (Fig. 4-9) coincides with the eastern gradient of magnetic anomaly R (Station A, Fig. 4-2). This suggests a structural relationship between the attitude of the sub-unconformity sediments (Figs. 4-7, 4-8 and 4-9) and the basement rise. If the top surface of the basement rise is of the order of 2 km WNW of the Shetlands it is most likely that the south-easterly dipping sediments causing gravity "low" E extend seawards over the rise to make up part of the slope forming sediments. The basement rise is therefore overlain by a sedimentary "anticline" at the shelf break in slope (Fig. 4-17).

The sediments causing gravity "low" E have been interpreted as at least Mesozoic-Tertiary in age. If the basement causing magnetic anomaly R underlies the sedimentary infill, a pre-Mesozoic age of the basement is indicated. It is unlikely that Palaeozoic rocks could be present because of their absence in the foreland region west of the Caledonian fold-belt in NW Scotland. The boundary separating the fold-belt from the shelf foreland region is interpreted as passing east of gravity "high" A (Section 5-1). If the NNE-SSW trend of magnetic anomaly R is extended SSW it continues into the Lewisian outcrops in the Outer Hebrides. Some of the largest structural elements in Lewis trend NNE-SSW (J. Watson, personal communication).

The Precambrian basement in NW Scotland and the Outer Hebrides is associated with long wavelength magnetic anomalies of up to 800 gamma (IGS, 1968 Sheets 12 and 13). The presence of magnetic rocks within the basement is also indicated from volume susceptibility measurements by D.W. Powell (personal communication) of the Scourie and Laxford assemblages in NW Scotland. The mean susceptibility of 90 samples of ultrabasic and granulite rocks from the Scourie assemblage is 2×10^{-3} emu/cm^3 which increases by 2×10^{-3} emu/cm^3 for each weight percent of Fe_2O_3. The geological and geophysical evidence is therefore consistent with the basement rise being of Precambrian age similar in magnetic properties to the Lewisian basement rocks in NW Scotland.

The interpretations of magnetic anomaly R (Fig. 4-14) cannot satisfactorily distinguish the type of the magnetic basement in relation to the known assemblages of Precambrian rocks in NW Scotland. The basement rise is located west of gravity "high" A and it is of interest to know if there is any evidence that the basement causing magnetic anomaly R is similar in properties to the dense basement, of variable magnetic properties, causing gravity "high" A. The magnetic anomaly R can be compared to the short wavelength, high amplitude, anomalies associated with gravity "high" A (Fig. 4-5) if the depth of burial of the rise can be allowed for. The magnetic anomaly profiles associated with "high" A were continued upwards using a computer programme written for the I.B.M. 360/67 the estimated depth of burial. If the basement rise is made up of rocks similar in properties to the basement associated with "high" A there should be no significant difference in the magnetic anomaly pattern compared to anomaly R. West of the Shetlands, gravity interpretations indicate a maximum likely depth to the basement rise of 2•3 km (Model 1, Fig. 4-10). If the corresponding magnetic anomaly profile across "high" A is upward continued 2•5 km an anomaly of approximately 18 km wavelength and 450 gamma is obtained which is of smaller wavelength and larger amplitude than that observed. This qualitatively indicates that the strongly magnetic rocks associated with 3 traverses of gravity "high" A (Fig. 4-5) are probably not present in the basement rise.

4-6. Gravity "low" F.

A broad N-S trending region of low Bouguer gravity anomaly occurs on the continental shelf between the Orkneys and the Shetlands (Region F, Fig. 4-1) reaching a minimum of -23 mgal at HU201094. The gravity "low" is associated with the south part of the Walls Peninsula, Shetland and extends to SW of Fair Isle. Gravity "low" F is characterised by steep marginal gradients (Fig. 4-1).

The geology of the Shetlands west of the Walls Boundary Fault has been discussed by Finlay (1930) and Flinn et al. (1968). In the north of the Walls Peninsula gneisses are unconformably overlain by Walls and Sandness sandstones which increase in thickness to the south. The sediments have been folded into a WSW-ENE trending synform (Finlay, 1930). They contain abundant ashes and lavas and are intruded in the south by the Sandsting granite. The sediments are dark coloured and compact and do not resemble Old Red Sandstone sediments in Melby or east of the Walls Boundary Fault. The Sandsting granite is a biotite-rich granite which has been dated by Miller and Flinn (1966) as 330 m.y. The granites are associated with basic assemblages varying in composition from quartz diorites to gabbros. Peach and Horne (1884) suggested the quartz diorites were basic modifications of the granite. The field relations of the Ronas Hill, Vementry and Sandsting granites suggested to Finlay (1930) they formed an extensive sheet complex. To explain the relationship of acid and basic rocks Finlay (1930) proposed that the granites formed by differentiation after emplacement rather than secondary intrusion.

Gravity surveys in NW Northmaven, Shetland show that the Bouguer anomaly increases eastwards across a line separating the Old Red Sandstone volcanic rocks of Esha Ness from an extension of the Ronas Hill granite complex to the west (McQuillin and Brooks, 1967). The main gravity gradients, however, have been outlined at sea between gravity "high" A and Esha Ness (Fig. 4-1). The observed Bouguer anomaly in Foula suggested that a steep decrease in gravity occurred towards the Walls Peninsula (McQuillin and Brooks, 1967). This is confirmed by the marine surveys which show that the Foula to Walls Peninsula steep gradients are part of a larger decrease of about 3 mgal/km from gravity "high" A to "low" F (Fig. 4-1).

The Bouguer anomaly in the Walls Peninsula decreases southwards to a minimum of +7 mgal at the coast where it is associated with the Sandsting granite (McQuillin and Brooks, 1967). The decrease in gravity and an extension of a positive magnetic anomaly (IGS, 1968 Sheet 16), associated with the basic part of the Sandsting granite complex, beyond the coast suggested to McQuillin and Brooks (1967) that the granite complex underlies the sea area south of the Peninsula. This suggestion is tentatively supported by a single seismic reflection profile 11 km south of the Walls Peninsula. The onset of a strongly reflecting crystalline basement occurs at HU229133 extending to HU332344, west of South Mainland, Shetland. The association of the strongly reflecting basement with low gravity anomalies also suggest an extension of the Sandsting granite complex south of the Walls Peninsula.

Speculations can now be made on the cause of the steep gravity gradients observed between gravity "high" A and "low" F, and between "high" A and Esha Ness (Fig. 4-1). The Bouguer anomaly decreases by 45 mgal between "high" A and Foula. The Old Red Sandstone in Foula is in faulted contact with granite intruded metamorphic rocks. Foula is associated with short wavelength positive magnetic anomalies (IGS, 1968 Sheet 16) suggesting that the Old Red Sandstone cover is thin. It is most unlikely, therefore, that Old Red Sandstone sediments are present between gravity "high" A and Foula to contribute to the observed gradients. The decrease in gravity could be due to a gradual SE dip of the dense rocks causing "high" A beneath their overlying metamorphic cover. The cause of the steep gradients between Foula and gravity "low" F is more difficult to explain from the geology of the Walls Peninsula. The surface geology suggest the decrease is caused by a density contrast between metamorphic rocks in Foula and the Old Red Sandstone assemblage in the Walls Peninsula. The Old Red Sandstone assemblage in the Walls Peninsula is associated with low Bouguer anomalies and gravity "low" F (Fig. 4-1) appears to be bounded by an extension of the proposed St. Magnus Bay Fault in the west (Flinn et al., 1968) and the Walls Boundary Fault in the east. The rocks which make up the Old Red Sandstone assemblage west of the Walls Boundary Fault, however, are not significantly lower in density than the metamorphic rocks in Foula. It is unlikely that the Esha Ness volcanics, the compact Walls and Sandness sandstones or the granite complexes (if the field relations of Finlay (1930) are accepted) could significantly contribute to the required density contrasts. There is therefore the possibility that the Old Red Sandstone assemblage of North Roe, North Mainland, Walls Peninsula and its southerly extension to gravity "low" F is underlain at no great depth by a large granite mass (M.H.P. Bott, personal communication). The decrease of about 110 mgal in the Bouguer anomaly between "high" A and "low" F could then be due partly to:

1. A gradual SE dip of the dense basement rocks, causing gravity "high" A, which have been interpreted as of Lewisian type.
2. A contrast of Old Red Sandstone (and younger ?) sediments with the metamorphic basement.
3. A granite mass of unknown extent beneath the Walls Peninsula and gravity "low" F which contrasts at depth with metamorphic rocks and possibly high density basement.

It is not possible on the evidence available to isolate the 3 contributions although it would be suggested that the first contribution is particularly significant between gravity "high" A and Foula, and "high" A and Esha Ness.

4-7. Continental slope anomalies.

The continental slope north of Scotland between 200 and 800 meters is associated with a number of circular gravity "lows" (Fig. 4-1). NW of the Shetlands the Bouguer gravity anomaly decreases from +55 mgal at the shelf break in slope to +45 mgal at 350 meters of water. This indicates a gravity "low" of about 20-30 mgal amplitude associated with the slope because the Bouguer anomaly is expected to increase from the shelf break in slope to the Faeroe-Shetland Channel (Section 3-4). Substantial thicknesses of sediments occur on the continental slopes west of Britain (Stride et al., 1969). It is most likely that the gravity and magnetic anomaly "lows" observed on the continental slope NW of the Shetlands are caused by a thickening of sediments seawards from the shelf break in slope.

The Bouguer anomaly profile ZZ' (Fig. 4-1) across the continental slope WNW of the Shetlands has been interpreted assuming the gravity "low" to be caused by low density sediments. For an assumed north-westerly increase in the regional gravity field of 0•7 mgal/km and for uniform density contrasts of $-0{\cdot}3$ g/cm^3 and $-0{\cdot}4$ g/cm^3, depths to the basement of 3•2 km and 2•5 km have been obtained from the sedimentary basin programme TRAPPIT (G.J. Laving, personal communication). There is an excellent correlation between the margins of the sedimentary trough and an increase in the observed magnetic anomaly (Fig. 4-15). A minimum magnetic anomaly of -235 gamma is observed at the centre of the interpreted models (Fig. 4-15). The increase in magnetic anomaly at the SE end of the profile, near the shelf break in slope, is associated with magnetic anomaly R (Fig. 4-2). Magnetic anomaly R has been interpreted as caused by a Precambrian basement rise so it is possible the basement rocks extend beneath the continental slope to underlie between 2 and 4 km thickness of sediments. The models also suggest a rise in the basement beneath the

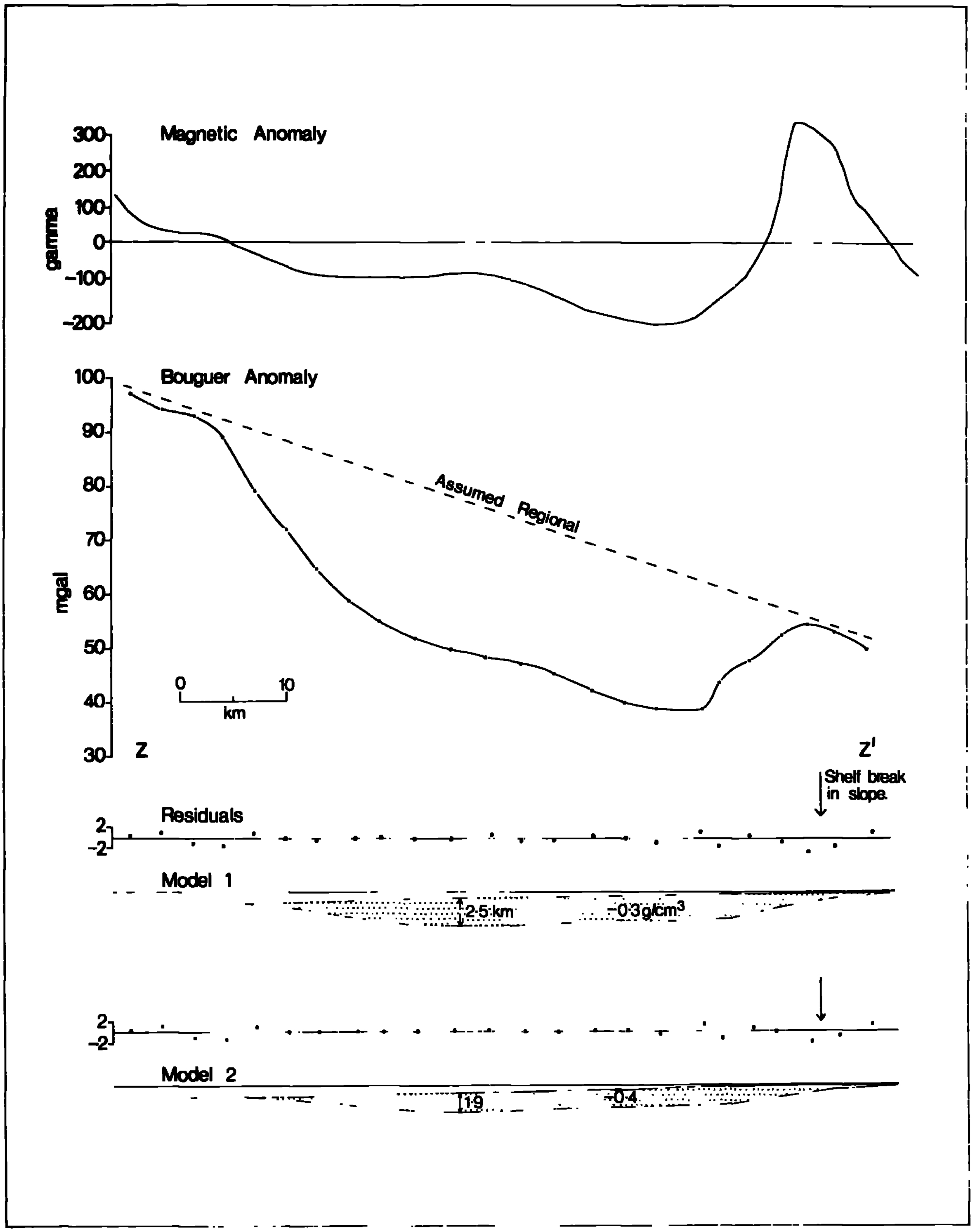


Fig. 4-15. Interpretation of Bouguer anomaly profile ZZ' (Fig. 4-1) across the continental slope west of the Shetlands. The models have been deduced for the assumed regional shown and for uniform density contrasts of -0·3 g/cm^3 and -0·4 g/cm^3.

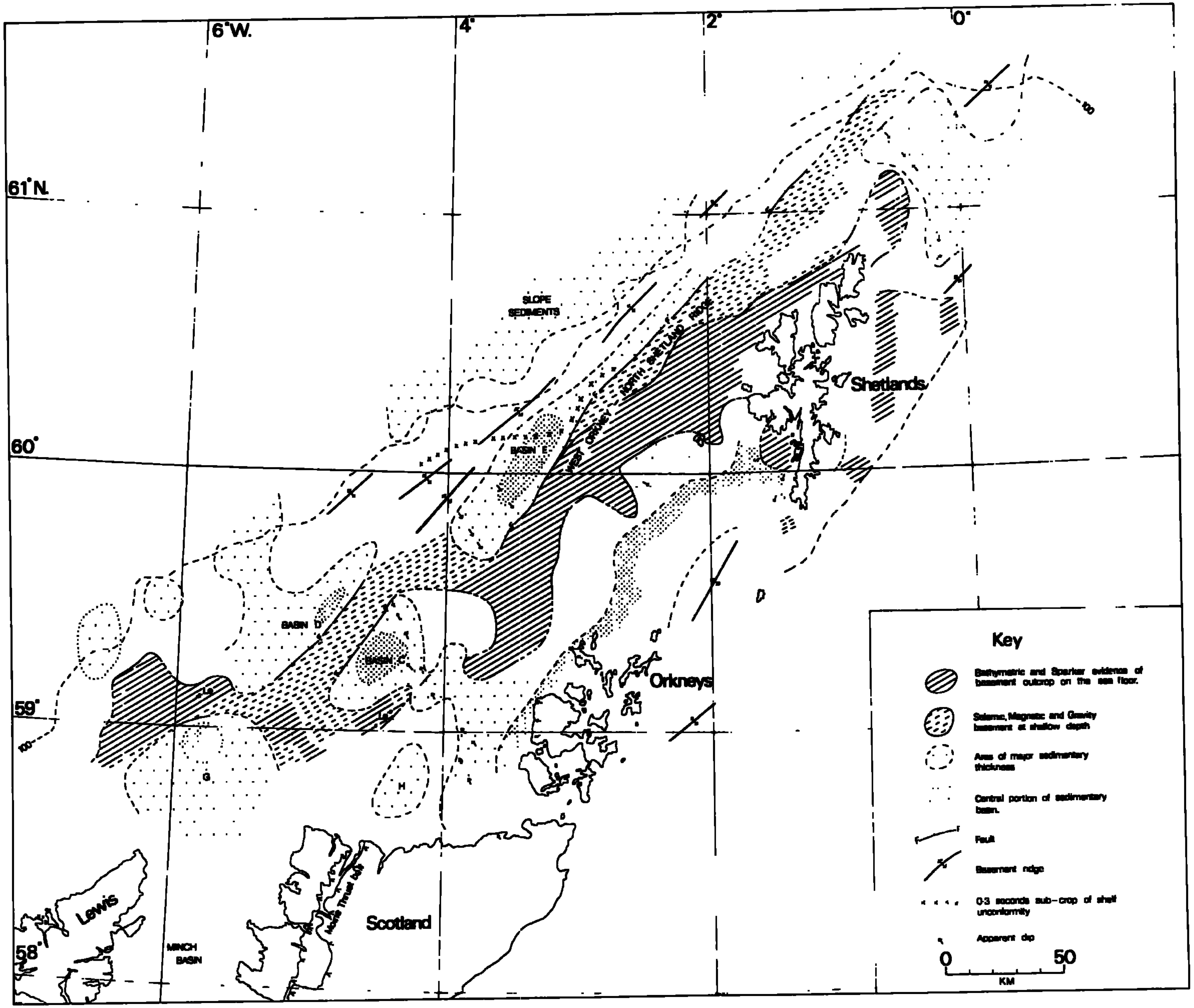
Faeroe-Shetland Channel where it is associated with the central magnetic "high" (Fig. 3-3).

Seismic reflection profiles across the continental shelf and slope west of the Shetlands suggest that the thin Quaternary sediments on the shelf thicken towards the slope (Figs. 4-7 and 4-8). Stride et al. (1969) suggest that the Quaternary sediments are thickest at the foot of the slope and that Tertiary sediments are normally 0•5 to 0•8 km thick on the slope. This estimate is of the order of thickness of post-basalt lava sediments observed SE of the Faeroe Islands (Section 3-5). Thick Tertiary/Quaternary sediments probably occur beneath the Porcupine Seabight (Stride et al., 1969), the Western Approaches to the English Channel (Hill and King, 1953) and the North Sea (Hinz, 1968). The interpreted depths to the basement (Models 1 and 2, Fig. 4-15) are greater than the normal thickness of Tertiary/Quaternary sediments from the continental slope west of Britain. This tentatively suggests that pre-Tertiary sediments occur WNW of the Shetlands unless local subsidence has caused an unusual thickness of Tertiary/Quaternary sediments.

4-8. Deep structure of the Hebridean-Shetland shelf.

A summary map of the interpretations of geophysical data from the continental shelf and slope north of Scotland is shown in Figure 4-16. The areas of the shelf where crystalline basement rocks outcrop on the sea floor or occur at shallow depths (less than about 300 meters) have been estimated from the seismic reflection and bathymetric profiles. A large area of the shelf where basement rocks outcrop or occur at shallow depth extends from NW of the Orkneys to north of the Shetlands (Fig. 4-16). The West Orkney-North Shetland ridge (Fig. 4-16) is associated for part of its extent with gravity "high" A (Fig. 4-1). The age of the basement rocks outcropping on the shelf can only be established by detailed bottom sampling.

Fig. 4-16. Summary map of the deep structure of the continental shelf and slope north of Scotland.



6°W.
4°
2°
0°
61°N.
60°
59°
58°
SLOPE SEDIMENTS
WEST ORKNEY - NORTH SHETLAND RIDGE
BASIN E
BASIN D
BASIN C
G
H
Shetlands
Orkneys
Scotland
Lewis
MINCH BASIN
Moine Thrust belt
100
Key
Bathymetric and Sparker evidence of basement outcrop on the sea floor.
Seismic, Magnetic and Gravity basement at shallow depth
Area of major sedimentary thickness
Central portion of sedimentary basin.
Fault
Basement ridge
0·3 seconds sub-crop of shelf unconformity
Apparent dip
0
50
KM

Crystalline basement outcrops on the sea floor extend from the metamorphic rocks in Foula and the north part of Walls Peninsula. It is probable that the basement rock outcrop south of the Walls Peninsula indicates an extension of the Sandsting granite. The basement rock outcrops adjacent to Basin C (Fig. 4-16) probably refer to Lewisian gneiss which outcrop in the Skerries and North Rona.

The areas of major sedimentary thickness on the shelf and slope have been estimated from the regions of gravity "low". Gravity "lows" C, D and E have been interpreted as caused by deep sedimentary basins. The interpreted models (Figs. 4-10 and 4-13) have been used to estimate the central part of the sedimentary basins. The apparent dip directions observed from the seismic reflection profiles refer to sedimentary dips below the shelf unconformity. The gentle seaward dips of the sediments above the unconformity (Quaternary ?), on the outer part of the shelf, have been omitted. The sediments on the shelf (Quaternary ?) thicken towards the continental slope which is shown by mapping the travel time to the sub-crop of the shelf unconformity. The 0•3 second two-way travel time to the sub-crop of the shelf unconformity shows that the presumed Quaternary sediments, above the unconformity, generally thicken seawards parallel to the strike of the present continental shelf break in slope (Fig. 4-16). This explains why the south-easterly dips below the shelf unconformity associated with gravity "low" E have only been observed at the SSW end of the "low". The northern end of the sedimentary basin causing the gravity "low" is obscured by slope forming sediments. This demonstrates that the older structures on the shelf associated with the deep sedimentary basins are truncated by recent slope forming sediments.

The close association of gravity and magnetic "highs" on regions of the shelf where crystalline basement rocks do not outcrop on the sea floor suggest the presence of buried basement ridges. The interpretation of magnetic anomaly R west of the West Orkney-North Shetland ridge and Basin E suggests it is caused by a rise in the magnetic basement to underlie approximately 1•5 to 2•5 km of sediments (Section 4-5). Additional basement NNE-SSW trending ridges probably occur on the outer part of the shelf. Seismic reflection profiles are required to establish their structure and relationship to the overlying sediments.

4-9. Faults.

The geophysical evidence suggest that large normal faults bound the deep sedimentary basins on the continental shelf north of Scotland. The steep normal fault associated with gravity "high" A and "low" E occurs at the NW margin of the West Orkney-North Shetland ridge (Fig. 4-16). The close association of the disappearance of the seismic basement and an abrupt decrease in the Bouguer anomaly (Fig. 4-4) suggests the faulting extends for most of the NW margin of the ridge (Fig. 4-16). The gravity interpretations of "lows" C and D suggest the basins are bounded by normal faults (Fig. 4-13). The line of faulting between Basins C and D may extend NNE to the margins of the basement rise causing magnetic anomaly R. The faults trend NNE-SSW and do not appear to extend between sedimentary basins. Normal faults which decrease in throw along their length are referred to as hinge-faults (Sherbon Hills, 1963). The faulting probably accompanied sedimentation so that the largest downthrows occur adjacent to the largest sediment thickness.

Two large transcurrent faults have been proposed to cross the shelf and slope north of Scotland. Dearnley (1962) suggested that the Scourie assemblages in the Outer Hebrides and NW Scotland were displaced by a sinistral transcurrent fault along the NW margin of the North Minch.

Avery et al. (1968) extended the fault NE across the shelf. The North Minch is associated with a gravity "low" with steep marginal gradients (Allerton, 1968). The gravity interpretations suggest that the North Minch is bounded by a normal fault downthrowing SE. The NNE-SSW trend of the fault would be on the same line as the fault deduced from the seismic reflection profiles at the NW margin of Basin C (Fig. 4-12) and also downthrowing SE. The evidence suggests that the proposed Minch Fault is associated with normal faulting although it cannot determine whether there has been any pre-Mesozoic transcurrent movement.

The extension of the sinistral transcurrent movement of the Great Glen Fault (Kennedy, 1946; Holgate, 1969) beyond the Moray Firth to the Walls Boundary Fault on the Shetlands and north to the continental slope has been proposed (Flinn, 1961). The Walls Boundary Fault in the Shetlands is a major dislocation separating contrasting types of Old Red Sandstone and metamorphic rocks. It is not possible to correlate between rocks on either side of the Fault (Flinn, 1961). The Fault occupies a shear and shatter zone. At Seli Voe, south of the Walls Peninsula, the Fault zone can be traced towards a submarine scarp west of Sunburgh Head (Flinn, 1961 and 1964). Steeply dipping Old Red Sandstone sediments (Appelby, 1961) on the west coast of Fair Isle provide evidence of a large fault to the west. The Walls Boundary Fault cuts the Walls and Sandness sandstones and the Sandsting granite. Age dating of the granite (Miller and Flinn, 1966) suggests that the Fault is younger than 330 m.y.

Gravity evidence north of the Shetlands (Fig. 4-1) show there is no displacement of "high" A, which has been interpreted as caused by Lewisian rocks, on the northern line proposed by Flinn (1961). This suggests that the extension of the Great Glen Fault <u>either</u> passes north of the Shetlands retaining the same strike north of the Walls Boundary

Fault as it had to the south (Flinn, 1970) <u>or</u> the Walls Boundary Fault is a splay of the main fault (Pitcher, 1969) which probably passes east of the Shetlands (Collette, 1960; Bott and Watts, 1970a). The second possibility avoids the need for two major changes in course not expected from a transcurrent fault unless it has been affected by later faulting or deformation (Bott and Watts, 1970b).

4-10. Discussion.

Geophysical investigations on the continental shelf and slope north of Scotland provide evidence on the structure and stratigraphy of the region. It is probable that large areas of Precambrian basement rocks outcrop on the shelf or occur at shallow depth. Gravity "high" A and magnetic anomaly R have been interpreted as caused by basement rocks similar in properties to the Lewisian in NW Scotland and the Outer Hebrides. The Precambrian shelf foreland region has been modified by post-Caledonian basin formation and normal faulting. Of particular geological interest is the cause of the NNE-SSW trends within the shelf foreland region and the history and cause of the post-Caledonian basin formation.

The deep sedimentary basins on the outer part of the shelf appear to be bounded by NNE-SSW trending normal faults which probably acted as hinge faults during sedimentation. The faults are probably related to NNE-SSW trends in the underlying basement which west of gravity "high" A and north of the Skerries (Fig. 4-1) is interpreted as Precambrian in age. NNE-SSW trends in Precambrian basement rocks appear to be unrelated to the WNW-ESE trending distribution of the Scourie and Laxford assemblages in the Lewisian of NW Scotland. The evidence suggests that the WNW-ESE trending magnetic anomaly "high" associated with the Scourie assemblage in NW Scotland between Point of Stoer and the Ben Stack Line (IGS, 1968 Sheet 13) is terminated by the eastern margin of the North Minch sedimentary basin. NNE-SSW structural trends are associated with the metamorphic belt of the Caledonian fold-belt in North Scotland (Dunning and Stubblefield, 1966). This suggests that the NNE-SSW trends in Precambrian basement rocks are probably more related to the late Caledonian movements, which affected the metamorphic belt, than to infra-basement structural directions. It is not clear, from the evidence available, how extensively the late Caledonian movements affected the marginal Precambrian basement to the west. The stable Precambrian basement rocks could have responded to the late Caledonian movements by fracturing on NNE-SSW directions. The location of the deepest sedimentary basins from Basin E, Basin C to the North Minch (Fig. 4-16) are closely associated with the proposed easterly extent of Precambrian basement rocks on the shelf (Section 5-1). It is suggested that post-Caledonian basin formation was most significant in regions where the underlying Precambrian basement was most closely involved in the late Caledonian movements of the fold-belt.

The geophysical evidence north of Scotland can be used to outline a tentative post-Caledonian development of the shelf and slope which is consistent with adjacent land areas and the conclusions of Stride et al. (1969) from seismic reflection profiles west of Britain.

1. Mesozoic sedimentation in narrow, fault bounded basins on the outer shelf and perhaps on the slope (Section 4-7). The basement rise causing magnetic anomaly R probably formed by marginal subsidence of adjacent sedimentary troughs. The basement rise may have acted as a source area to the sediments infilling Basin E and the slope basins. The initiation of basin subsidence was probably pre-Lias as indicated by the Lower Lias limestones in the Shiant Islands and NW Scotland. The sedimentary basins were closely controlled by contemporaneous faulting along NNE-SSW trends in the basement.

2. Post-Upper Cretaceous, pre-Tertiary uplift of the shelf, accompanied by erosion and normal faulting in NW Scotland. The resulting hiatus is the "main" unconformity identified by Stride et al. (1969, Profiles 2 to 7) but has not been recognised with the seismic reflection system available north of Scotland. It is probable that a considerable amount of the south-easterly dipping sediments infilling Basin E were removed during this erosion phase.
3. Tertiary sedimentation following the extrusion of basalt lavas in the Faeroe Islands. The Tertiary was probably the main period of slope building adjacent to the Faeroe-Shetland Channel. Sedimentation probably continued in the shelf basins.
4. Post-Tertiary, pre-Quaternary uplift (?) and erosion producing the shelf unconformity observed north of Scotland (Figs. 4-7, 4-8 and 4-12). This is in agreement with the interpretation of Stride et al. (1969) of the shallow unconformity observed NW of the Pentland Firth.
5. Quaternary sedimentation on the shelf and slope and the development of the present shelf morphology. The cause of the deep inner part of the shelf (Fig. 4-11) is probably related to the large normal fault bounding the SE margin of "low" E. There is no evidence of disturbed bedding or slumping at the base of the continental slope.

The post-Caledonian stratigraphy of the shelf and slope is summarised in a schematic structure section west of the Shetlands (Fig. 4-17). The basement configuration has been obtained from the gravity interpretation (Model 1, Fig. 4-10) of Bouguer anomaly profile XX' (Fig. 4-1). The south-easterly apparent dips observed below the shelf unconformity at the SSW end of Basin E are shown with seaward dipping

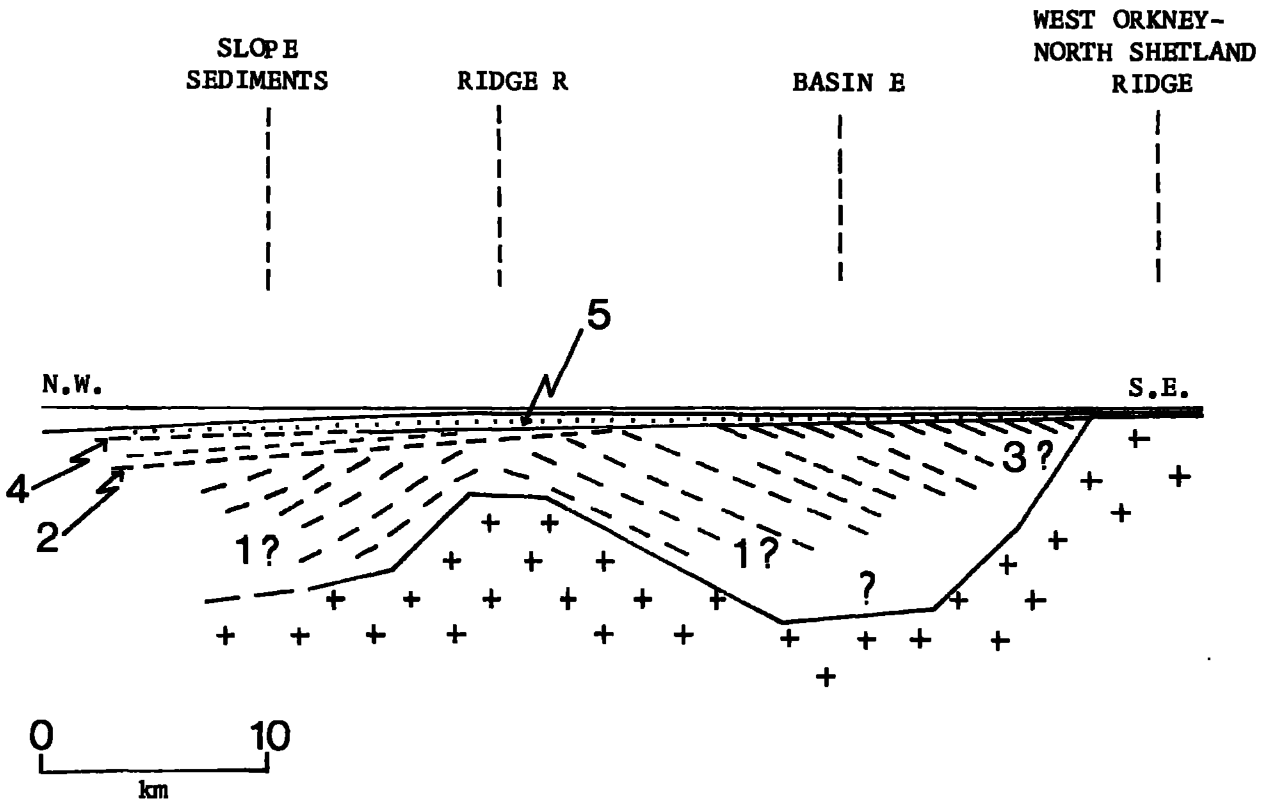


Fig. 4-17. Schematic representation of the structure and stratigraphy of the continental shelf and slope west of the Shetlands. Numbers refer to post-Caledonian history outlined on pages 64 and 65. Basement configuration after Model 1 (Fig. 4-10). Vertical scale is twice horizontal.

sediments (Quaternary ?) thickening towards the slope (Figs. 4-7, 4-8 and 4-9). The structure section is intended as a working hypothesis which is consistent with the geophysical evidence at present available west of the Shetlands. The model could be tested by improved seismic reflection and refraction profiling and by bottom sampling.

CHAPTER 5

GEOLOGICAL INTERPRETATION OF THE FAEROES TO SCOTLAND REGION AND ITS REGIONAL IMPLICATIONS

5-1. Seaward extension of the North Scottish Caledonian fold-belt.

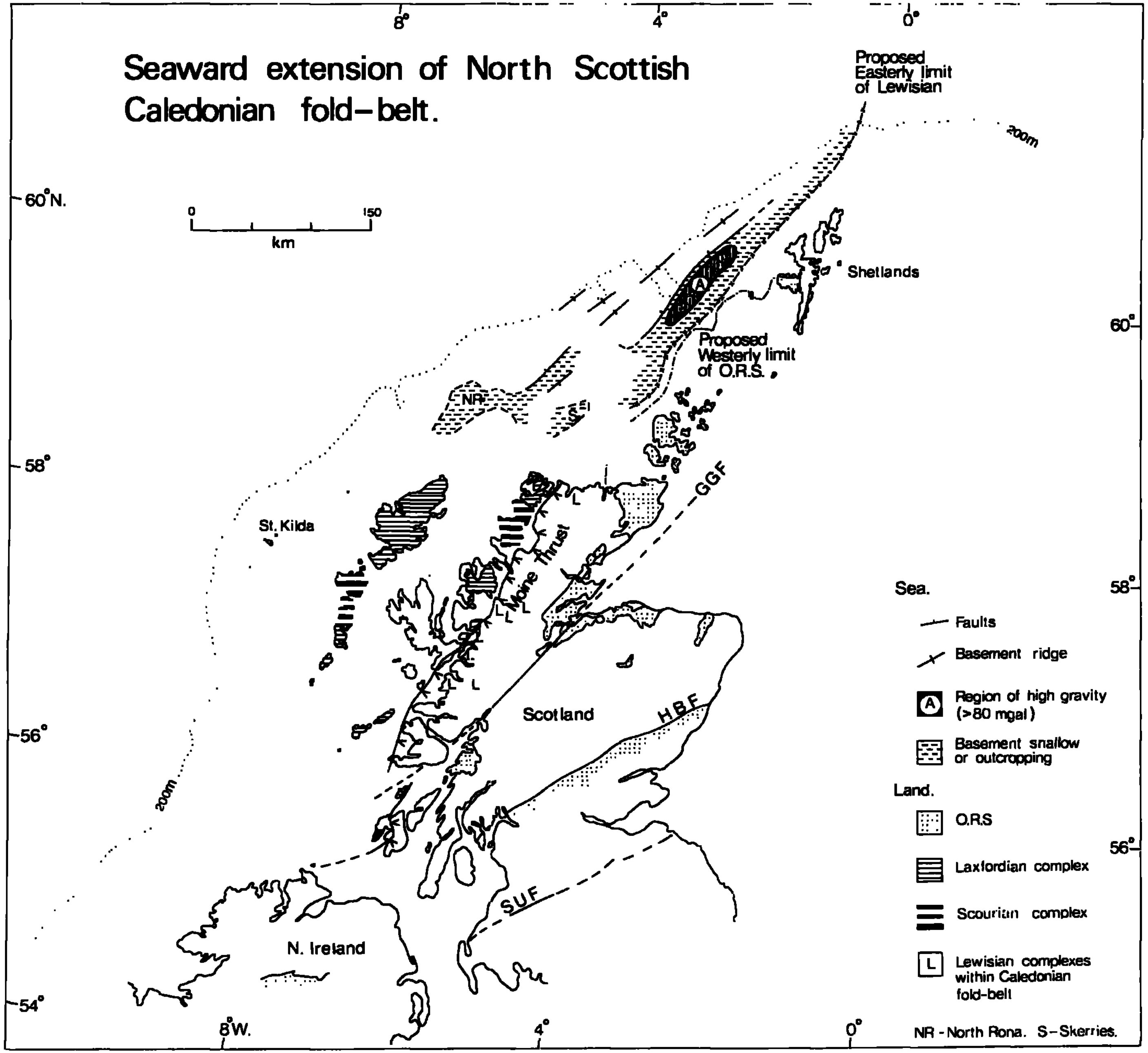
Wager and Hamilton (1964) have shown that the metamorphic basement west of the East Greenland Caledonian fold-belt (Haller and Kulp, 1962) is of comparable age to the Lewisian basement west of the Moine Thrust belt in NW Scotland. The path of the fold-belt beyond the coastlines of North Scotland and East Greenland has been estimated by Wager and Hamilton (1964) assuming the Bullard et al. (1965) distribution of pre-Atlantic Ocean basin continents. The proposed path extends across a large area of continental shelf and slope adjacent to East Greenland and North Scotland which had not previously been investigated. The geological interpretation of geophysical data from the continental shelf and slope north of Scotland can be used to test, in part, the Wager and Hamilton (1964) hypothesis.

The individual tectonic units which make up a fold-belt can be extended seawards providing they are of diagnostic physical properties. Lewisian basement rocks in NW Scotland are distinguished from its metamorphic cover by high gravity and variable magnetic anomaly patterns. Gravity surveys in NW Sutherland (Storry, 1969) show that the Scourie assemblage south of the Ben Stack Line and north of Achiltibuie is associated with a gravity anomaly of about +35 mgal. This decreases to the NNE across the Ben Stack Line and ESE towards the Moine Thrust belt. The Scourie assemblage is associated with a broad WNW-ESE trending positive magnetic anomaly reaching a peak value of +450 gamma near Scourie (IGS, 1968 Sheet 13). Bouguer anomalies between +60 and +70 mgal occur on the east coast of the Outer Hebrides in association with grey gneiss and pyroxene granulite (R. McQuillin, personal communication). The physical distinction of the Lewisian from its overlying metamorphic cover is not, however, as clear as it might be. The Torridonian cover of the Lewisian is in part substantial and areas of the Lewisian south of Achiltibuie cannot be distinguished from the Moines on the basis of magnetic anomaly pattern. Density measurements from the Lewisian suggest that a small contrast should occur between the Laxford assemblage and normal metamorphic rocks of Moine or Dalradian type (Tuson, 1959; Storry, 1969).

Gravity "high" A (Fig. 4-1) has been interpreted as caused by dense basement rocks of Lewisian type, similar in properties to the Scourie assemblage of NW Scotland (Fig. 4-6). Density measurements in NW Scotland show that a contrast of at least $+0{\cdot}15$ g/cm^3 is indicated between the Scourie assemblage and normal density metamorphic rocks (Storry, 1969). The decrease in gravity from the Lewisian of the shelf foreland region to the proposed extension of metamorphic rocks of the fold-belt is probably less than expected because the Lewisian basement dips gently ESE beneath the metamorphic rocks. This is indicated in NW Scotland by the extension of the magnetic anomaly pattern associated with the Scourie and Laxford assemblages ESE of the Moine Thrust for up to 15 km (IGS, 1968 Sheet 13) and the involvement of basement in tectonic events within the fold-belt (Watson, 1967). The easterly limit of gravity "high" A north of Scotland can then be used, with magnetic and echo-sounder evidence, to predict the easterly extent of high density basement rocks on the shelf (Fig. 5-1). North of the Shetlands and NW of the Orkneys where gravity "high" A is reduced in amplitude the extent of the dense basement rocks cannot be predicted with the same confidence. A further complication occurs NW of the Shetlands. It is not clear to what extent the proposed mass

Fig. 5-1. Seaward extension of the North Scottish Caledonian fold-belt. The proposed westerly limit of Old Red Sandstone sediments has been estimated from the gravity and magnetic "lows" which extend from outcrops in Foula, Walls Peninsula, Fair Isle and the Orkneys. Land geology after Dunning and Stubblefield (1966). GGF = Great Glen Fault, ORS = Old Red Sandstone, HBF = Highland Boundary Fault and SUP = Southern Uplands Fault.

Seaward extension of North Scottish Caledonian fold-belt.



deficiency beneath the Shetlands (Section 4-6) and the dense basement rocks causing "high" A contribute to the steep gravity gradients NW of Esha Ness, Shetland. Miller and Flinn (1966) have suggested that the gneisses of Northmaven may be related to the basement of the Caledonian fold-belt. The gneisses also appear to be associated with an extension of the complex magnetic anomaly pattern of gravity "high" A. If this is so, a slightly different course of the Lewisian would be indicated NW of the Shetlands. The shelf foreland region extends west of the proposed easterly limit of Lewisian basement (Fig. 5-1). In this region, Lewisian basement either outcrops on the sea floor (or above sea-level) or is obscured by younger sediments. The depth to the basement increases towards the continental slope where NNE-SSW trending basement ridges are buried by 1·5 - 2·5 km of sediments (Fig. 4-14). The proposed extension of the North Scotland Caledonian fold-belt (Fig. 5-1) is therefore in general agreement with the hypothesis of Wager and Hamilton (1964). It is clear that the continental shelf and the upper part of the slope north of Scotland is associated with an extension of the main structural units of the Caledonian fold-belt in northern Scotland.

The observation that the seaward extension of the Caledonian fold-belt is obscured at the continental slope by a thick sequence of recent sediments is in agreement with the seaward extension of fold-belts elsewhere (e.g. Canadian Appalachians, Fenwick et al., 1968). The evidence north of Scotland cannot be used, however, to determine whether the fold-belt is truncated at the continental slope or continues beyond it to underlie the Faeroe-Shetland Channel. It is clear that the pre-Mesozoic rocks of the fold-belt terminate in an area between the continental shelf break in slope west of the Shetlands and the oceanic magnetic lineations of the south part of the Norwegian Basin.

Seismic investigations of the continental margin east of Florida show that the continental shelf break in slope is underlain by a buried crystalline basement ridge (Sheridan et al., 1966). Further observations suggest that a basement ridge underlies at least part of the shelf break in slope SE of Nova Scotia (Berger et al., 1965). The ridges separate a sedimentary trough on the outer part of the shelf from a trough underlying the continental rise. The trend of the ridges on the eastern seaboard of North America suggest they are related to the adjacent Appalachian fold-belt. Other examples of buried ridges at the shelf break in slope have been described by Burk (1967). West of the Shetlands a NNE-SSW trending basement ridge related to the Precambrian of the shelf foreland region occurs near the shelf break in slope. The basement ridge separates a sedimentary trough beneath the continental slope (Fig. 4-15) from Basin E (Fig. 4-10). It is most likely that the ridge west of the Shetlands has been produced by post-Palaeozoic subsidence of adjacent sedimentary troughs in accord with the probable origin of the basement rise separating Basins C and D (Fig. 4-16).

5-2. Implications on the origin of the Faeroe Islands and the Faeroe-Shetland Channel.

The Tertiary basalt lavas of the Faeroe Islands outcrop on the NE part of the Faeroe Rise which includes Rockall Plateau to the SW (Fig. 1-1). Recent seismic refraction experiments (Whitmarsh, 1970; Scrutton et al., 1970) estimate a crustal thickness of about 30 km beneath Rockall Bank. The thickness of crust confirms earlier suggestions (Bullard et al., 1965; Vine, 1966; Moorbath and Welke, 1969) that the Rockall Plateau is continental. A steep increase in the observed Bouguer anomaly NW of the Faeroe Islands has been outlined by Stacey (1968).

This has been interpreted as caused by a transition from "Iceland type" crust on the Iceland-Faeroes Rise to lower density "continental type" crust beneath the Faeroe Islands (Bott and Watts, 1970c). Gravity considerations between the Faeroes and Scotland suggest that the Faeroe-Shetland Channel is approximately in isostatic equilibrium and that the crust is probably as thick beneath the Faeroe Islands as it is beneath the Hebridean-Shetland continental shelf (Fig. 3-5). This suggests, therefore, that the entire Faeroe Rise probably represents a continental fragment.

The basalt lavas on the Faeroes were probably extruded on a continental basement similar to the structural environment of the Tertiary plateau basalts in NW Britain. Chemical analysis of the Faeroes lavas suggest they are more similar to East Iceland and Greenland than to dredged lavas from the mid-ocean ridge systems (Noe-Nygaard, 1966). The early extrusives are Quartz tholeiites followed by a mixed lava sequence and then Olivine tholeiites. Noe-Nygaard (1968) suggests on the basis of experimental work by Green and Ringwood (1967) that the magma source of the Quartz tholeiites must have been concentrated at depths shallower than 15 km. The later extrusives were probably segregated at greater depths. The required temporary rise of a thermal front during the extrusion of the Quartz tholeiites followed by its gradual subsidence suggested to Noe-Nygaard (1968) that the lavas were produced at an old ridge system. The presence of a thick continental crust beneath the Faeroe Islands would discount this hypothesis. The localised rise in the thermal front during the early Tertiary could have occurred within continental crust.

The geophysical and geological evidence suggest two possible origins for the basement beneath the Faeroe-Shetland Channel. The basement could be either oceanic crust or subsided continental crust.

(1) Oceanic crust: the suggestion that the Faeroe-Shetland Channel is underlain by oceanic crust is an extension of the hypothesis of Bullard et al. (1965) and Vine (1966) that the Rockall Trough formed by a lateral displacement of Rockall Plateau from the continental shelf west of the Outer Hebrides. Oceanic magnetic lineations have been outlined west of Rockall Plateau which are broadly parallel to the crest of the Rekyjanes Ridge (Godby et al., 1968). Anomaly number 24 has been identified by Avery et al. (1969) near the 2000 meter depth contour adjacent to the NW margin of Rockall Plateau which has been dated on the Heitzler et al. (1968) time scale as 60 m.y. If the displacement of Rockall Plateau occurred during the early Tertiary the magnetic pattern would be expected to narrow towards the SE between the Rekyjanes Ridge and Rockall Plateau (Stacey, 1968). The evidence available suggests that this is not observed. Displacement of Rockall Plateau would therefore have occurred in pre-Tertiary times before sea-floor spreading at the Rekyjanes Ridge. Rockall Trough is a magnetic "quiet" zone (Roberts, 1970a). No seismic refraction experiments have reached the Moho beneath Rockall Trough but at station E10 (Ewing and Ewing, 1959) about 8 km of sediments are present. If the Rockall Trough is underlain by oceanic crust the presence of a magnetic "quiet" zone suggests that <u>either</u> the Trough formed during a period of normal sea-floor spreading when there were no mixed magnetic polarities of the geomagnetic field <u>or</u> the magnetic oceanic crust is obscured by thick sediments. As Roberts (1970b) has indicated the magnetic field is also "quiet" at station E12 (Ewing and Ewing, 1959) where only 2 km of sediments are present. This might tentatively suggest that deep burial of the magnetic oceanic crust is not a significant factor.

The appeal of the hypothesis that Rockall Trough formed by lateral displacement of Rockall Plateau suggests a similar origin for the

Faeroe-Shetland Channel (Roberts, 1970a). Palaeomagnetic (Abrahamsen, 1967) and magnetic anomaly pattern evidence (Vogt et al., 1970) suggest that any displacement of the Faeroes shelf from north of Scotland must have occurred in pre-Tertiary times, like the proposed displacement of Rockall Plateau. Unlike the Rockall Trough, however, the Faeroe-Shetland Channel is not a magnetic "quiet" zone (Avery et al., 1968; Fig. 3-3). The Channel is associated with NNE-SSW trending magnetic "highs" and "lows" of up to 400 gamma amplitude.

(2) Subsided continental crust: the suggestion that the Faeroe-Shetland Channel is underlain by a thin continental crust extends from the geophysical evidence that the entire Faeroe Rise is probably continental. According to this hypothesis the basement underlying the Channel is probably an extension of the Precambrian basement occuring on the continental shelf north of Scotland.

The geophysical evidence available cannot clearly distinguish between the two hypotheses. It appears most likely that the Rockall Trough formed by a pre-Tertiary rotation of Rockall Plateau. This adequately explains the thin crust beneath the Trough predicted by the Airy-Heiskanen isostatic hypothesis and the geometrical relation between the SW margin of Rockall Plateau and the continental margin west of the Outer Hebrides. Lateral displacement of Rockall Plateau most probably occurred by the addition of oceanic crust at a Triassic or earlier ridge crest during a period of uniform polarity of the geomagnetic field (Bott and Watts, 1970c). The extent of any lateral displacement of the Faeroes shelf from the shelf north of Scotland cannot be clearly established. The underlying basement in the Faeroes to Scotland region has been obscured by Mesozoic-Tertiary sedimentation and Lower Tertiary extrusion of lava. The similarity of the sedimentary structure of bordering slopes suggest that the Faeroe-Shetland Channel has been a sedimentary trough since at least early Tertiary times. If the magnetic pattern observed over the central part of the Channel is significantly caused by relief of a magnetic basement it would suggest that normal faulting and subsidence have been more important processes in the pre-Tertiary history of the Channel than lateral displacement.

5-3. Reassembly of Greenland, Scotland and the Faeroe Rise into a pre-drift position.

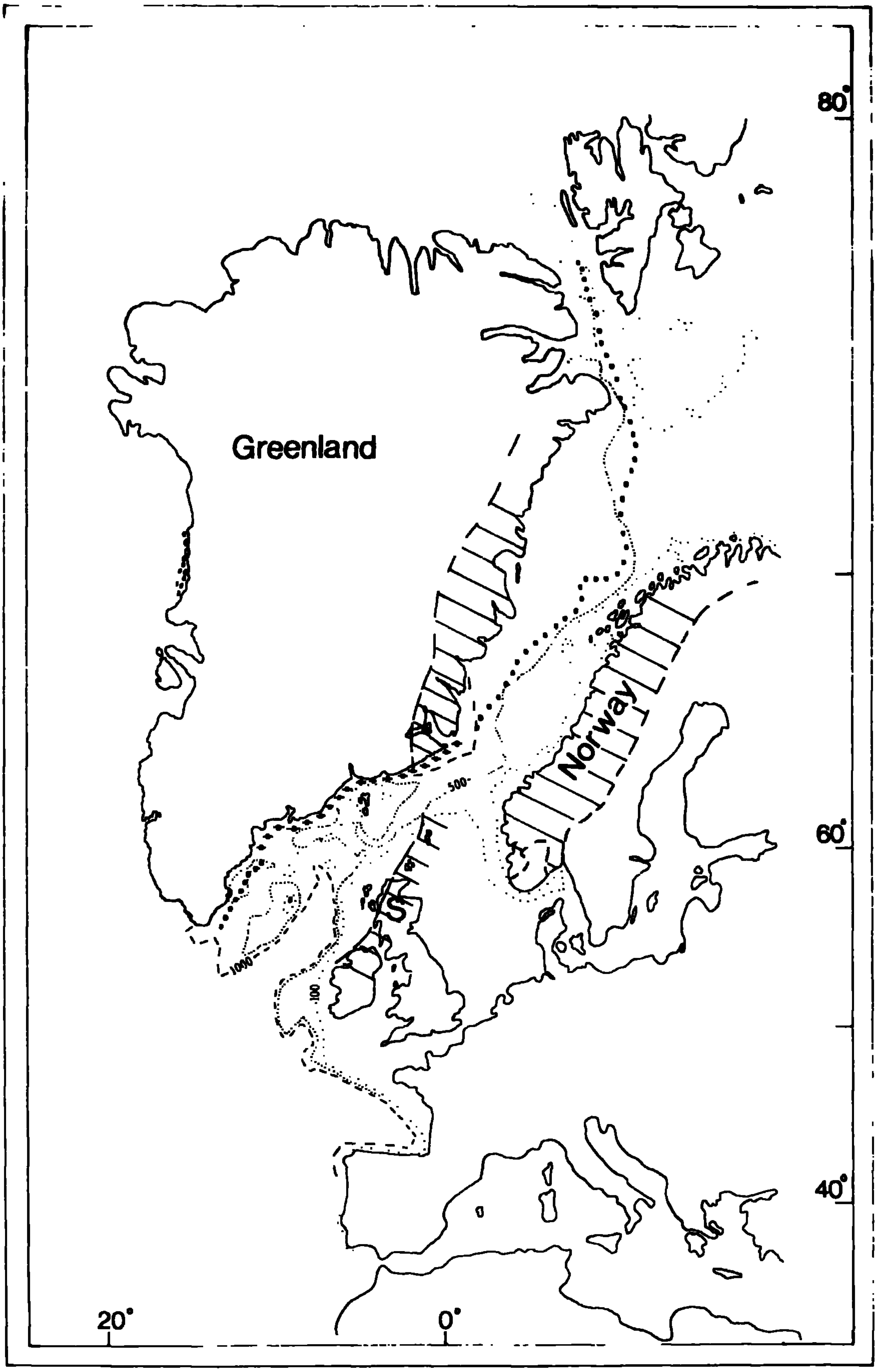
The distribution of pre-Atlantic Ocean basin continents has been proposed by Bullard et al. (1965) based on a least squares criterion of fit between the 900 meter depth contour on adjacent coastlines of the Atlantic Ocean. The fit of Greenland to Europe was obtained for a pole of rotation of 73•0°N and 96•5°E and an angle of rotation of 22°. The amount of "misfit" of the coastlines was indicated as regions of overlaps or gaps. Optimisation techniques have been applied to the fit of Greenland to Europe (M. Al-Chalabi, personal communication). By mapping the objective function, M. Al-Chalabi (personal communication) has shown that a wide range of possible solutions for the pole of rotation can occur. For the fit of Greenland to Europe an optimum pole of 60•0°N and 113 0°E can vary by up to ±20° of latitude and ±7° of longitude and still give equally good solutions. The fit proposed by Bullard et al. (1965) must therefore be regarded with caution since the pole of rotation is located among a wide range of possible solutions. This could result in a significantly different distribution of overlaps and gaps.

Geological considerations suggest difficulties with the proposed fit of Bullard et al. (1965). The proposed fit of Greenland to Europe shows a large overlap between the SE Greenland shelf and the shelf north of Scotland. The amount of overlap increases if the continental margin passes NW of the Faeroe Islands (Bott and Watts, 1970c; Section 5-2). The Bullard et al. (1965) fit only include the Rockall, Hatton and

George Bligh Banks and no account was made for the intervening sea areas on Rockall Plateau. The geophysical evidence suggests that the entire Faeroe Rise is continental and account should be taken of it in continental reconstructions. In an attempt to improve on the Bullard et al. (1965) fit a distribution of pre-Atlantic Ocean basin continents has been obtained which is in agreement with the recent geological and geophysical evidence (Fig. 5-2). A satisfactory fit was obtained for a pole of rotation at 58°N and 117°E (M.H.P. Bott, personal communication). The improved fit allows for:

1. Continental crust to underlie the Faeroe Rise including the Rockall Bank, Hatton Bank, George Bligh Bank and Faeroe Bank in their present positions on the Rise.
2. Continental crust to underlie the Faeroe-Shetland Channel. The fit is also consistent with oceanic crust underlying the Channel if the displacement of the Faeroes shelf from the continental shelf north of Scotland occurred in pre-Tertiary times.
3. The continental margin to pass NW of the Faeroe Islands.
4. Continuity between the proposed seaward extension of the North Scottish Caledonian fold-belt (Fig. 5-1) and the East Greenland fold-belt assuming it to extend across the narrow part of the Greenland shelf south of Scorsby Sound.
5. A pre-Tertiary displacement of the Rockall Plateau from the continental shelf west of the Outer Hebrides.

The interpretation of magnetic anomaly patterns associated with the North Atlantic Ocean (Heirtzler et al., 1966; Avery et al., 1969; Vogt et al., 1970) suggest that the Bullard et al. (1965) fit and the proposed fit (Fig. 5-2) refer to the pre-Tertiary distribution of Greenland and Europe. The land areas adjacent to the future lines of splitting are closely associated with rocks of the Caledonian fold-belt and its



Key

Greenland coast	Europe coast
✦✦✦✦ 100 fathom	······ 100 fathom
•••• 500 fathom	········ 500 fathom
	– – – 1000 fathom

Fig. 5-2. Reassembly of Greenland, the Faerøe Rise and Norway into a pre-drift position by rotating Greenland 14° about a pole of rotation at 58°N and 117°E. The Caledonian fold-belt in East Greenland (Berthelsen and Noe-Nygaard, 1965), Norway and NW Scotland (Rutten, 1969) is shown by diagonal shading.

marginal Precambrian basement. The similarity in the time of the final uplift and plutonism that terminated the Caledonian movements in Spitsbergen, East Greenland, Norway and NW Scotland suggest they formed part of a continuous stabilised fold-belt (Sutton, 1968). There is a relation between the location and structural trend of the fold-belt in East Greenland and Norway and the future Tertiary continental displacement. There is also a good correlation in trend between the eastern North America continental margin and the Appalachian and West Africa fold-belts, stabilised in the Carboniferous and Permian. Sutton (1968) suggests that the location of continental displacement preferentially follows the paths of stabilised fold-belts first established in the late Precambrian. The East Greenland and Norway Caledonian fold-belts were probably displaced during the Tertiary by the addition of oceanic crust at the Mohns Ridge, the Iceland Jan-Mayen Ridge and an extinct ridge underlying the Norwegian Basin (Vogt et al., 1970). The line of the displacement between SW Greenland and the Faeroe Rise appears to cut across the trend of the fold-belt into the marginal Precambrian basement. The displacement most probably occurred within Precambrian basement rocks between Scorsby Sound and west of Rockall Plateau by the addition of oceanic crust at the Rekyjanes Ridge and part of the Iceland Jan-Mayen Ridge. The future development of Iceland and the Iceland-Faeroes Rise occurred between regions of Precambrian basement rocks. SW of Rockall Plateau, the displacement followed the trend of the Appalachian and West Africa fold-belts.

The re-direction of the displacement from the Caledonian fold-belt into its marginal Precambrian basement between Scorsby Sound and Rockall Plateau may be significant in establishing the cause of Mesozoic basin formation in the Faeroes to Scotland region. Deep Mesozoic sedimentary basins occur within the pre-Mesozoic stabilised fold-belts of East Greenland, Spitsbergen, north-west Africa and the Atlantic coasts of

North America and southern Africa. Two origins of the development of the basins have recently been proposed:

1. The formation of Mesozoic basins is related to fold-belts stabilised in the Upper Palaeozoic as is evidenced by their general absence on Precambrian foreland rocks (Sutton, 1968).
2. Basin formation is related to the continental splitting and the development of the new continental margin (Bott and Watts, 1970c). The location of deep basins within the fold-belts is therefore due to their close proximity to developing ocean basins.

The isolation of these hypotheses is difficult because of the general association of Mesozoic basins with the stabilised fold-belts and the new ocean basins. In East Greenland, for example, N-S trending Mesozoic basins are underlain by the Caledonian fold-belt adjacent to the western continental margin of the Greenland sea. The initiation of the subsidence appears to have been in the Carboniferous but was particularly significant in the Lower Tertiary (Vischer, 1943) at the time of oceanic crust addition at the Mohns Ridge crest (Vogt et al., 1970). The discovery of deep Mesozoic-Tertiary sedimentary basins on Precambrian basement rocks north of Scotland, and perhaps on the Faeroe Rise, may therefore be significant. The subsidence causing the deep shelf basins may be more related to continental splitting and the development of the East Atlantic continental margin than to the adjacent Caledonian fold-belt. This would be clarified when the stratigraphy of the sediments infilling the deep basins on the Precambrian basement rocks north of Scotland and the Faeroe Rise (?) is more accurately known.

APPENDIX A

MARINE GRAVITY REDUCTION PROGRAMME

The purpose of the marine gravity reduction programme (MGRED) is to compute free air gravity anomalies at sea from the analogue records of a sea gravimeter. The programme was written in PL/1 for use on the N.U.M.A.C. I.B.M. 360/67. The programme incorporates a "smoothing" technique to compute the Eötvös correction, described in Section 2-2-3. The input and output specifications of the programme are followed by a "flow-diagram" and a "print-out".

A-1. Data format specifications.

The data input to MGRED consists of gravity header cards followed by a set of navigation and gravity cards.

(a) Gravity header cards.

LEG = identification of the cruise "leg".
G1 = gravity at first base station (mgal).
P1 = Enograph reading (chart divisions, 0-999).
Z1 = Enograph pen zero (Left, Centre or Right).
S1 = upper spring value (mgal).
D1 = day number.
H1 = hour
T1 = minutes.

The specifications of G1 to T1 are then repeated for the second base station.

SC = upper spring calibration (mgal/turn).
PC = Enograph calibration (mgal/division).
ND = approximate number of navigation cards.
NC = approximate number of courses.
EXS = heading tolerance specification for course changes (degrees).
RHO = density of topography (g/cm^3).

LL = 1 for printed results only

= 2 for printed results and punched card output.

CRU = cruise identification number for punched cards (0-99).

LEG is a character string of maximum length 50. The specifications G1 to CRU are each preceded by a blank. Z1 is a character string of length 1.

(b) Trigger card.

Columns 1-79 : blank

Column 80 : semi-colon

(c) Navigation cards.

The navigation cards are obtained as punched card output from a programme, DETOG, which converts Deccometer readings to geographical coordinates. Each card has the following format:

Column 1 : blank

Columns 2-4 : DAY

Column 5 : blank

Columns 6-8 : day number

Columns 9-12 : blank

Columns 13-14 : hour

Columns 15-16 : minutes

Columns 17-26 : latitude of station to a thousandth of a degree. The decimal point is in column 23.

Column 27 : N if latitude in northern hemisphere.

Columns 28-37 : longitude of station to a thousandth of a degree. The decimal point is in column 34.

Column 38 : E if east of Greenwich.

Columns 39-80 : blank

(d) Trigger card.

Columns 1-80 : blank

(e) Gravity cards.

The gravity cards include the position of the pen on the Enograph recorder and bathymetry in corrected meters. Each card has the following format:

Columns 1-3 : DAY*
Column 4 : blank
Columns 5-7 : day number*
Columns 8-15 : blank
Columns 16-17 : hour
Columns 18-19 : minutes
Columns 20-23 : Enograph reading in chart divisions (0-999)
Column 24 : position of pen zero on Enograph* (Left, Centre or Right)
Columns 25-38 : blank
Columns 39-40 : upper spring value*
Columns 41-51 : blank
Columns 52-55 : depth in corrected meters. Unit position in column 55.*
Columns 56-61 : blank
Columns 62-66 : ship's log in nautical miles*
Columns 67-80 : blank

The asterisks indicate if the data specifications are optional or, only need to be included if there has been a change from the previous value. The DAY (columns 1-3) and upper spring value (columns 39-40) are required for example, on the first gravity card and on subsequent cards only if they change.

The punched card output from MGRED is used in gravity display programmes written for the I.B.M. 1130 and for the reduction of magnetic and seismic reflection data. The format follows descriptions by Talwani (1966a).

Columns 1-3 : day number

Columns 4-5 : hour

Columns 6-7 : minutes

Columns 8-14 : latitude of station to a thousandth of a degree. Decimal point in column 11.

Column 15 : blank

Columns 16-22 : longitude of station. Negative if west of Greenwich. Decimal point in column 19.

Columns 23-30 : National Grid co-ordinates to nearest meter. Northings with unit position in column 30.

Columns 31-38 : Eastings with unit position in column 38.

Columns 39-46 : accumulating distance to one tenth of a km. Decimal point in column 45.

Column 47-51 : depth of water in corrected meters. Unit position in column 51.

Column 52 : blank

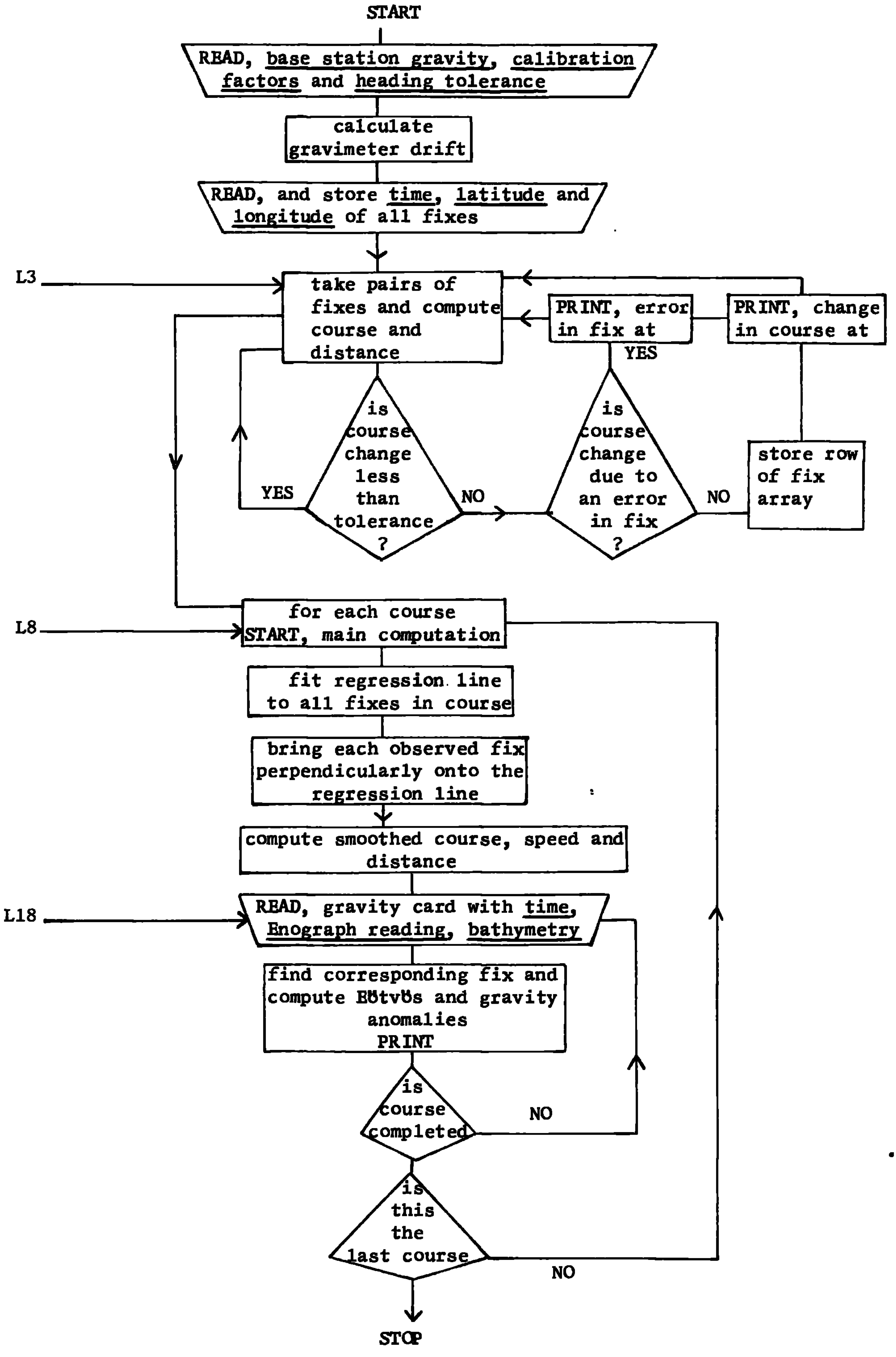
Columns 53-60 : gravity at station to one tenth of a mgal. Decimal point in column 59.

Columns 61-66 : free air anomaly to one tenth of a mgal. Decimal point in column 65.

Columns 67-72 : simple Bouguer anomaly to one tenth of a mgal. Decimal point in column 71.

Columns 73-74 : cruise identification number (0-99).

A-2. Flow diagram of MGRED.



APPENDIX A-3. PROGRAMME PRINT OUT.

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MGRED1: PROC OPTIONS(MAIN)  /*MARINE GRAVITY REDUCTION PROGRAMME */

      /********************************************************/
      /*    MARINE GRAVITY REDUCTION PROGRAMME.   I.B.M.360/67 */
      /*    PROGRAMME CALCULATES FREE AIR AND BOUGUER GRAVITY   */
      /*    ANOMALIES AT SEA. DATA INPUT INCLUDES ONE SET OF    */
      /*    TIME,LATITUDE AND LONGITUDE CARDS AND ONE SET OF    */
      /*    TIME,ENOGRAPH READING,ZERO POSITION,BATHYMETRY AND  */
      /*    DISTANCE LOGGED CARDS. BATHYMETRY AND DISTANCE ARE  */
      /*    OPTIONAL. OUTPUT IS CARD PUNCHED (OPTIONAL) FOR     */
      /*    INPUT TO I.B.M.1130 PLOTTING PROGRAMMES.            */
      /********************************************************/
      DCL (Z0,Z1,Z2) CHAR(1), LEG CHAR(50)
      DCL DAY CHAR(7), ABY CHAR(61), ANAA CHAR(43)
      DCL (EPS,AV,AVV,AVVV,PX,PXX,PXXX,CAAA,A6A,DR,
      EA,LATSF,LONGSF,GRN,GRE,CAA,A7A,YBAR2) DEC (15)
      DCL GRID ENTRY (DEC(15),DEC(15),DEC(15),DEC(15))
      DCL DE MERC ENTRY (DEC (15),DEC (15)) RETURNS (DEC (15))
      DCL MERC ENTRY (DEC (15)) RETURNS (DEC (15))
      DCL DISD ENTRY(,,,FLOAT DEC),PEN ENTRY(,FLOAT DEC),
      GETS ENTRY(,FLOAT DEC),STAN ENTRY(,,FLOAT DEC)
      DCL SCALE ENTRY (DEC(15)) RETURNS (DEC(15)),
      DTOT ENTRY(,,,FLOAT DEC)
      SPMA=12.0    SPMI=3.0
      /********************************************************/
      /*            READ GRAVITY HEADER CARDS                  */
      /*                                                       */
      /*    G1 = GRAVITY AT FIRST BASE STATION (MGALS)         */
      /*    P1 = ENOGRAPH READING (CHART DIVISIONS 0-999)      */
      /*    Z1 = ENOGRAPH PEN ZERO                             */
      /*    S1 = UPPER SPRING READING (MGALS)                  */
      /*    D1 = DAY NUMBER                                    */
      /*    H1 = HOUR                                          */
      /*    T1 = MINUTES                                       */
      /*                                                       */
      /*    REPEAT INFORMATION FOR SECOND BASE STATION         */
      /*                                                       */
      /*    SC = UPPER SPRING CALIBRATION (MGALS/SPRING)       */
      /*    PC = ENOGRAPH CHART CALIBRATION (MGALS/DIVISION)   */
      /*    ND = APPROXIMATE NUMBER OF NAVIGATIONAL FIXES      */
      /*    NC = APPROXIMATE NUMBER OF COURSE CHANGES          */
      /*    EXS = TOLERANCE FOR COURSE CHANGES (DEG.)          */
      /*    RHO = DENSITY OF TOPOGRAPHY (G/CC)                 */
      /*    LL =1 FOR PRINTED RESULTS ONLY                     */
      /*    LL =2 FOR PRINTED RESULTS AND PUNCHED CARDS        */
      /*    CRU= CRUISE IDENTIFICATION NUMBER (0-99)           */
      /*                                                       */
      /********************************************************/
      GET LIST (LEG)
      GET LIST (G1,P1,Z1,S1,D1,H1,T1,G2,P2,Z2,S2,D2,H2,T2)
      GET LIST (SC,PC,ND,NC,EXS,RHO,LL,CRU)
      GET DATA
      /********************************************************/
      RT=1000  CEN=500  RHO=RHO-1.03   PUT PAGE LIST(LEG)
      /********************************************************/
      /*    CALCULATION OF METER DRIFT RATE                    */
      /********************************************************/
```

```
   S0  =S1 + (PC*PEN(Z1,P1) -G1)/SC
   GS =(S1 -S0)*SC
   GR2 =G1 + (S2 -S1)*SC + (PEN(Z2,P2) - PEN(Z1,P1))*PC
   T1=D1+H1/24+T1/1440      T2=D2+H2/24+T2/1440
   DR =(GR2 - G2)/(T2-T1)
   B1=PEN(Z1,P1)
   PUT EDIT ('GRAVITY AT BASE STATION 1 =',G1,'MGALS')
   (SKIP(3),A,F(10,1),A)
   PUT EDIT ('GRAVITY AT BASE STATION 2 =',G2,'MGALS')
   (SKIP(1),A,F(10,1),A)
   PUT EDIT ('DRIFT RATE =',DR,'MGALS/DAY')
   (SKIP(3),A,F(6,3),A)
   /************************************************************/
   /*                  READ NAVIGATION CARDS                   */
   /*                                                          */
   /*    DETERMINATION OF COURSE CHANGES AND ERROR FIXES       */
   /************************************************************/
L0:BEGIN
   DCL SFIX (ND,5),FIX (ND,3)
   DCL (BC,BCO) (NC)
   DCL (CD3,EOTCON) (ND)
   DO JQ=1 TO ND
   GET EDIT (DAY) (A(4))   CALL GETS(TD1,4)
   IF TD1=0 THEN GOTO L1     DT=TD1
L1:GET EDIT (TH1,TM1) (F(6,0),F(2,0))
   GET EDIT (FIX(JQ,2)) (F(10,3))   GET EDIT (ZO) (A(1))
   IF ZO='S' THEN FIX(JQ,2)=-FIX(JQ,2)
   GET EDIT (FIX(JQ,3)) (F(10,3))   GET EDIT (ZO) (A(1))
   IF ZO='E' THEN FIX(JQ,3)=-FIX(JQ,3)
   GET EDIT (ANAA) (A(42))
   IF ZO=' ' THEN GOTO L2
   FIX(JQ,1)=DT+TH1/24+TM1/1440
   END
L2:ND=JQ-1
   PUT EDIT ('TOTAL NUMBER OF FIXES IN CRUISE NO.',CRU,'=',ND)
   (SKIP(3),A,F(2),A,F(4))
   PUT EDIT ('COURSE DETAILS ********') (SKIP(5),A,SKIP(2))
   PUT EDIT ('COURSE CHANGES','ERROR FIXES') (A,X(25),A)
   LL11=0  N100=0  EK=1  EPS=0.01  FAC=1.853  TTOL=2.0
   N=0  J=1  KK=1  KJ=1  NM=0
   CT=FIX(J,1)   CA=FIX(J,2)   CO=FIX(J,3)
L3:IF (J+1)=ND THEN GOTO L7
   CTT=FIX((J+1),1)   CAA=FIX((J+1),2)   COO=FIX((J+1),3)
   IF J>1 THEN GOTO L4  Y1=CAA-CA  X1=(CO-COO)*SCALE(CAA)
   CD1=ATAND(X1,Y1)  CD3(J)=STAN(X1,Y1,CD1)
   S6=DISD(X1,Y1,CTT,CT)
   EOTCON(J)=7.487*S6*SIND(CD3(J))*COSD(CAA)
L4:CTTT=FIX((J+2),1)  CAAA=FIX((J+2),2)  COOO=FIX((J+2),3)
   Y2=CAAA-CAA  X2=(COO-COOO)*SCALE(CAA)
   CTTTT=FIX((J+3),1)        CAAAA=FIX((J+3),2)
   COOOO=FIX((J+3),3)  Y3=CAAAA-CAAA
   X3=(COOO-COOOO)*SCALE(CAAA)
   IF (X2=0) | (Y2=0) THEN GOTO L7
   CD2=ATAND(X2,Y2)
   CD3(J+1)=STAN(X2,Y2,CD2)
   S6=DISD(X2,Y2,CTTT,CTT)
   EOTCON(J+1)=7.487*S6*SIND(CD3(J+1))*COSD(CAA)
   YY1A=360-EXS/2               YY2A=EXS/2
   IF (CD3(J+1)>=YY1A) & (CD3(J)<=YY2A) THEN DO
   TOL=EXS-1          GOTO L5     END
   IF (CD3(J)>=YY1A) & (CD3(J+1)<=YY2A) THEN DO
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   TOL=EXS-1    GOTO L5   END
   IF CD3(J+1) =CD3(J) THEN DO
   TOL = (CD3(J+1) - CD3(J))  END
   ELSE DO
   TOL = (CD3(J) - CD3(J+1))  END
L5:IF TOL<EXS THEN J=J+1
   ELSE DO  J=J+1
   S2=DISD(Y2,X2,CTTT,CTT)
   S3=DISD(Y3,X3,CTTTT,CTTT)
   IF KK>1 THEN IF (J=BC(KK-1)+1) | (J=BC(KK-1)+2) THEN GOTO L6
   IF (S2>SPMA) | (S3>SPMA) | (S2<SPMI) | (S3<SPMI) THEN DO
   FIX((J+1),2)=(FIX(J,2)+FIX((J+2),2))/2
   FIX((J+1),3)=(FIX(J,3)+FIX((J+2),3))/2
   Y2=FIX((J+1),2)-CAA    X2=(COO-FIX((J+1),3))*SCALE(CAA)
   S7=DISD(X2,Y2,CTTT,CTT)
   CD3(J)=CD3(J-1)
   EOTCON(J)=7.487*S7*SIND(CD3(J))*COSD(CAA)
   BCO(KJ)=J+1      KJ=KJ+1
   CALL DTOT(CTTT,AD,AM,AM)
   PUT EDIT ('ERROR IN FIX AT ',AD,AH,AM) (SKIP(1),X(48),
   A,3(F(5)))
   GOTO L6  END   CP=1
   IF KK=1 THEN DO  CP=3  END
   BC(KK) = J
   CALL DTOT(CTT,AD,AH,AM)
   PUT EDIT ('CHANGE IN COURSE AT ',AD,AH,AM)
   (SKIP(CP),A,3(F(5)))          KK=KK+1
L6:N=N+1              END     GOTO L3
   /************************************************************/
   /*               MAIN COMPUTATION LOOP                      */
   /*                                                          */
   /*    EACH COURSE IS PROCESSED SEPARATELY. A REGRESSION     */
   /*    LINE IS FITTED TO EACH COURSE. BEFORE EACH            */
   /*    PROCEEDURE THE FIXES ARE CONVERTED TO MERCATOR        */
   /*    COORDINATES. THE OBSERVED FIXES ARE THEN BROUGHT      */
   /*    PERPENDICULARILY ONTO THE REGRESSION LINE. THE        */
   /*    APPROPRIATE NUMBER OF GRAVITY CARDS ARE THEN READ     */
   /*    AND COMPUTATION RETURNED.                             */
   /*                                                          */
   /************************************************************/
L7:JJ=0  JK=0  JL=1  JM=0  JX=0  BCO=0  JS=0  YY3A=0  LLL=0  K2=0
   YY4A=KJ-1       YY5A=KK-1
   PUT EDIT ('END OF COURSE DETAILS***************************')
   (SKIP(3),A)
   PUT EDIT ('HEADING TOLERANCE =',EXS)
   (SKIP(2),A,F(5,1))
L8:DO II=1 TO KK
   NDI=0   IF YY3A=2 THEN GOTO L26
   IF (JX>=(ND-3)) THEN GOTO L26
   NCA = BC(II)
   IF II=1 THEN DO  NNCA=NCA  END
   IF II>=2 THEN DO  NNCA=NCA-JJ  END
   IF (NNCA<0) THEN DO  NCA=ND-1  NNCA=NCA-JJ  YY3A=2  END
   IF II=1 THEN DO  JL=JL+1  END
   SUY=0    SUX=0
L9:JJ=JJ+1   AV=FIX(JJ,2)
   IF AV=0 THEN GOTO L9
   PX=6.0825*FIX(JJ,3)
   SUY=SUY+MERC(AV)
   SUX=SUX+PX
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    IF JJ=NCA THEN GOTO L10
    GOTO L9
L10:XBAR=SUX/NNCA   YBAR=SUY/NNCA  XXYY=0  XX2=0   YY2=0
L11:JJ=JS+1   AVV=FIX(JJ,2)
    PXX=6.0825*FIX(JJ,3)
    IF AVV=0 THEN GOTO L11
    XXYY=XXYY+(PXX-XBAR)*(MERC(AVV)-YBAR)
    YY2=YY2+(MERC(AVV)-YBAR)**2
    XX2=XX2+(PXX-XBAR)**2
    IF JJ=NCA THEN GOTO L12
    JS=JS+1   GOTO L11
L12:AM=(YY2-EK*XX2)/(2*XXYY)
    A3=AM+SQRT(AM*AM+EK)
    A33=AM-SQRT(AM*AM+EK)                  A333=A3+A33
    IF (A333>0) THEN DO  A=A3  END
    IF (A333<=0) THEN DO  A=A33  END
L13:JJ=JK+1
    AVVV=FIX(JJ,2)
    IF AVVV=0 THEN DO  JK=JK+1  GOTO L13  END
    PXXX=6.0825*FIX(JJ,3)
    A6=(PXXX+(A*MERC(AVVV)+A*A*XBAR-A*YBAR))/(A*A+1)
    A6A=A*(A6-XBAR)+YBAR
    SFIX(JJ,1)=FIX(JJ,1)
    SFIX(JJ,2)=DE_MERC(A6A,EPS)
    A7A=SFIX(JJ,2)
    SFIX(JJ,3)=A6*SCALE(A7A)/6.0825
    IF JJ=NCA THEN GOTO L14
    JK=JK+1
    GOTO L13
    /*********************************************************/
    /*    CALCULATION OF COURSE,DISTANCE AND SPEED MADE GOOD  */
    /*    ALONG SMOOTHED TRACK.                               */
    /*********************************************************/
L14:L=LLL+1
    XS=SFIX(L,3)-SFIX(NCA,3)   YS=SFIX(NCA,2)-SFIX(L,2)
    CS = ATAND(XS,YS)
    COURSES = STAN(XS,YS,CS)
    IF II=1 THEN DO
    PUT PAGE EDIT ('    GRAVITY RESULTS***********************')
    (SKIP(1),A)
    PUT LIST (LEG)
    LLL=NCA+1   GOTO L15   END
    LLL=NCA
L15:IF II=1 THEN DO
    S1S =(SFIX(1,2)-SFIX(2,2))**2
    S2S =(SFIX(1,3)-SFIX(2,3))**2
    A=SQRT(S1S + S2S)*60
    TD=(SFIX(2,1)-SFIX(1,1))*24
    SFIX(1,4)=SX  SFIX(2,4)=A+SX  SFIX(2,5)=A/TD   SFIX(1,5)=A/TD
    END
L16:JJ=JL+1   IF JJ =NCA THEN GOTO L17
    S1SS = (SFIX((JJ+1),2)-SFIX(JJ,2))**2
    S2SS = (SFIX((JJ+1),3)-SFIX(JJ,3))**2
    B=SQRT(S1SS+S2SS)*60
    TDS=(SFIX((JJ+1),1)-SFIX(JJ,1))*24
    SFIX((JJ+1),5)=B/TDS
    SFIX((JJ+1),4) = SFIX(JJ,4) + B
    IF (SFIX((JJ+1),5) 20)   (SFIX((JJ+1),5) -20) THEN DO
    SFIX((JJ+1),5)=SFIX((JJ-1),5)   END
    IF JJ>=NCA-1 THEN GOTO L17
    JL=JL+1
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      GOTO L16
  L17:IF NDI>0 THEN JJ=JJ+NDI
      IF II>=2 THEN DO  JJ=JJ+1  END
      /**********************************************************/
      /*                READ GRAVITY CARDS                      */
      /*                                                        */
      /*    BEGIN CALCULATION OF FREE AIR AND BOUGUER ANOMALIES */
      /**********************************************************/
  L18:JX=JM+1
  L19:GET EDIT(DAY) (A(3))      CALL GETS(DT,4)
      IF DT=0 THEN GOTO L19A
      TD1=DT
      PUT EDIT (DAY,'  *****') (SKIP(2),X(4),A(7),A)
      PUT EDIT (' D  H  M','LAT.','LONG.','NORTHINGS','EASTINGS',
      'DEPTH','DISTANCE','CURRENT','EOTVOS','GRAVITY','FREEAIR',
      'BOUGUER COURSE')
      (SKIP(2),A,2(X(3),A),2(X(2),A),X(4),A,X(4),A,X(1),A,X(1),A,X(2)
      ,A,X(2),A,X(1),A)
 L19A:GET EDIT (TH1,TM1) (F(10),F(2))   STIME=TD1+TH1/24+TM1/1440
      IF STIME=SFIX(JX,1) THEN GOTO L21
  L20:STID=(STIME-SFIX(JX,1))*1440
      IF STID=0 THEN GOTO L21
      /**********************************************************/
      /*     TIME OF FIX AND GRAVITY READINGS MUST              */
      /*     CORRESPOND TO WITHIN (TTOL) MINUTES.               */
      /**********************************************************/
      IF (STID>=-TTOL) & (STID<0) THEN DO
      PUT EDIT ('GRAVITY READING BEHIND NAV.FIX BY',STID,
      ' MINUTES') (SKIP(2),A,F(3),A)
      GOTO L21  END
      IF (STID<=TTOL) & (STID>0) THEN DO
      PUT EDIT ('GRAVITY READING AHEAD OF NAV.FIX BY',STID,
      ' MINUTES') (SKIP(2),A,F(3),A)
      GOTO L21  END
      IF (STID>TTOL) THEN DO
      CALL DTOT(SFIX(JX,1),AD,AH,AM)
      PUT EDIT (AD,AH,AM,
      '  GRAVITY READING NOT AVAILABLE AT TIME OF FIX ')
      (SKIP(2),3(F(3)),X(2),A)
      IF JX>=NCA THEN DO   K2=1   GOTO L21   END
      JM=JM+1  JX=JX+1  GOTO L20  END
      IF (STID<-TTOL) THEN DO
      CALL DTOT(STIME,AD,AH,AM)
      PUT EDIT (AD,AH,AM,
      '    NAV.FIX NOT AVAILABLE AT SAME TIME AS GRAVITY READING')
      (SKIP(2),3(F(3)),A)    K2=2   GOTO L21   END
  L21:CALL GETS(GR,4)
      IF GR=0 & K2=0 THEN DO
      PUT EDIT (SFIX(JX,1),'     GRAVITY READING NOT AVAILABLE')
      (SKIP(2),X(4),F(4),A)
      GET EDIT (ANAA) (A(43))   GOTO L24   END
      GET EDIT (ZO) (A(1))
      IF ZO='R' THEN DO  IP=1  B=GR-RT  END
      IF ZO='L' THEN DO  IP=2  B=GR  END
      IF ZO='C' THEN DO  IP=3  B=GR-CEN  END
      IF ZO=' ' THEN
                IF IP=1 THEN DO  B=GR-RT  END
                IF IP=2 THEN DO  B=GR  END
                IF IP=3 THEN DO  B=GR-CEN  END
      CALL GETS(SPR,16)
      IF SPR=0 THEN GOTO L22
```

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    SPRI = SPR
L22:GS=(B-B1)*PC+G1+(SPRI-S1)*SC
    CALL GETS(BATH,15)
    CALL GETS(DIST,11)
    IF (K2>0) THEN DO  CALL GETS(AN,14)  END
    IF (K2=1) THEN DO  K2=0  GOTO L24  END
    IF (K2=2) THEN DO  K2=0  GOTO L19  END
    IF DIST=0 THEN GOTO L23
    DIST = (DIST/100 - SX)*FAC
L23:DISTAN=SFIX(JX,4)*FAC
    CURR=EOTCON(JX)
    IF (JX>2) & (JX<NCA) THEN DO
    SFIX(JX,5)=(SFIX((JX-1),5)+SFIX((JX-2),5)+SFIX((JX+1),5)
    +SFIX(JX,5))/4
    END
    EOT  = 7.487*SFIX(JX,5)*SIND(COURSES)*COSD(SFIX(JX,2))
    GRI = 978049.0*(1 + 0.0052884*(SIND(SFIX(JX,2))**2)
         -0.0000059*SIND(2*SFIX(JX,2))**2)
    FAA  = GS + EOT - GRI -DR/1440
    BCOR =0.0419*RHO*BATH
    BA   = FAA + BCOR
    LATSF=SFIX(JX,2)
    LONGSF=-SFIX(JX,3)/SCALE(LATSF)
    CALL DTOT(SFIX(JX,1),AD,AH,AM)
    CALL GRID(LATSF,LONGSF,GRN,GRE)
    PUT EDIT (AD,AH,AM,LATSF,LONGSF,GRN,GRE,BATH,DISTAN,CURR,
    EOT,GS,FAA,BA,COURSES)
    (SKIP(2),3(F(3)),X(1),2(F(7,3)),2(F(10,1)),F(8),
    F(11,1),F(9,1),F(8,2),F(10,1),F(7,2),F(8,2),F(7,1))
    IF LL=2 THEN DO
    PUT FILE (ANY) EDIT (AD,AH,AM,LATSF,LONGSF,GRN,GRE,
    DISTAN,BATH,GS,BA,FAA,CRU,EOT)
    (F(3),2(F(2)),F(7,3),X(1),F(7,3),F(8),F(8),F(8,1),F(5),F(9,1),
    2(F(6,1)),F(2),X(1),F(5,1))
    N100=N100+1
    END
    GOTO L24
L24:CALL GETS(AN,14)
    IF JX=2 THEN JX=JX+1
    IF (II=1) & (JX>=JJ) THEN GOTO L25
    IF (II>1) & (JX>=NCA) THEN GOTO L25
    JM=JM+1
    GOTO L18
L25:N=NM+1  NM=NM+1  JK=JK+1  JM=JM+1  JS=JS+1
    END L8
    END L0
    /**********************************************************/
    /*                                                        */
    /*              END OF COMPUTATION LOOP                   */
    /*                                                        */
    /**********************************************************/
L26:PUT EDIT ('    END OF CRUISE********************************')
    (SKIP(5),A)
    IF LL=2 THEN DO
    PUT EDIT ('    TOTAL NUMBER OF CARDS PUNCHED=',N100)
    (SKIP(4),A,F(7))                    END
```

```
           /**************************************************************/
           /*                                                            */
           /*          PROCEEDURES  USED  IN  MAIN  PROGRAMME            */
           /*                                                            */
           /**************************************************************/
      DISD:PROC(A,B,C,D)
           /*     CALCULATION OF SPEED (KNOTS) FROM CORRECTED LAT       */
           /*     AND LONGITUDE.                                        */
           DCL (A,B,C,D,E,F,G,H) FLOAT DEC
           E=SQRT((A**2)+(B**2))*60
           H=(C-D)*1440    ES=E*60/H   RETURN(ES)
           END DISD
           /*************************************************************/
       PEN:PROC(A,B)
           /*     DETERMINATION OF ENOGRAPH READING FROM PEN ZERO      */
           DCL A CHAR(1)   RT=1000   CEN=500
           IF A ='L' THEN RETURN (B)  ELSE
           IF A ='C' THEN RETURN (B - CEN)  ELSE
           IF A ='R' THEN RETURN (B - RT )
           END PEN
           /*************************************************************/
      DTOT:PROC(A,B,C,D)
           /*     CONVERSION OF FRACTION OF DAY TO DAY, HOUR, MINS.    */
           LA=A   B=(A-LA)*24   LH=B
           LM=(B-LH)*60+0.5   B=LA  C=LH  D=LM
           IF D=60 THEN DO  D=0  C=C+1  END
           RETURN
           END DTOT
           /*************************************************************/
   DE_MERC:PROC(Y,EPS) DEC (15)
           /*     CONVERSION OF LATITUDES TO MERCATOR COORDINATES       */
           /*     (MERC). CONVERSION OF MERCATOR COORDINATES TO         */
           /*     LATITUDES (DE_MERC).                                 */
           DCL LATM DEC (15)
           DCL PI  DEC (15) INIT (3.1415926536), PI1  DEC (15)
           DCL (DEG,LAT M,EPS,R1,R2,K,Y,THETA,D THETA) DEC (15)
    DCL MR ENTRY (DEC (15)) RETURNS (DEC (15))
           K=-3587.46775960
           PI1 = 180/PI
           THETA=  2*ATAND(EXP(Y/K))
           I=0
      ITER:D THETA=(Y-MR(THETA))*PI1/(K*COSH(Y/K))
           I=I+1
           THETA =THETA + D THETA
           IF ABS(Y - MR(THETA))   EPS      THEN
                RETURN (90  - THETA)
              ELSE  IF I 20 THEN GOTO ITER  ELSE RETURN (10**20)
      MERC:ENTRY(LATM ) DEC (15)
           LAT M=90-LATM
           RETURN (MR(LAT M))
        MR:PROC(LAT M) DEC (15)
           DCL (LAT M,Q,EC,Y,R) DEC (15)
           DCL K DEC (15)
           K=-3587.46775960   EC=0.082874   Q=EC*COSD(LAT M)
           Y=TAND(LAT_M/2)   R=Y*SQRT((1+Q)/(1-Q))   Y=K*LOG(R)
           RETURN (Y)
           END MR
           END DE MERC
           /*************************************************************/
      GETS:PROC(N,P)
           /*     INPUT SUBROUTINE FOR DATA .                           */
```

```
       DCL N FLOAT DEC
       ON CONVERSION GOTO L1
       GET EDIT (N) (F(P))
    L1:ON CONVERSION SYSTEM
       END GETS
       /*************************************************************/
 SCALE:PROC(A) DEC (15)
       /*    CONVERSION OF LATITUDE TO CORRECTED SCALE FACTOR      */
       /*    FOR USE IN TRUE HEADING DETERMINATIONS.               */
       DCL FORMP ENTRY (DEC(15)) RETURNS (DEC(15))
       DCL (A,AA,SC) DEC(15)
       AA=A-1/60   SC=FORMP(A)-FORMP(AA)   RETURN(1/SC)
 FORMP:PROC(X) DEC (15)
       DCL (THET,X,MP,X1,Y,Y1,KK) DEC(15)
       KK=7915.704456   THET=45+X/2
       X1=SIND(X)      Y=TAND(THET)       Y1=LOG10 (Y)
       MP=(KK*Y1)-23.38871*X1-0.053042*(X1**3)-0.000216523*(X1**5)
       RETURN (MP)
       END FORMP
       END SCALE
       /*************************************************************/
  GRID:PROC(SLA,SLO,OR,EA)
       /*     CONVERTS GEOGRAPHICALS TO GRID COORDINATES           */
       DCL (SEC,SO,ST,CO,TT,ZM,V,RM,UN,P1,P2,P3,P3A,P4,P5,P6,BP,OR,
       SLA,SLO,T1,T2,T3,T4,A,B,EE,EA,X,Y,L) FLOAT DEC (15)
       DCL (AMBO,S1X,C1X,S2Y,C2Y,PI,Q) DEC(15)
       B=6.35372249007714E6       EE=6.67054000012360E-3
       A=6.37502048134223E6        T1=1.00167672574868
       T2=5.02807222639481E-3
       T3=5.25815749753227E-6    T4=6.83150177464533E-9
       PI=3.1415926536   AMBO=-2.0000000   SEC=1/3600
       L=4.90E1  X=SLA-L  Y=SLA+L  Q=X*PI/180
       S1X=SIND(X)   C1X=COSD(X)   S2Y=SIND(Y)   C2Y=COSD(Y)
       ZM=B*(T1*Q-T2*S1X*C2Y+T3*2*S1X*C1X*(1-2*S2Y*C2Y)
       -T4*(3*S1X-4*S1X*S1X*S1X)*(4*C2Y*C2Y*C2Y-3*C2Y))
       SO=SIND(SLA)    ST=SIND(SEC)    CO=COSD(SLA)   TT=TAND(SLA)
       V=A/SQRT(1-EE*(SO**2))     RM=V*(1-EE)/(1-EE*SO*SO)
       UN=((V/RM)-1)    P1=ZM-100000.0
       P2=V*(ST**2)*SO*CO*(10**8)/2
       P3=V*(ST**4)*SO*(CO**3)*(5-(TT**2)+9*UN)*(10**16)/24
      P3A=V*(ST**6)*SO*(CO**5)*(61-58*(TT**2)+(TT**4))*(10**24)/720
       P4=V*ST*CO*(10**4)
       P5=V*(ST**3)*(CO**3)*((V/RM)-(TT**2))*(10**12)/6
       P5=-P5   V=V/120
       P6=V*(ST**5)*(CO**5)*(5-18*(TT**2)+(TT**4)+14*UN
       -58*(TT**2)*UN+2*(TT**4)*UN)*(10**20)   P6=-P6
       BP=(SLO-AMBO)*3600*(10**-4)
      OR=P1+P2*(BP**2)+P3*(BP**4)+P3A*(BP**6)
      EA=400000+P4*BP-P5*(BP**3)-P6*(BP**5)
       RETURN
       END GRID
       /*************************************************************/
  STAN:PROC(A,B,C)
       /*    CONVERSION OF TANGENTS OF ANGLES TO HEADING.          */
       IF A>0 & B>0 THEN RETURN (C)  ELSE
       IF A>0 & B<0 THEN RETURN (C)  ELSE
       IF A<0 & B<0 THEN RETURN (360+C)  ELSE
       IF (A<0) & (B<0) THEN RETURN (360+C)
       END STAN
       /*************************************************************/
       END MGRED1
```

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