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INTERPRETATION OF GRAVITY AND MAGNETIC
ANOMALIES IN THE N.E. ATLANTIC

By

Andrew P. Stacey

A thesis submitted for the degree of Doctor of Philosophy
in the University of Durham

University College  July 1968
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SUMMARY

Gravity and magnetic observations were made across the continental margin west of Ireland aboard R.R.S. Discovery in September 1966 and across the Iceland-Faeroes Rise with R.R.S. John Murray during May/June 1967. The project west of Ireland was designed to study the nature of the transition from continental to oceanic crust with particular reference to the crust beneath Porcupine Bight. The purpose of the Iceland-Faeroes Rise survey has been to compare the deep structures of Iceland and Faeroes with the intermediate rise, and to study the relationship of the Iceland-Faeroes Rise to the Norwegian Basin in the north and the basins of the eastern Atlantic in the south. The magnetic data from each survey has been reduced using an electronic digital computer.

Ocean magnetic lineations are discussed with regard to recently completed surveys and several current ideas on ocean basin evolution are criticised. An interpretation has been made of a single magnetic/seismic reflection profile across the southern Norwegian Sea using a two-dimensional matrix method for assessing the variations in the intensity of magnetisation within the magnetic layer of the ocean crust. Details of this method of interpretation are provided.
The continental margin of western Europe is described together with several possibly related structures and geothermal features observed on the continent. Lead-zinc mineralisation in Ireland is discussed with regard to the proximity of Ireland to the continental margin.
ACKNOWLEDGEMENTS

I wish to thank Professor K.C. Dunham and Professor G.M. Brown for providing the facilities for this research, and Professor M.H.P. Bott for his supervision. The work was financed by an N.E.R.C. Research Studentship for two years, and by a British Petroleum Company grant for one year.
CHAPTER 1

INTRODUCTION

The gravity and magnetic investigations described in this thesis concern primarily the evolution of oceanic crust and the deformation of continental crust in the area of the N.E. Atlantic. The sources of gravity and magnetic data include results from two Durham University surveys - Porcupine Bank (R.R.S. Discovery, Cruise 14), and the Iceland-Faeroes Rise (R.R.S. John Murray, Cruise 2) - and two reconnaissance gravity and magnetic lines made in co-operation with the Hydrographic Department between Faeroes and Iceland by H.M.S. Hecla in November 1965. Reference is also made to the U.S. Naval Oceanographic Office aeromagnetic survey of the Norwegian Sea, the aeromagnetic survey of Iceland by Dominion Observatory, and the aeromagnetic survey of the Reykjanes Ridge (Heirtzler et al, 1966). The locations of the various geomorphological units of the N.E. Atlantic that are referred to in this thesis are given in Fig.1.1.

Details are given in Chapter 2 of the gravity and magnetic surveys across Porcupine Bank during the September 1966 cruise of R.R.S. Discovery and over the Iceland-Faeroes Rise during the May - June 1967 cruise of the R.R.S. John Murray. The errors in the gravity, magnetic and navigational data are discussed, and
Fig. 1.1 Physiographic Map of the N.E. Atlantic
suggestions are made for the improvement of future survey results. The problems of processing marine geophysical information are outlined together with a description of a programme designed specifically to reduce marine magnetic data. From an analogue record of the magnetic readings this programme evaluates the observed total intensity magnetic field in gamma; assesses the regional gradients if required; and prints out total field and residual field in gamma relative to latitude and longitude, and square grid coordinates. For convenience in interpretation two scaled analogue records can be prepared — total intensity magnetic field in gamma against distance in kilometres, together with the regional; and the residual magnetic field in gamma also with respect to distance in kilometres.

The computer methods of interpretation include techniques described by Stacey (1961) for calculating the gravity and magnetic anomalies due to assumed two-dimensional bodies with defined densities or directions and intensities of magnetisation. In Chapter 3 a description is given of a matrix method for the interpretation of ocean magnetic anomaly profiles. The purpose of this programme is to assess the distribution of magnetisation within the magnetic layer of the ocean crust for an assumed direction of magnetisation. The upper and lower surfaces of the model representing this layer can be varied which is a
particular advantage if seismic reflection or refraction
control is available.

In Chapter 4 a study is made of ocean magnetic lineation
patterns and attention is drawn to areas which appear incompatible
with the Hess (1960) and Dietz (1961) hypotheses for the
formation of ocean crust from a narrow zone on the crest of
a mid-ocean ridge. Evidence is also given in support of the
suggestions by Wilson (1965) that the movements along a
mid-ocean ridge may combine both rifting and shearing i.e.
the direction of ocean-floor spreading may not be perpendicular
to the axis of a ridge. The principles developed in Chapter
4 are then applied in the interpretation of the magnetic
anomaly patterns associated with Iceland-Faeroes Rise, with
particular reference to the 'fan-shaped' lineations to the
south-east of Iceland.

The object of the gravity and magnetic survey of the
Iceland-Faeroes Rise has been to study the change in crustal
structure along the axis of the rise, and also perpendicular
to the rise from the Norwegian Basin in the north to the basins
of the eastern Atlantic in the south. The interpretation has
concentrated upon the relationship of the rise to Iceland and
the Faeroes block, as well as the nature of the crust and upper mantle beneath the rise itself. The location of the Iceland-Faeroes Rise is discussed with regard to the evolution of the N.E. Atlantic, and evidence is given suggesting that this feature may represent a zone that separates two oceanic areas whose mode of formation and structure may differ considerably. An interpretation has been made of a magnetic-seismic reflection profile at the southern end of the Norwegian Basin which provides information on the distribution of magnetisation within the magnetic layer of the ocean crust in this area.

The survey of Porcupine Bank was designed to study the transition from continental to oceanic crust off the west coast of Ireland. The possibility of thin crust beneath Porcupine Bight is discussed in conjunction with rotation of Porcupine Bank relative to the main continental mass of Europe. The survey results from this cruise have provided additional information on the nature of the crust between Rockall and Porcupine Banks, and have also confirmed gravity lows south of Ireland over a previously suspected granite at latitude 49°28' N, longitude 9°25' W and the Haig Fras granite at latitude 50°12' N, longitude 7°50' W.
In the last chapter an attempt has been made to identify structures on the continental shelf of western Europe with the formation of the continental margin. From a study of the topography of the margin it appears that two structural trends play an important part in controlling the configuration of the continental edge, and that similar trends may also exist well within the continent of Europe. The possibility of mineralisation occurring adjacent to a continental margin is discussed in some detail with particular reference to the distribution of lead-zinc mineralisation in Ireland.

Included in the appendices are copies of the computer programmes for the reduction and interpretation of ocean magnetic anomalies, together with their data formats. The values of the Free-Air anomalies obtained during the Iceland-Faeroes Rise survey and the Porcupine Bank survey are presented on 1:1,000,000 mercator projection sheets.
CHAPTER 2

THE SURVEYS AND THEIR REDUCTION

2.1 The Surveys

Gravity and magnetic observations were made across Porcupine Bank during the September 1966 cruise of R.R.S. Discovery (2667 gross tons., 261 ft. length) and over the Iceland-Faeroes Rise during the May - June 1967 cruise of the R.R.S. John Murray (441.1 gross tons., 132 ft. length). The Porcupine Bank survey was designed as a continental margin project to study the transition from continental to oceanic crust. The continental slope delineating the western edge of Porcupine Bank is approximately north-south, and so a series of gravity and magnetic lines each about 500 kilometres in length were made from the west coast of Ireland, across the continental margin, to the ocean basin separating Rockall from Porcupine Bank. Two further lines were made available by the Department of Geodosy and Geophysics, Cambridge University - a gravity line along the 12° meridian made by H.M.S. Vidal in 1964, and a similar line along latitude 49° by Snellius in 1965. The purpose of the Iceland-Faeroes Rise survey was to obtain information on the crustal variations along the length of the rise, and also its structural relationship with the Norwegian Basin to the north and the basins of the eastern Atlantic to the south. Thus, a total of seven
gravity and magnetic lines were completed parallel to the axis of the rise from the coast of the Faeroes to Iceland, plus a single line at right angles to the rise. An additional line from Iceland to Faeroes was made in November 1965 in co-operation with the Hydrographic Department by H.M.S. Hecla. The survey lines for the Porcupine Bank cruise and the Iceland-Faeroes Rise cruise are included in Fig.2.1.

An Askania Gss-2 surface-ship gravimeter kindly loaned by the Department of Geodesy and Geophysics, Cambridge University was used on both surveys. This instrument was not fitted with a servo-motor for changing the tension in the range spring, and so the measuring spring required manual adjustment.

The gravimeter was mounted on a gyrostabilised platform manufactured by Anschutz Company. The vertical reference was an oil-erected gyro for the Discovery cruise, but a recently developed electrically erected gyro system was fitted for the John Murray cruise. The main advantage of the new electric gyro is that it provides an automatic cut-off during course alterations when the angle and rate of turn exceeds $5^\circ$ and $0.3^\circ$ per second, respectively.
Fig. 2.1 Ship's track for Porcupine Bank and Iceland-Faeroes Rise Surveys
In addition, if the course transducer is used, there is automatic earth rate compensation. (The west pointing error of the gyro is removed by applying erection voltages to the torque motors. The error varies with the cosine of the latitude and its components in the directions of the axes of the platform are determined from the ship's heading by a resolver). Unfortunately, a fault developed in the normal erection mode so that the gyro failed to erect properly, but the fault did not occur in fast erection and so the gyro was operated in that mode. An Anschütz engineer adjusted the output voltage of the 400 HZ alternator in Thorshavn, but the fault persisted and for the rest of the period fast erection was used. Consequently, the full benefits of the electrically erected gyro system were not appreciated on this cruise, but it is believed that inability to operate in the normal erection mode has not significantly effected the results.

The variations in the total intensity magnetic field were measured using a proton precession magnetometer built by F.Gray for the Porcupine Bank survey, and a Varian direct reading proton magnetometer supplied by the Natural Environmental Research Council for the Iceland-Faeroes Rise survey. Echo-soundings on Discovery were made using a Precision Depth Recorder developed
by the National Institute of Oceanography, and on John Murray by a T.H. Gifft model GDR-T recorder and a Marconi Seagraph III. The Gifft recorder proved unreliable and so the Marconi system was used for much of this survey.

Navigation over Porcupine Bank out to the edge of the continental shelf was with the aid of two Decca chains - the North British and the South-West British - used simultaneously to improve accuracy. Beyond the range of Decca the navigation was a combination of dead reckoning and celestial fixes, but near the coast of Ireland radar fixes were used to confirm the Decca positions. The Loran A coverage over the Iceland-Faeroes Rise proved inadequate in some areas. Positions on this cruise were determined by Loran A and celestial fixes, radio direction finding, dead reckoning and radar fixes on the islands and coastline.

Time marks on the analogue records of the gravimeter and magnetometer during each cruise were provided by a common digital clock. The automatic time coding system already incorporated into the echo-sounding equipment was synchronised with this clock.
2.2 Gravity

The gravity records were reduced manually. Details of the gravity work are described for each cruise.

2.2.1 R.R.S. Discovery, Cruise 14

The reference bases for this survey were Mill Bay Dock, Plymouth \( (g_o = 981,130.6 \text{ mgal}) \) on 1 September 1966, and on the quay at Cork \( (g_o = 981,244.89 \text{ mgal}) \) on 16 September. The upper spring calibration factor used was \( F = 64.47 \text{ mgal}/ \) (measuring spring division) as supplied by the manufacturer, and the enograph analogue chart calibration was calculated as \( 1.286 \text{ mgal}/ \) (chart division). The total drift between Plymouth and Cork was \(-3.86 \text{ mgal}\), equivalent to a linear drift rate of \(-0.26 \text{ mgal/day}\).

In the measurement of gravity at sea on a surface ship, the use of a meter mounted on a stabilised platform can result in errors due to periodic off levelling of the meter in the presence of horizontal accelerations of the same period. If the meter is of the weighbeam type, similar to the Askania Gss-2, the periodic motion of the beam in the presence of horizontal accelerations of the same period results in the cross-coupling error. The presence of these errors was first pointed out by LaCoste and Harrison (1961). The size of these
errors throughout this cruise is difficult to assess as no cross-coupling equipment was available. However, a series of gravity lines have been completed by Discovery (Howarth) across the gravity range off Plymouth made by M.H.P.Bott using a bottom gravimeter. The tables below represent estimated errors based on five lines across this range in a variety of sea conditions on 16 April 1966, using the same Askania meter and stabilised platform that was operational during the Porcupine Bank survey.

<table>
<thead>
<tr>
<th>Time</th>
<th>Swell w.r.t. ship</th>
<th>Error (m gal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0255-0345</td>
<td>030°</td>
<td>+8.9 ± 3.9</td>
</tr>
<tr>
<td>0420-0505</td>
<td>210°</td>
<td>-1.6 ± 3.3</td>
</tr>
<tr>
<td>0520-0605</td>
<td>320°</td>
<td>+5.7 ± 1.3</td>
</tr>
<tr>
<td>0645-0750</td>
<td>120°</td>
<td>+2.4 ± 1.3</td>
</tr>
<tr>
<td>0820-0920</td>
<td>300°</td>
<td>+6.4 ± 1.7</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Time</th>
<th>Wind</th>
<th>Swell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dir.</td>
<td>Vel(knots)</td>
<td>Dir.</td>
</tr>
<tr>
<td>2400</td>
<td>234°</td>
<td>230°</td>
</tr>
<tr>
<td>0400</td>
<td>265°</td>
<td>-</td>
</tr>
<tr>
<td>0800</td>
<td>270°</td>
<td>260</td>
</tr>
<tr>
<td>1200</td>
<td>212</td>
<td>210</td>
</tr>
</tbody>
</table>
The errors quoted are the differences between the range values and the measured Free-Air anomalies, and it is thought that a positive bias of approximately 3 mgal exists in all these estimates due to drift within the instrument. Navigation over the range is extremely good, and so the errors are considered to be due almost entirely to cross-coupling effects. The cross-coupling errors measured by Howarth across the Bay of Biscay in severe weather conditions between 16 and 19 April suggested a maximum error of approximately 10 mgal. Therefore, as the gravity data reduced was restricted to recordings during relatively good weather, it is thought by this somewhat indirect comparative study that the errors due to cross-coupling effects are probably less than 6 mgal.

Gravity measured from a ship must also be corrected for the vertical components of the Coriolis and centrifugal accelerations generated by the ship's motion with respect to the spherical rotating earth. The correction is given by Worzel (1959) as,

$$
\Delta g = 7.487V \sin \phi \cos \lambda + 0.00415V^2 \quad (1)
$$

where $V =$ speed of ship in knots

$\phi =$ true course made good

$\lambda =$ latitude
The significance of the first term to gravity measurements at sea was first pointed out by Eötvös and the correlation, actually the vertical component of Coriolis, is referred to as the Eötvös correlation. The second term is the vertical component of the centrifugal acceleration under motion, it is small and has been neglected in these reductions.

However, the speed and course of a ship under constant propulsion will vary because of ocean currents and forces exerted by the waves and wind. The average Eötvös correction for a chosen period of time is found by determining a position at the beginning and the end of the period, and from this, the average easterly velocity. The minimum length of the period is controlled by the navigational accuracy available. Short-term variations in Eötvös correction occurring within the averaging period remain and constitute probably a large source of error.

By differentiating equation (1), it has been shown by Bower (1967) that for a speed of 10 knots and at a latitude of 45°,

\[
d(\Delta g) = 52.5(\cos \phi d\phi + \sin \phi \frac{dV}{V}) \tag{2}
\]
from which it can be seen that the correction is course-sensitive on north-south headings and speed-sensitive on east-west headings, with rates of 1 mgal/degree and 5 mgal/knot respectively.

An analogue record of the ship's head was obtained for the whole of the Discovery cruise and it shows an average short period yaw of 50-60 secs, with a variation from the mean course of 3.5 degrees. It is thought that the effect of this high frequency variation in the course would be filtered out by the gravimeter before appearing on the enograph record. However, a longer period variation occurs with a half-wavelength of about 30 minutes that has a variation from the mean course of about 3 degrees. If the ship was going north-south this would constitute an error of about 3 mgal, but as the survey lines are all east-west errors due to alterations in the ship's head are considered negligible.

Errors due to changes in velocity are thought to be significant, but due to the lack of good navigational control it is difficult to assess their value. No detailed velocity variations have ever been recorded on Discovery so only by comparison with a ship of similar tonnage and length can some idea be gained on the order of velocity variation one might expect.
Several test lines in variable weather conditions have been made by C.S.S. Baffin (3457 gross tons., 385 ft. length) and from these measurements (Bower and Loncarevic, 1967) it appears that the standard deviation from the mean velocity is on average about 0.3 knots. If one assumes that the changes in velocity of Baffin is similar to that experienced by Discovery, then for these east-west survey lines one can expect errors in the Eötvös correction of about ± 2 mgal.

The Free-Air gravity anomalies were calculated using the International Gravity Formula, and so discrepancies in the latitude will cause further errors. An estimated error of 3 mgal is thought to exist at the western ends of each line due to uncertainties of position.

Nevertheless, the cross-over errors of the east-west Discovery lines with the north-south line made by Vidal are all less than 5 mgal. It is estimated therefore, that composite errors of about ± 8 mgal may exist at the western ends of the lines, and about ± 5 mgal at the eastern ends.

2.2.2 R.R.S. John Murray, Cruise 2

The reference bases for this survey were Stornoway Town, Lewis (g₀ = 981,830.3 mgal) on 27 May 1967 and at Thorshavn, Faeroes
(Lighthouse, \( g_o = 982,105.33 \text{ mgal} \), King's Monument, \( g_o = 982,101.10 \text{ mgal} \)) on 7 June and 17 June. Tie in between base station and quay was done using a Worden 'Master' gravimeter loaned by the Department of Geodesy and Geophysics, Cambridge University. The upper spring calibration factor used was \( F = 64.47 \text{ mgal/ (measuring spring division)} \) as supplied by the manufacturer, and the enograph analogue chart calibration was calculated to be \( 1.264 \text{ mgal/ (chart division)} \). The drift between Stornoway and Thorshavn (27 May - 7 June) was calculated as a total of \(-3.1 \text{ mgal} \), a drift rate of \(-0.29 \text{ mgal /day} \). The drift between Thorshavn on 8 June and Thorshavn on 17 June was calculated as a total of \(0 \text{ mgal} \), a drift rate of \(0 \text{ mgal /day} \). The gravimeter and platform had to be clamped during the second leg of this cruise at 0500 hours on 8 June due to bad weather. The ship took shelter in Seydisfjordur from 1900 hours on 9 June to 0930 hours on 12 June.

A means for providing a continuous record of cross-coupling errors was not available but measurements were taken on this cruise for a variety of course directions in different sea conditions by G.A.Day of the Department of Geodesy and Geophysics, Cambridge University (unpublished report).
<table>
<thead>
<tr>
<th>Time</th>
<th>Swell w.r.t. ship</th>
<th>Vel (knots)</th>
<th>Cross-coupling Error (mgal)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Dir. Ht.(ft.) Period (secs)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2040/153</td>
<td>315° 5 5</td>
<td>8</td>
<td>+8</td>
</tr>
<tr>
<td>0930/154</td>
<td>010° 7-10 6</td>
<td>10</td>
<td>+8</td>
</tr>
<tr>
<td>1850/154</td>
<td>000° 9 6</td>
<td>6</td>
<td>+3</td>
</tr>
<tr>
<td>1855/154</td>
<td>170° 9 6</td>
<td>6</td>
<td>-3</td>
</tr>
<tr>
<td>1900/154</td>
<td>170° 9 6</td>
<td>10</td>
<td>-2</td>
</tr>
<tr>
<td>1150/155</td>
<td>220° 9 7</td>
<td>10</td>
<td>-15</td>
</tr>
</tbody>
</table>

It can be seen from this table that appreciable cross-coupling errors were present in all sea states above 3 (slight sea or swell). The phase relationship to the surge acceleration is constant for all headings into the sea, and opposite for courses going with the sea, as observed in other ships (Wall, Talwani, and Worzel, 1966).

The survey lines for this cruise are labelled A to K in Fig.2.1. The sea was calm for lines A, B, C, D, F, G, I and J and it is thought that the cross-coupling errors for these lines are negligible. However, the weather was bad for the majority of lines E, K and H, but by comparison with the above table some idea of the sizes of error involved can be obtained. On line E the wind increased from force 5 to 8 towards Iceland from a southerly direction. It is thought that cross-coupling errors in this line may be as high as -10 to -12 mgal. The weather also deteriorated...
along line K, but the errors have been measured and increase to about +8 mgal. Line H made from Iceland to Faeroes suffered from a strong sea increasing from the south-west. The effect of seas from directly abeam of the ship has not been estimated but according to Bower (1966) the cross-coupling error should theoretically be zero.

The errors in the evaluation of the Eötvös correction are difficult to assess as a fault developed in the ship's head recorder, and no detailed record of minor variations in velocity was possible. The John Murray has not undergone trials to estimate the consistency in velocity or course, and therefore it is at present difficult to give any reliable value for the error involved in the Eötvös correction.

However, it appears that the cross-coupling errors quoted for the various lines would in every case almost completely account for the discrepancies at the cross-over points. Consequently, the cross-coupling error estimated for each line can be considered to represent the major proportion of the total error. Errors in the latitude correction due to uncertainties in position are probably greatest at the Iceland end of the survey as Loran A was particularly weak in this region.
Another possible source of error concerns the often severe vibrations experienced on many vessels. The problems of vibration causing large deflections to the gravity record were noticed with the Askania gravimeter on H.M.S. Protector in 1965-66 (report in preparation by Comolet-Tirman), and with the LaCoste and Romberg land gravimeter (Hamilton and Brulé, 1967). Consequently, tests were made on the John Murray to study the effect of the ship's engines with the gravimeter running from a shore supply. Both main engines and the auxiliary caused a deflection when idling, but at full speed the gravimeter record was unaffected. Vibrations may also be produced at different settings of the propeller pitch. Normally the propeller pitch is altered by discrete steps by a control on the bridge. No obvious change in the gravimeter output was observed when the speed was adjusted in this way, but on one occasion in a calm sea a slight adjustment of pitch in the engine room produced a disturbed gravity record. However, this characteristic was not observed on the actual survey, and so the errors due to vibration are considered negligible.

2.2.3 Results

The Free-Air anomalies for the Porcupine Bank survey and the Iceland-Faeroes Rise survey are presented on 1:1,000,000 sheets in the appendix. Provisional contoured Free-Air anomaly maps on the same scale are also available.
2.3 Magnetics

2.3.1 Introduction

A programme has been written to reduce the magnetic data collected during Cruise 14 of R.R.S. Discovery and Cruise 2 of R.R.S. John Murray. The programme is restricted firstly in order to deal with the form and conditions in which data had been recorded on these cruises, and secondly in the way the reduced data is output. However, although such input and output restrictions exist, it is hoped that the major part of this programme will act as a basis for the future development of marine magnetic reduction methods.

Before going into details of this programme it is perhaps advisable to comment initially on the problems involved in the variety of forms of input and output.

(i) Data Input Variations. The form of data input is controlled by the method and degree of accuracy of navigation, and the manner in which magnetic readings are recorded.

(a) Navigational Data. Essentially any magnetic reduction programme requires at some stage the latitude and longitude with respect to time. The method by which these co-ordinates are obtained will depend upon the navigational system used and also
the technique for smoothing the observed ship's track. If the navigation is both accurate and sufficiently frequent it is thought that smoothing the ship's track to within a maximum deviation and/or maximum standard deviation by computer would be the most efficient. For average quality navigational data, where certain co-ordinates are more reliable than others, the application of weighting factors would again allow computer smoothing techniques. However, if the navigational data is sporadic with a variable degree of accuracy, it is thought that smoothing by hand might be the most effective method.

It must be stressed that the decision for manual or automatic smoothing is the critical factor governing the necessity of automatic computer conversions from navigational co-ordinates to latitude and longitude. If automatic smoothing is possible then computerised navigational conversions are essential; if hand smoothing must be relied upon then it is considered that computerised navigational conversions are unnecessary, and a completely different approach to the preparation of navigational input data is required.

The method of approach followed by this programme for the handling of poor quality data has been the replotting and manual smoothing of the ship's track from a navigational chart onto
an admiralty plotting sheet. Then the position co-ordinates are digitised using a pen-follower to produce a punch tape in terms of pen-follower units. The conversion from pen-follower co-ordinates to latitude and longitude is done by computer. (If necessary the hand smoothed position fixes may be optimised still further by computer.)

The major points in this discussion on navigational data are illustrated in Fig.2.2. The method used in this reduction programme is 'system A' designed for poor quality navigational data. However, it must be emphasised that a general magnetic reduction programme is incomplete unless it includes all three systems.

One final comment on the problem of navigation is that it is obvious from what has been discussed already that the entire problem of reduction is due to the shortcomings of the present survey navigational equipment. Ideally, it is thought that satellite navigation with fixes every half hour together with frequent outputs of the ship's head and ship's log averaged over a chosen period would greatly enhance deep-sea surveying. The recently developed Decca Logger 1984 which provides position co-ordinates every four minutes would also be considered a tremendous advantage.
NAVIGATIONAL CO-ORDS.
e.g. DECCA
LORAN

SYSTEM A  
for Poor
quality data

| Plot ship's track on navigational chart |
| Replot hand-smoothed positions on admiralty plot sheets |
| Digitise ship's track using pen-follower |
| Computer conversion from p-f co-ords to lat./long. |
| Lat./long. |

SYSTEM B  
for Average
quality data

| Computer conversion from Nav.co-ords to lat./long. |
| Application of Weighting factors |
| Computer smoothing Techniques |
| Lat./Long. |

SYSTEM C  
for High
quality data

| Computer conversion from co-ords. to lat./long. |
| Application of Weighting factors |
| Computer smoothing Techniques |
| Lat./Long. |

Fig.2.2 Reduction of Navigational Data
(b) Magnetic Data. The majority of problems concerning the conversion from magnetic readings to total intensity magnetic field in gamma are due to the numerous forms in which the magnetic data is initially recorded. Basically, the method of recording involves digital and/or analogue techniques; however, it is the variety of scaling factors and codes used by different types of equipment which creates the complications. Thus, in any general magnetic reduction programme it would probably be necessary to provide a special sub-routine or procedure for each type of magnetometer used.

With regard to the advantages and disadvantages of either analogue or digital recording the following remarks are perhaps worth considering assuming a digital computer is to be used for the processing of magnetic data. If one uses punch tape output from the magnetometer several editing problems exist. Such problems include the removal of incorrect readings, and usually a reduction in the number of readings according to the wavelength of the anomaly. A six second sampling rate as output from a Varian magnetometer over long wavelength anomaly areas would create an inefficient data processing system. A more acceptable method of digital recording is on magnetic tape in conjunction with a shipboard computer which could provide immediate editing facilities.
An alternative method of preparation of magnetic data input is based upon the application of a pen-follower. This method is surprisingly rapid and overcomes immediately the editing difficulties previously mentioned. Fig. 2.3 illustrates the differences in the two reduction processes.

It is hoped that in this brief discussion most of the important general problems of data input preparation have been covered. I would now like to mention a few points regarding the forms of output that a magnetic reduction programme might produce.

(ii) Data Output Variations. Essentially two principles control the general form of output of reduced magnetic data—convenience in relating magnetic field measurements to geographical position, and secondly convenience for interpretation. It is suggested, therefore, that output information should include a print out relating total field and residual field with grid co-ordinates and/or latitude and longitude, and also an analogue output on squared graph paper of the residual field with respect to distance. If a reasonably comprehensive survey over a new area has been completed justifying a separate assessment of the regional, then regional gradients eastwards and northwards in gamma/kilometre should also be output. Automatic contouring
Magnetometer

**Analogue Record**
- Digitise Analogue using pen-follower
  - Computer conversion from p-f co-ords to gamma
    - Total magnetic field in gamma

**Digital Record**
- Editing
  - Computer conversion from readings to gamma
    - Total magnetic field in gamma

**Fig. 2.3 Reduction of Magnetic Data**
methods have been completed in Canada, the United States, and Holland and should provide a valuable addition to output presentation. A summary of these suggestions is given diagrammatically in Fig.2.4.

(iii) Information-Flow. Before finishing this discussion on input and output forms a few comments are perhaps relevant regarding the problems of exchange of data. Ideally, a magnetic data processing system should be able to provide copies of survey data at every stage in the form convenient for any organisation whatever their facilities. This suggestion is probably unpractical if not impossible for most university geophysics departments, and so it would be advantageous if a government department acted as a main data processing centre. Each university geophysics department should be capable of providing magnetic information in either reduced or observed form which can be handled efficiently by the centre's computer facilities.

If digital records are to be exchanged it is recommended that information is produced as much as possible on magnetic tape. Facilities should also be available at a data processing centre for providing microfilm copies of total magnetic intensity analogue recordings, together with a microfilm index, which sequentially lists survey tracks for each microfilm reel.
Total Mag. field

Lat./Long.

Regional gradients
if required

Magnetic Reduction
Programme

Total field
Residual field
Lat./Long.
East/North

Analogue record
of Res. field
against
distance

Magnetic data
tape for
automatic
contouring

Estimate of
reg. gradients
east/north if
required

Fig. 2.4 Input and Output Requirements
2.3.2 Purpose of Magnetic Reduction Programme.

This computer programme is designed to provide a reduction system for marine magnetic data when the navigational data is of poor quality, i.e. a magnetic reduction method corresponding to 'system A' described in the introduction. The technique is dependent upon an analogue record of the magnetic readings, and knowledge of position on a 1:1,000,000 mercator projection sheet, so that both can be digitised using a D-Mac Pen-follower. From this information the programme calculates the observed total intensity magnetic field in gamma; assesses the regional gradients eastwards and northwards; and prints out total field and residual field in gamma relative to latitude and longitude, and square grid co-ordinates. For convenience in interpretation two scaled analogue records can be prepared - total intensity magnetic field in gamma against distance in kilometres, together with the regional, and the residual magnetic field in gamma with respect to distance in kilometres.

This programme was written primarily for data collected by John Murray and Discovery in the survey areas of Iceland-Faeroes Rise and Porcupine Bank. Consequently it is specialised in many ways and must be regarded very much as a first generation technique. A print out of the programme and the data format specifications are provided in the appendix.
2.2.3 Programme Descriptions

The programme is written in Algol 60 Language for an Elliott 803 computer. Due to the small storage capacity of this computer the programme has been divided into four separate programmes, plus a trigger programme at the beginning. This does not mean, however, that the amount of data the computer can handle is badly restricted as only discrete sections of data are processed at one time.

(i) Magnetic Reduction Programme, Trigger. This programme simply ensures that all 64 words in block 49 of the magnetic film are equal to zero.

(ii) Magnetic Reduction Programme, Part 1. The purpose of this programme is to calculate from the pen-follower co-ordinates representing the magnetic readings and ship's track, the values of the magnetics in gamma, and the navigation in terms of latitude and longitude, and kilometres north and kilometres east relative to a defined origin. The correlation of magnetic readings with geographical position is done with respect to time, although the actual time is not used in the data. Correlation is achieved by initial data organisation rather than computer search methods. The programme was written in this form due to computer time and storage problems - for a more flexible programme
the time should be included. Basically there are five stages to this programme: a counter for the number of survey lines read into the programme; conversion from pen-follower co-ordinates to latitude and longitude; conversion from latitude and longitude to kilometres north and kilometres east, and interpolation of intermediate positions; conversion from pen-follower co-ordinates to observed total magnetic field in gamma; and the writing of these results on film, together with the number of the last block used.

(a) Counter. This simply counts the number of survey lines that are read into the programme, and writes the results in the first word of block 49. The total number of survey lines entered is required in a later part of the reduction system.

(b) Pen-follower co-ordinates to Latitude and Longitude. To obviate errors due to possible distortions in the shape of the plotting chart it is necessary to calculate scaling factors in both x (easterly) and y (northerly) directions. In the programme these scale factors are \( x_T/x_0 \) for the x direction, and \( y_T/y_0 \) for the y direction.
\( x_T = \) Theoretical distance in feet between two meridians on the same latitude.

\( x_O = \) Observed distance in feet.

\( y_T = \) Theoretical distance in feet between two lines of latitude on the same meridian.

\( y_O = \) Observed distance in feet.

\( x_T \) is based upon the equation,

\[
\text{One degree of longitude on latitude } \phi = 0.017453 \cdot R \cdot \cos \phi
\]

where \( \phi \) is the latitude for which the scale is quoted, and \( R \) is defined as the radius of curvature of the scaled model at that latitude in feet.

\( y_T \) is based upon the formula which expresses the distance of any parallel on a mercator projection map from the equator.

At latitude \( \phi \), distance from equator = \( R \log_e \tan(45 + \phi/2) \)

To find the latitude and longitude of a given position, one calculates the corrected distances in pen-follower co-ordinates from the two base lines, and then converts these using the following expressions to give the degrees of latitude and longitude:

\[
\text{Latitude in degrees} = 2 \tan^{-1}\left(\frac{y'}{R \cos \phi - 45}\right)
\]

where \( y' \) is the distance between the base absissae and the required position.
Longitude in degrees = zerolong + x / Rcosφ

where x is the distance between the base ordinate and the required position; and zerolong is the value in degrees of the meridian corresponding to the base ordinate.

(c) Latitude and Longitude to Km.N and Km.E. The formulae for this conversion is given in 'Constants, Formulae, and Methods used in Transverse Mercator Projection' published by H.M.S.O. The method assumes a square grid over a transverse mercator projection. In order to minimise errors in this technique it is important to choose the true origin on the central meridian through the survey area. It is conventional for the true origin to be at the southern end of this meridian, with the false origin in the south-west corner of the grid. Once the positions in terms of grid co-ordinates have been obtained, the interpolation for intermediate positions must be made, such that the total number of navigational fixes less one equals the total number of magnetic values.

(d) Pen-follower Co-ordinates to Gamma. The practical problems of digitising a 100 ft. analogue record are overcome by loading take-up spools at each end of the D-Mac pen-follower. The record is then moved beneath a transparent overlay consisting
of parallel lines representing the chosen time intervals for digitisation. The programme then calculates the value of the anomaly in terms of pen-follower co-ordinates and converts this to gamma. Changes in the value of the base line in gamma and any alterations in scale, e.g. 100 gamma to 1000 gamma full-scale deflection, are included in the data, so that the anomalies can be quoted in terms of magnetic field in gamma.

(e) Results on Magnetic Film. Each block on the magnetic film contains 64 words. For every station three words are required - magnetic reading, kilometres east, kilometres north - and so a convenient number of stations per block is twelve. The chosen number of stations per block and the latitude and longitude of the first station in a line are written in the first three words of the first block. The latitude and longitude of the last station in each block is also recorded.

In block 49 the first word represents the total number of survey lines the programme has received, the second word gives the number of the last block to be used in line 1, the third word gives the number of the last block used in line 2, etc. Thus, as the programme is written the total number of lines is restricted to 63.
Assuming two survey lines of one hour in length with a sampling interval of 2.5 mins., the results on magnetic film should be arranged as shown in Fig.2.5.

(iii) Magnetic Reduction Programme, Part 2. This part of the reduction system calculates and stores in block 48 the linear regional gradients of the magnetic field and the value of the regional at the false origin. If these values are already known from previous studies then this programme is not required, but the values must still be written on block 48, see Fig.2.6. The regional is obtained by a least squares method which enables one to calculate the 'best-fitting' plane through the observed magnetic anomalies such that the square of the residuals is a minimum. Details of this method are adequately described in 'Advanced Theory of Statistics', volume 2 by Kendal and Stuart.

(iv) Magnetic Reduction Programme, Part 3. In order that data is presented in a convenient form for interpretation, an analogue output of both the observed and residual anomalies are prepared by this programme. In addition, the regional estimated from the whole survey is drawn through the observed profile. The Elliott 803 computer provides a 5-hole output, and the curves are produced by a Benson-Lehner X-Y Plotter. For each
Fig. 2.5 Storage of Results on Magnetic Film

Fig. 2.6 Parameters of Regional Gradient on Block 48.
profile a print out is provided of the observed field value in gamma at the origin; and for each residual anomaly profile a print out of the anomaly value at the origin, and also the horizontal and vertical scales.

The data defining the parameters of the graph plot is read in on 8 hole tape, but the data giving the observed value in gamma with its position co-ordinates in kilometres north and kilometres east is read off magnetic film. The only calculations required are the evaluations of scale factors in terms of kilometres per inch and gamma per inch, and the distance of each station along a single traverse. Also the value of the regional at a given station must be calculated.

Finally, the programme is designed to begin at the start of any line in case of unforseen stoppages.

(v) Magnetic Reduction Programme, Part 4. This part of the reduction system prints out the information that had previously been stored on magnetic film. The print out has the form,

<table>
<thead>
<tr>
<th>Latitude</th>
<th>Longitude</th>
<th>Observed Gamma</th>
<th>Residual Gamma</th>
</tr>
</thead>
</table>

This type of output may become obsolete when profile and contour methods have been optimised.
2.3.4 Results

In the reduction of the magnetic data collected during cruise 4 of the Discovery and cruise 2 of John Murray no corrections were made for diurnal variations, although magnetograms from Eskdalemuir Observatory were studied to ensure that no unusually large variations had occurred. The residual field magnetic anomaly profiles for Porcupine Bank are included in chapter 6, and for the Iceland-Faeroes Rise in chapter 5. The regional gradients based upon data collected from these two surveys are as follows:

Porcupine Bank: Regional Background at False Origin = 47137 gamma

Regional Gradient Eastwards = -0.402 gamma/km.

Regional Gradient Northwards = 2.949 gamma/km.

(False origin is situated 100 km.N. and 400 km.W of the true origin at latitude 49°N, longitude 02°W.)

Iceland-Faeroes Rise: Regional Background at False Origin = 50484 gamma

Regional Gradient Eastwards = -1.019 gamma/km.

Regional Gradient Northwards = 1.722 gamma/km.

(False origin situated 100 km.N. and 300 km.W of the true origin at latitude 60°N, longitude 09°W.)

However, the residual field anomalies for Porcupine Bank presented in chapter 6 are based upon the regional variations for the North-East Atlantic Ocean as estimated by Bullard (1962). These variations approximate to the following linear gradients:
Porcupine Bank: Regional Background at False Origin = 48200 gamma

Regional Gradient Eastwards = -0.915 gamma/km.

Regional Gradient Northwards = 3.240 gamma/km.

(False origin situated at latitude 52°N, longitude 15°W.)

For comparison the regional gradients for Great Britain as estimated by the Geological Survey are also included:

Great Britain: Regional Background at False origin = 47033.4 gamma

Regional Gradient Eastwards = -0.259 gamma/km.

Regional Gradient Northwards = 2.1728 gamma/km.

(False origin is situated 100 km.N. and 400 km.W. of the true origin at latitude 49°N, longitude 02°W.)
CHAPTER 3

METHOD OF INTERPRETATION OF OCEAN MAGNETIC ANOMALIES

(MXOCEAN MK 2)

3.1 Introduction

The programme which has been used for the interpretation of ocean magnetic anomalies is a development of the matrix method first described by Bott (1967). The magnetic layer within the crust is represented by a series of two-dimensional blocks with a defined direction of magnetisation, and the purpose of the programme is to calculate the intensity of magnetisation for each block that will produce an anomaly profile consistent with the observed profile with the regional gradient removed. Blocks must be of constant width and sufficiently small to allow the assumption of uniform magnetisation. The improvement on the previous method for the interpretation of ocean magnetic anomalies is that the depth to the top and bottom surfaces of the model can now be varied. This is of a particular advantage if seismic refraction or reflection control is available.

The theory for the matrix method of solving the linear version of the inverse problem in magnetic interpretation is based upon the finite summation,

\[ A_i = \sum_{j=1}^{m} k_{ij} J_j \]  (i = 1, 2, ..., n)  (1)
where the anomaly $A_i(x,z)$ is known at $n$ points and there are $n$ blocks. Assuming unit magnetisation, the anomaly at the $i$th field point caused by the $j$th block is equal to $k_{ij}$. It is dependent only upon the shape of the block and its position relative to the field point, and the inclination and azimuth of both the Earth's field and the magnetisation within the body (Bott, 1967). If the number of field points is equal to the number of blocks, as in this case, the intensity of magnetisation is obtained by solving a set of $n$ linear equations, which in matrix notation is given by,

$$
J = k^{-1} A
$$

Thus, given the observed anomaly profile the problem reduces to the calculation of the kernel functions $k_{ij}$ for a defined number of blocks each side of every field point, and inverting the matrix formed by them.

In order to reduce computation otherwise repetitive calculations have been separated from the main programme and are included as procedures. Also, when evaluating the field value at a given field point the two-dimensional blocks have been approximated to line dipoles beyond a defined number of blocks each side of that field point, Fig.3.1a. The magnetic field due to a line dipole can be calculated more rapidly than the field due to a two-dimensional block, and at a given distance the error involved is minimal.
Fig. 3.1 Approximation of Blocks: (a) To line dipoles (b) To Magnetic Sheets
However, the main problem in reducing computation time concerns the matrix inversion. The matrix method described by Bott for a magnetic layer of constant depth and thickness requires only a single inversion, but in this development of the matrix method, where the depths to the top and bottom of a model can be varied, a large number of matrix inversions are necessary. It is important, therefore, to construct a much smaller matrix dependent upon fewer field points.

The diagram in Fig.3.1b. shows how this approximation is achieved. The value of the field at a given field point could normally be dependent upon numerous blocks each side of that field point. However, blocks beyond a defined distance can be grouped together and approximated to magnetic sheets such that the field value is only dependent upon a few polygonal blocks, plus a standard series of magnetic sheets. Thus, the size of the square matrix to be inverted is limited to the field values at relatively few field points.

The equation for the intensity of magnetisation of a single block should now be written as,

$$J_o = \sum_{i=-n}^{n} W_i A_i \quad (3)$$

where there are a total of $n$ blocks or sheets considered to effect
the value of the field, and \( W_i \) is the approximation of \( k^{-1} \).

Computer storage restrictions require the programme to be divided into two parts. For each field point, part 1 calculates and writes on magnetic tape the values of \( k_{ij} \) and the values of \( W'_1 \) (the central row of the inverted matrix \( W_i \)). The values of \( W'_1 \) act as weighting factors in the evaluation of the intensity of magnetisation such that,

\[
J = \sum W'_i A_i \quad (4)
\]

This evaluation is done in part 2, but due to the various approximations made in part 1 an iterative method is necessary to minimise the residuals between the calculated and observed anomalies.

The original version of this programme was made available by Professor M.H.P.Bott in Algol 60 language. Initial development was completed on the Durham University Elliott 803 computer, and then translated and finally tested on the Newcastle University KDF9 computer. The data formats and definitions for both parts of this programme are given in Appendix B.
3.2. Description of Part 1 of Programme

The important logic problems in this part of the programme includes for each field point (1) the calculation of those elements of the kernel function $k_{ij}$ that significantly contribute to the anomaly at that field point, and (2) the construction of a matrix whose inverse approximates to the inverse of matrix $k_{ij}$. Before going into the details of these logic problems a brief explanation is given of the procedures used in calculating the magnetic field due to a single body.

To obtain the field due to a two-dimensional body with vertical sides, it is necessary to subtract the anomalies due to two vertical semi-infinite dykes with identical widths, one situated immediately above the other. The total magnetic field due to a vertical semi-infinite slab or dyke is a function of the co-ordinates defining the shape of the dyke, its position relative to the field point, as well as the direction of the Earth's field and the magnetisation. Procedure "top" provides the variables dependent on the shape of the body and the field directions. Procedure "magsdyke" evaluates the parameters defining the position of the dyke with respect to the field point.
The expression for the total magnetic field that represents an approximation of a two-dimensional body to a line dipole may be deduced from Poisson's Theorem, and the size and shape of the initial two-dimensional body. Procedure "magline" calculates the variables within this expression, and procedure "mean" evaluates the area of each block and the position co-ordinates of the line dipole.

With these four procedures it is possible to calculate the anomaly due to a single body, but the anomaly at a chosen field point will be affected by several bodies each side of such a point. The model given in Fig.3.1a shows that within a specified distance (nmx blocks) on either side of the ith field point the bodies are assumed to be two-dimensional polygons, but beyond this distance the blocks are approximated to line dipoles. Blocks beyond a second specified distance (nmag blocks) from the field point are ignored. Assuming unit magnetisation the total anomaly can be calculated at the ith field point using the procedures "top" and "magsdyke" for the two-dimensional blocks, and procedures "mean" and "magline" for the line dipole approximations.

This type of computation is done for each field point, but difficulties arise at the ends of the profile. For example,
Fig. 3.2 End Corrections

Fig. 3.3 Construction of Rectangular Matrix

Fig. 3.4 Results of Part I on Tape assuming nmx = 4
when calculating the values of the kernel functions at the first field point \((i=1)\) only \(nmag+1\) blocks are available in the initial model. To produce the required uniformity for each field point it is necessary therefore to assume a further \(nmag\) blocks at each end of the profile whose kernel function values are zero. Thus, for the first field point \((xsta[1])\) dummy blocks are assumed for \(j=-nmag\) to \(-1\); and \(j=0\) to \(nmag\) are then the first \(nmag+1\) blocks of the model. For the second field point \((xsta[2])\) dummy blocks are required only from \(j=-nmag\) to \(-2\); and \(j=-1\) to \(nmag\) are the first \(nmag+2\) blocks of the model. Eventually, at \(xsta[nmag+1]\) no dummy blocks will be necessary as the full range from \(j=-nmag\) to \(nmag\) can be obtained within the original model. Similarly, at the other end of the profile at \(xsta[nsta-nmag+1]\), where \(nsta\) is the total number of field points, a single dummy block is required, and by \(xsta[nsta]\) a total of \(nmag\) dummy blocks are necessary. This argument is presented diagrammatically in Fig.3.2, and the relevant part of the programme to which this refers is within the loops following the conditional statements - 

\['if\ count\leq nmag + 1'\]

and 

\['if\ count > nsta-nmag'\] (count being equivalent to the number of the field point.)

The second problem in the logic of this programme concerns the formation of the kernel matrix for the \(i\)th field point which
can be inverted such that the central row can be used to
give a series of weighting values which when convolved with
the observed anomalies gives the intensity of magnetisation of
the ith block. This means that a matrix inversion is required
for every field point, and so to minimise computing time it is
necessary to construct a smaller matrix that represents a good
approximation of the larger matrix k. This is achieved by
using only those elements symmetrically about the centre of
matrix k which can provide a $2 \times nmx + 1$ by $2 \times nmx + 1$ square
matrix. The elements in the central row of this smaller
matrix will be dependent only upon evaluations from two-
dimensional blocks. This is achieved in the programme by first
constructing a $4 \times nmx + 1$ by $2 \times nmx + 1$ rectangular matrix.
Then by selecting those elements within the rhombus illustrated
in Fig. 3.3, and finally 'squaring up' the rhombus, the required
matrix can be formed.

The construction of the $4 \times nmx + 1$ by $2 \times nmx + 1$ matrix
is in three parts:

(i) All $n$ elements of $p[i]$, representing the values of the
kernel function, are set to zero, where $n=(4 \times nmx+1)X
(2 \times nmx + 1)$.

(ii) In the first loop of the programme:

(a) All rows are moved up one, so that the top row is now
lost \((p[i] := p[i+m], \text{ where } m = 4 \times nmx + 1)\)

(b) The bottom row is then filled with the values of \(k_{ij}\) due to \(2 \times nmx\) blocks either side and including the first field point, i.e. \(k_{10}\) is at the centre of the bottom row.

(iii) This is repeated for \(2 \times nmx + 1\) loops of the programme so that the \(k_{ij}\) values relative to the first field point are on the top row, and the \(k_{ij}\) values relative to the \(2 \times nmx + 1\) field point is along the bottom. The field points are at the centre of each row.

Only at this stage is it possible to construct the required square matrix by taking those elements within the rhombus defined in the programme as \(p[mm+j]\). The resulting square matrix is termed \(K[i,j]\).

Unfortunately, when high frequency magnetic anomalies are superimposed upon a very long wavelength component, the approximation using this type of matrix has proved inadequate causing a rapid divergence of the residuals in part 2 of the programme. To improve the approximation a standard matrix is constructed which includes elements dependent on blocks much further from a given field point. The model illustrated in Fig.3.1b shows a magnetic layer represented as blocks that have been approximated to a series of magnetic sheets of unit thickness,
at a constant depth corresponding to the average depth to
the centre of gravity of all the blocks in the profile.
The sheets within a certain specified distance (nmx) are of
similar width to the two dimensional blocks, but the three
sheets beyond this distance at each end of the model all have
a width equivalent to several blocks grouped together in order
to reduce computation. A $2 \times nmx + 7$ by $2 \times nmx + 7$ square matrix,
also termed $K[i,j]$, is built up representing the field values
above the centre of each successive sheet due to the other
magnetic sheets in the profile. The procedure "magsheet"
evaluates the variables in the formula for the total field
developed from Poisson's Theorem.

When $2 \times nmx + 1$ loops of the programme have been completed
the first matrix inversion can be made. The matrix to be
inverted is now the larger $2 \times nmx + 7$ by $2 \times nmx + 7$ square
matrix with the smaller $2 \times nmx + 1$ by $2 \times nmx + 1$ matrix
substituting the central elements whose $i$ and $j$ values
are between $-nmx$ and $nmx$. The central row of the first
inverted matrix $W$ represents the weighting factors $W$ required
to calculate the intensity of magnetisation of block $nmx + 1$. 
The values of the kernel function are written on magnetic tape for each field point, but the elements in the central row of the inverted matrix $dK$ are not written on tape until after $2\times nmx + 1$ loops of the programme. Fig. 3.4 illustrates the form of the beginning of the magnetic tape assuming $nmx = 4$; array $A$ represents the kernel functions for successive field points, and array $B$ represents the inverted elements.

3.3. Description of Part 2 of Programme

The purpose of this part of the programme is to calculate the intensity of magnetisation of each block within the magnetic layer model that will produce an anomaly consistent with the observed magnetic profile. The formula for the inverse problem in magnetic interpretation can be approximated to equation (4), where the anomaly $A(x,z)$ is known at $nsta$ points and there are considered to be only $nmx$ significant blocks each side of every field point. The values of the weighting functions $W$, the elements in the central row of the inverted matrix, have of course already been calculated and can be read off the magnetic tape.

The anomaly due to the resulting magnetisation distribution is then evaluated using equation (1) for $j=-nmag$ to $nmag$, and the residual anomaly is formed by subtracting the observed from the calculated
values. An improved estimate is possible by obtaining a magnetisation distribution due to the residual anomaly, and adding it to the original intensities. By iterating in this way the residuals can be reduced to acceptable proportions.

Unfortunately, the intensity of magnetisation of a few blocks at the ends of the profile cannot be calculated, whilst others near the ends are inaccurate. The first and last \( n_{mx} + 1 \) blocks are lost because it has not been possible to calculate their weighting functions in part 1. Also, when calculating the anomaly due to the first estimate of the magnetisation distribution it is not worthwhile assessing the anomaly at field points from \( n_{mx} + 1 \) to \( 2n_{nmx} + 1 \) and from \( n_{sta} - 2n_{nmx} - 1 \) to \( n_{sta} - n_{mx} \) as a reasonable estimate of an anomaly can only be obtained on the basis of \( n_{mx} \) two-dimensional blocks each side of a field point. This criterion is not satisfied for the first and last \( 2n_{nmx} + 1 \) field points, and so the residual anomaly is evaluated at field points within the range \( 2n_{nmx} + 2 \) to \( n_{sta} - 2n_{nmx} - 1 \). By a similar argument the iterative corrections to the intensity of magnetisation for blocks from \( 2n_{nmx} + 2 \) to \( 3n_{nmx} + 2 \) and from \( n_{sta} - 3n_{nmx} - 1 \) to \( n_{sta} - 2n_{nmx} - 1 \) will be suspect due to the absence of significant residual anomaly values at each end.
A print out is provided for the intensity of magnetisation in e.m.u./cm\(^3\) and the residual anomaly in gamma for each block from 2nmx + 2 to nsta-2 nmx - 1, but the values at each end will be a little inaccurate, in particular the first and last nmx blocks.
CHAPTER 4

OCEAN MAGNETIC ANOMALIES AND THEIR INTERPRETATION

4.1. Introduction

In the last five years a vast amount of magnetic data has been collected from oceanic areas, and so in this chapter a further look is made at ocean magnetic anomalies to see if the current theories for their origin are still valid. The first systematic magnetic survey of an oceanic area was made in the North-East Pacific off the western seaboard of the United States (Mason and Raff, 1961; Raff and Mason, 1961). The results from this survey demonstrated the existence of an impressive series of magnetic lineations roughly parallel to the continental margin and occasionally offset by long east-west fracture zones. The individual anomalies have a magnitude of several hundred gammas, a width of a few tens of kilometres, and a length of about 1000 kilometres. The sharpness of these anomalies requires that at least the upper part of the magnetic body must be at a shallow depth, and so the lineations were interpreted by Mason and Raff (1961) as either lavas within layer 2 of the oceanic crust; an upwarp of layer 3 effectively cutting out layer 2; or as a block of high magnetic susceptibility both in layer 2 and layer 3.
However, since then Vine and Matthews (1963) have suggested a fourth possibility based on current ideas of ocean-floor spreading and periodic reversals in the Earth's magnetic field. If oceanic crust is formed over a convective up-current in the mantle, then the newly formed crust will be magnetised in the direction of the Earth's field which existed at that time. Assuming the whole of the oceanic crust is comparatively young, probably not older than 150 my., the thermo-remnant component of its magnetisation is therefore either essentially normal, or reversed with respect to the present field of the Earth.

Thus, if spreading of the ocean floor occurs, blocks of alternately normal and reversed magnetised material would drift away from the centre of the ridge and parallel to the crest of it. In this way Vine and Matthews overcome the problem of high susceptibility contrasts between adjacent blocks without recourse to major inhomogeneities of rock type within the main crustal layer, or to unusually strongly magnetised rocks.

The problem of high magnetisation contrast was emphasised by Vine and Wilson (1965) and shown to exist by Bott (1967) across the Juan de Fuca Ridge. In Bott's detailed interpretation he demonstrates that the anomalies cannot be accounted for in layer 3 alone, but could be explained entirely by magnetic material in layer 2. However, the contrast in the intensity of magnetisation
must be in the order of \(0.02 \text{ e.m.u.}/\text{cm}^3\). Rocks as highly magnetic as this are extremely rare, and therefore it seems essential to invoke reversals in the direction of magnetisation as suggested in the Vine and Matthews hypothesis. The model proposed by Bott layer 2 also shows a conspicuous symmetry about the centre of the Juan de Fuca Ridge, supporting the hypothesis that the anomalies are caused during the process of ocean-floor spreading in both directions from the centre.

Nevertheless, criticism of the Vine and Matthews hypothesis has been expressed by Talwani et al. (1965) with regard to the magnetic survey results of the Reykjanes Ridge off south-west Iceland, and from several other profiles across the Mid-Atlantic Ridge further south. It appears that the magnetic anomalies which parallel the Mid-Atlantic Ridge can be subdivided into two types - those along the axial zone of the ridge, and those along the flanks of the ridge. The axial zone of the ridge is characterised by a single large anomaly or by a very striking pattern of almost constant wavelength, the amplitude being greatest at the crest and decreasing symmetrically either side. In contrast the anomalies over the flanks of the ridge have a longer wavelength than the axial anomalies, show no diminution in amplitude away from the ridge, and are generally not as regular in shape as the axial anomalies. However, it
appears that the flank anomalies are also linear, though their linearity is not always as pronounced. As a result of the flankward diminution in amplitude of the axial anomalies and the difference in character between flank anomalies and axial anomalies, Talwani maintains that the Vine and Matthews hypothesis is untenable, at least in its present form.

A more serious objection to the Vine and Matthews hypothesis results from the extension of the Reykjanes Ridge survey into Iceland which was completed by the Magnetics Division of Dominion Observatory in 1966. The anomaly pattern found by Heirtzler et al. (1966) along the Reykjanes Ridge shows a straight central axis, the A magnetic zone, and about 80 km to each side are the B magnetic zones, termed by Einarsson (1967) B_w (western) and B_e (eastern), Fig.4.1. The measurements by Dominion Observatory enable one to trace the A zone from Reykjanes Ridge to the Reykjanes peninsula where a major offset of the anomaly occurs to the east, mapped in detail by Sigurgeirsson (1967), before continuing in a straight north-east direction across Hengill, Thingvellin and Langjökull. As pointed out by Einarsson, the A magnetic zone in Iceland is associated with short parallel volcanic fissures in Reykjanes, and a 20 km wide post-glacial volcanic and tectonic belt to Langjökull. In a similar way the B_e anomaly can be traced towards
Fig. 4.1 Magnetic Anomalies in and S.W. of Ireland (Sersen et al. 1966)
The Correlations of Anomalies A and B are by Birarsson (1967)
Iceland until it reaches the shelf off Selvogsbanki where a major jump to the east occurs similar to that in Reykjanes. Recent volcanic activity is known at the eastern end of this offset, namely in the presently active Surtsey, and in the many craters of the Westmann Isles. After resumption of its normal course the $B_e$ anomaly corresponds to the main recent volcanic zone in Iceland. The $B_w$ anomaly extends across submarine hills, whose nature is unknown but thought by Einarsson to be remnants of volcanoes, and continues straight to the great post-glacial volcano Snaefellsjökull. Thus, the main anomalies, $A$, $B_e$, and $B_w$, seem unmistakably to correspond with the three recent volcanic zones of Iceland. Einarsson therefore maintains that this refutes the suggestion by Pitman (1966) and the hypothesis of Vine and Matthews that the symmetric array of anomalies is caused by drift away from a central axis. By relating low magnetic anomalies to known Earth field reversals Pitman suggests that the $B$ anomalies are about 8 my old, whereas most probably they are of recent age. The story is complicated still further by a strontium isotope date of a basalt lava near Borganes of $13.2 \pm 2.0 \text{ my}$. (Sigurdsson and Moorbath, personal communication). This age date is from a sample about half-way between the $A$ anomaly zone and the $B_w$ anomaly on the west coast of Iceland, but according to Pitman the date should have been about 4 my. Thus, if Einarsson's extrapolations are correct Pitman's dating
of the magnetic anomalies for the Reykjanes Ridge is not only unlikely for the so-called B anomaly, but also for the intermediate anomalies nearer the A zone. Consequently, any estimation of drift rate based on known magnetic reversals must presumably be suspect.

Einarsson's work implies that the Dietz (1961) and Hess (1960) hypotheses for the formation of oceanic crust from a narrow zone on the crest of a mid-ocean ridge must now be regarded with some doubt, and that multiple intrusion of dykes over a large area must be considered as a distinct possibility.


At the time Vine and Matthews proposed their hypothesis for the origin of ocean magnetic lineations, knowledge of such features was restricted to the North-East Pacific, parts of the Mid-Atlantic Ridge and the Carlsberg Ridge in the Indian Ocean. Each of these areas show remarkably uniform and continuous anomalies only terminated by distinct cross-faults, later termed transform faults by Wilson (1965). However, since then magnetic surveys have been done in the North-West Pacific, over the Nansen-Amundsen Basin in the Arctic Ocean, the Norwegian Basin in the North Atlantic, as well as several other smaller areas. The importance of these more recent surveys is that they demonstrate
a far greater variety of ocean magnetic anomalies than was previously supposed.

In the Nansen-Amundsen Basin magnetic lineations exist, but as pointed out by Demenitskaya (1965) the degree of linearity of the anomalies is somewhat lower than in the North-East Pacific. The anomalies are less continuous, variable in width, and not always parallel to the Mid-Arctic Ridge. In the North-West Pacific the anomalies have a uniform trend but appear even more discontinuous than in the Arctic. It seems, therefore, that either the oceanic crust in these two areas is relatively old and has been subjected to later volcanic and tectonic phases, or that the hypothesis of formation of oceanic crust along a single median fissure is perhaps an over-simplification.

Possibly the most unusual oceanic area is the Norwegian Basin surveyed by the U.S. Oceanographic Office, Fig.4.2. The M.G.S. bathymetric charts show that the Norwegian Basin has a depth of about 2000 fm and is limited in the west by the South Jan Mayen Ridge, in the east by the Norwegian avant-shelf or Helgeland Plateau, in the north by the Mon Ridge which is that part of the Mid-Atlantic Ridge joining Jan Mayen and the Svalbard continental rise, and in the south by the Iceland-Faeroes Rise. The basin is further characterised by a linear north-south basin and knoll
Fig. 4.2 Magnetic anomalies over the Norwegian Sea (U.S. Naval Oceanographic Office)
province, the aseismic Pinro volcanorium, situated approximately
down the centre of the Norwegian Sea. The results of the
aeromagnetic survey of the Norwegian Sea show elongate anomalies
or discontinuous lineations parallel to the trend of this median
feature, which seems to give strong support to the suggestion of
Demenitskaya and Dibner (1965) that the Pinro volcanorium represents
a transverse branch of the Mid-Atlantic Ridge which is now no
longer active. The magnetic features in the Norwegian Basin
are separated from the anomalies associated with the active Mid-
Atlantic Ridge between Iceland and Jan Mayen by the relatively
non-magnetic South Jan Mayen Ridge and North Iceland Basin. The
importance of this hypothesis is that the idea of a single source
for the formation of oceanic crust must again be regarded with
some suspicion.

A requirement of the Vine and Matthews hypothesis is that
the magnetic lineations in the ocean should be parallel to the
mid-ocean ridge system. Although this seems to be valid in the
majority of cases exceptions to this rule do occur particularly
in the North Atlantic. The lineations on the Reykjanes Ridge
as mentioned previously can now be traced into Iceland where the
lineations complete a series of offsets towards the east, but remain
essentially parallel to the Mid-Atlantic Ridge. The lineations
nearer Rockall surveyed by the U.S. Naval Oceanographic Office are also parallel to the ridge, but then swing towards the ridge when approaching the Iceland-Faeroes Rise, Fig.4.3. Consequently, the total effect is for the lineations to the east of the Reykjanes Ridge and south of Iceland to be systematically terminated off eastern Iceland. Pitman has tried to explain such non-parallelism by varying the rate of formation of oceanic crust along the axis of the ridge, Fig.4.4. However, such an hypothesis would cause either deformation of pre-existing crust or migration of the mid-ocean ridge. Alternatively, crustal extension could occur in areas considered to be oceanic by a process very different from that proposed by Hess and Dietz.

Another striking example of ocean anomalies not being parallel to the mid-ocean ridge is along the Mon Ridge. Here the so-called flank anomalies are parallel to the ridge but what might have represented the axial anomaly zone instead of having a uniform strike along the crest of the ridge, about 070°, the anomalies are irregular with a tendency to align in an almost north-south direction. The anomalies in this area give the impression of very complex volcanic activity far removed from the single median fissure hypothesis.

However, perhaps the most difficult area to account for by the Vine and Matthews hypothesis is the Lofoten Basin which represents a
Fig. 4.3 Magnetic anomalies associated with the Reykjanes Ridge and the Iceland-Faeroes Rise.
a large V-shaped depression in the continental rise of western Europe separating the Svalbard Rise from the Norwegian Plateau. The Lofoten Basin has an average depth of about 1700 fm. and is characterised by a very marked series of magnetic lineations almost at right angles to the continental margin, whereas both the Svalbard Rise and the Norwegian Plateau are relatively non-magnetic. The total width of the area containing magnetic lineations within this basin is in the order of 100 miles. If the Vine and Matthews hypothesis for the origin of ocean magnetic anomalies is valid for this region it would mean that the continental rise must separate from a central line and move a considerable distance to the north and the south. Evidence for such large scale displacements is not apparent either in northern Norway or on the Norwegian shelf.

It appears therefore, that although the Vine and Matthews hypothesis seems adequate for the more regular magnetic lineations of the type identified in the North-East Pacific, the less uniform lineation recently discovered in many other oceanic areas are more difficult to explain. On evidence from the Arctic, the North-West Pacific, and particularly the Norwegian Sea it is suggested that more than one line for the formation of oceanic crust may exist, and that the non-parallelism of many lineations to the mid-ocean ridge is difficult to account for.
purely by a differential rate in the spreading of ocean floor as suggested by Pitman. Finally, in the case of the Lofoten Basin, magnetic lineations occur but there is no evidence of lateral movements in the direction envisaged by Vine and Matthews.

4.3. Ocean Magnetic Lineations and the Rate of Ocean-floor Spreading.

If one assumes that the Hess and Dietz hypothesis for the formation of ocean crust is correct and that the Vine and Matthews hypothesis for the origin of ocean magnetic lineations is tenable for the majority of oceanic areas, then as pointed out by Vine (1966) the pattern of anomalies should represent the entire history of the ocean basins. However, to interpret these patterns it is necessary to make certain assumptions on the rate at which the ocean-floor is spreading.

Recently the evidence indicating possible reversals of the Earth's field has been examined more critically and a periodicity has been suggested by Cox et al. (1964) for the past 4 my. With this information Vine and Wilson attempted to verify the original suggestion of Vine and Matthews by calculating the rate of drift required to explain the anomalies across a young and active ocean ridge. On the assumption that there have been major reversals of the Earth's field at 1, 2.5 and 3.4 my, and short-lived reversals at about 1.9 and 3 my,
it was estimated that an average rate of spreading of approximately 1.5 cm/yr. could account for the anomaly distribution associated with the Juan de Fuca Ridge, which closely corresponds to the commonly suggested rates of 1-2 cm/yr.

This technique was then applied by Pitman et al. to the Pacific-Antarctic Ridge and the Reykjanes Ridge in the Atlantic. The remarkable symmetry of the profiles across both these ridges suggested that the Vine and Matthews hypothesis could again be tested by a similar method to that proposed by Vine and Wilson. Thus, assuming a uniform spreading rate and using the known history of magnetic reversals a drift of 4.5 cm/yr. was estimated for the Pacific-Antarctic Ridge, and 1 cm/yr for the Reykjanes Ridge.

Nevertheless, the difficulties of relating magnetic anomalies to reversals of the Earth's field still remains a somewhat ambiguous problem. In order to demonstrate the reliability of this technique it is necessary to try to date independently the age of each lineation. The only place that this has been attempted is in Iceland, where as mentioned previously there appears to be no correlation between the ages suggested by Pitman based on the Vine and Wilson method and the ages of exposed rocks noted by Einarsson and dated by strontium
isotope techniques by Sigurdsson and Moorbath. Consequently, this method of estimating rate of spreading of ocean-floor must be regarded as doubtful and unreliable.

Another criticism of the Vine and Wilson method concerns the assumption made on the direction of drift - when estimating the rate of spreading it is always assumed that the formation of ocean crust is essentially at right angles to the crest of the mid-ocean ridge. Fig. 4.4 is reproduced from the article by Pitman designed to show how spreading from non-parallel axes of a ridge e.g. the junction of the Juan de Fuca and the Gorda ridges, can produce a disturbed area. The arrows indicate the direction of formation of ocean crust. However, a more reasonable explanation for such a configuration would be similar to that proposed by Wilson (1965) where he suggests that the motion along the ridge can combine both rifting and shearing i.e. the direction of ocean-floor spreading can be at an oblique angle to the crest of the ridge. Therefore, assessment of the rate of drift should not necessarily be made perpendicular to the magnetic lineations as this can only provide the minimum rate of spreading.

On a larger scale it has often been pointed out that not only is there a striking correlation between the continental margins
Fig. 4.4 Formation of Non-parallel Magnetic Lineations according to Pitman (1966)
around the Atlantic, but also the Mid-Atlantic Ridge follows very much the same configuration. It appears, therefore, that as well as Europe having drifted to the east relative to North America, Europe has also moved eastwards with respect to the Mid-Atlantic Ridge. This is supported by the distribution of earthquakes in Iceland which according to Stefanson (1967) also suggests east-west tension. Thus, the Reykjanes Ridge may represent a section where a shearing as well as a rifting motion has occurred during the formation of oceanic crust. The strike of the crest of the Reykjanes Ridge is about $040^\circ$ and so if the direction of drift has been east-west the rate of spreading may be as high as 1.3 cm/yr rather than 1 cm/yr as suggested by Pitman, assuming drift at right angles to the ridge. This compares well with the average east-west drift rate of 1.2 cm/yr for eastern Iceland estimated by Sigurdsson and Moorbath.

From this brief criticism it is evident that the present methods of estimating the rate of ocean-floor spreading may have several defects and ambiguities which complicate the interpretation of the magnetic lineation patterns that exist in many oceanic areas. The history of ocean basin evolution is confused still further by the distinct possibility that the spreading of the sea floor is an intermittent process. On the basis of an abrupt change in sediment thickness between the crests and flanks of the mid-ocean
ridges it is suggested by Ewing et al. (1967) that the present cycle of spreading commenced around 10 my ago, following a long period of quiescence during which most of the observed sediments were deposited. Another difficulty is created by the likelihood of different rates of formation of oceanic crust either side of a ridge - the Bay of Biscay may perhaps be sighted as an example of this phenomena. Continental reconstructions of western Europe often include the northern margin of Spain adjacent to the Atlantic seaboard of France, and the magnetic lineations identified by Matthews support the idea of rotation of Spain with the assymmetric production of oceanic crust from the foot of the continental rise off France.

4.4. Discussion

In this chapter an attempt has been made to apply current ideas of ocean basin evolution to areas where magnetic surveys have only recently been completed. As a result it appears that many of the assumptions made during the interpretation of magnetic lineation patterns may be suspect, particularly the belief that ocean crust is formed from a single median ridge. Evidence for separate but parallel fissures mutually involved in the formation of oceanic crust exists in Iceland and perhaps along the Reykjanes Ridge, and also along the Mon Ridge where elongate magnetic anomalies give a distinct en echelon appearance.
In addition it has been indicated that the degree of linearity of the anomalies in the Nansen-Amundsen Basin and the North-West Pacific is lower than in the North-East Pacific and several other areas, but that perhaps the most anomalous oceanic areas so far surveyed are the Norwegian and Lofoten Basins. The problems of larger lateral displacements required by the Vine and Matthews hypothesis to explain the magnetic lineations in the Lofoten Basin has already been discussed.

Thus, one has the situation whereby the occurrence of parallel volcanic fissures seem a feasible possibility, plus the existence of ocean magnetic lineations where lateral displacements appear to be minimal. Attention might also be drawn to the gently dipping continental slope between Norway and the Shetlands where the degree of linearity of the magnetic anomalies appears to increase from the 'cluster' type anomaly common on the shelf to the reasonably continuous lineations that occur at the foot of the continental rise. It is therefore suggested that lineations may also be produced by a series of parallel fissures controlled partly by the current stress field and partly by structural lines of weakness already existent within the basement. The implication of such an hypothesis is that the formation of the ocean basins beneath the Norwegian Sea may be caused by multiple intrusive activity into an initially continental crust. The effect of such
intense volcanic activity over a large area would be to produce a certain amount of lateral displacement, and perhaps also crustal deformation in the vertical sense.

Consequently, the mode of formation of the Lofoten Basin and perhaps the Norwegian Basin may represent an intermediate geological process between the method of formation of the North Sea where no lateral displacements are evident, and the more typical ocean basin formed in accordance with the Hess and Dietz hypotheses.
CHAPTER 5

GRAVITY AND MAGNETIC INTERPRETATION OF THE ICELAND-FAEROES RISE

5.1 Introduction

The Iceland-Faeroes Rise is a strong topographic feature in the North-East Atlantic characterised by a relatively steep slope to the north-east and a gradual slope to the south-west. This aseismic rise provides a natural boundary between the Norwegian Basin and the abyssal plains of the main Atlantic Ocean, and forms a shallow water region from the Mid-Atlantic Ridge towards the continental margin of Europe.

A considerable amount of geological and geophysical evidence has been obtained from Iceland and Faeroes during recent years, but little is known of the rise linking these two islands. With this view in mind a marine gravity and magnetic survey of the Iceland-Faeroes Rise by R.R.S. John Murray was organised by the Geology Department, Durham University during May/June 1967. The survey equipment included an Askania-Graf Gss-2 gravimeter kindly loaned by the Department of Geodosy and Geophysics, Cambridge University, and a Varian magnetometer owned by the Natural Environmental Research Council. Also a compilation of magnetic data relating to the Iceland-Faeroes Rise has been made, and includes part of the aeromagnetic results of the Norwegian Sea.
completed by the U.S. Naval Oceanographic Office and the aeromagnetic map of the Reykjanes Ridge (Heirtzler et al, 1966).

The purpose of this project has been to provide information on crustal variations along the rise, and to ascertain limits on the physical nature of the upper mantle beneath the rise. The magnetic data has been used to assess variations in the intensity of magnetisation within the crustal rocks, and to study the change in structural fabric from south-west of the rise across to the Norwegian Basin.

5.2 Previous Hypotheses and Research related to the Origin of the Iceland-Faeroes Rise

The Iceland-Faeroes Rise was considered by Th. Thorodson (1906) and many other geologists of this period to be a product of a once large, continuous volcanic landmass that stretched across the North Atlantic from Scotland to Greenland during the early Tertiary. After a pause in volcanic activity characterised by lignite formations, regional subsidence occurred which was believed to be complete by the late Miocene except for Iceland, the Faeroes and the basalt areas of Scotland and Greenland. The phase of recent activity was thought to have started in early Pliocene, and be confined to a narrow belt across Iceland.
Since that time a considerable amount of geological and geophysical knowledge has become available. One of the more recent hypotheses for the formation of Iceland and Faeroes assumes the pre-existence of an Atlantic Ocean, and then subsequent submarine volcanic activity at the beginning of the Tertiary built thick piles of low density pyroclastics upon the ocean floor. This hypothesis was introduced by Einarsson (1960, 1963) to explain the large gravity low over the centre of Iceland, and a similar idea was expressed by Saxov and Abrahamson (1964) and supported by Noe-Nygaard (1966) to account for the gravity low situated in the north-west of Faeroes. However, it is now clear from research on Surtsey and on the submerged flanks of the Hawaiian Islands, that the initial phase of submarine eruptions is pillow lava. Production of low density tephra, scoria or pyroclastic material does not normally begin until just below the sea level (Sigurdsson, 1967).

Wilson (1965) includes the Iceland-Faeroes Rise in his hypothesis for the formation of lateral ridges by continental drift. On the assumption that the position of Iceland has been a 'hot-spot' on the Mid-Atlantic Ridge throughout the period of drift, then the rise represents a trail of extinct volcanoes that were initially formed within Iceland along the
zone of present volcanic activity. This is similar to the Bodvarsson and Walker (1964) hypothesis for Iceland, whereby dyke injection along the central volcanic belt has wedged the east and west halves of Iceland apart with time, whilst younger rocks have been continually forming in the middle. This drift hypothesis is supported by stratigraphic evidence in Iceland (Walker, 1959), and isotope dating in eastern Iceland where the ages increase systematically from the active zone to a maximum of 12.5 my on the east west, (Sigurdsson and Moorbath, 1968). The age date for Faeroes using a similar isotope method is given by Tarling and Gale as about 50-60 mybp. (Personal communication).

To verify these hypotheses it is essential to have detailed knowledge of the chemical and physical state of the crust and upper mantle. In this connection it is of interest that acid rocks make up an estimated 10-12% of the exposed Tertiary plateau in eastern Iceland (Walker, 1959). If this figure is representative of the volume of Tertiary rocks then such a high proportion is difficult to explain by differentiation of a basic magma as only 2-5% acid residuum as normally produced by this process, and if Carmichael's (1964) theoretical maximum of 7-12% was reached then evidence of such thorough extraction should be obvious in the basalt lavas. Consequently, a relatively old sialic layer within the crust of Iceland has been suggested
(Walker, 1965). Unfortunately, the geochemical approach has not proved conclusive as isotope studies using the \( \text{Sr}^{86}/\text{Sr}^{87} \) ratio suggests a common origin for the acid and basic fractions as both types have identical ages, (Moorbath and Walker 1965, Moorbath and Bell 1965, Heier et al 1966, Sigurdsson 1967).

The majority of seismic refraction work in Iceland has been aimed at defining the upper part of the crust to a depth of 5-10 km. (Palmason, 1967). This method has been able to identify what is thought by Palmason to represent the distribution and thickness of the Quaternary volcanics, and the upper and lower parts of the Tertiary Basalts, but so far only a 253 km. long profile by Båth (1960) in western Iceland has been capable of defining the thickness of the so-called layer 3. Båth's interpretation suggests that the base of this layer is at a depth of 18 km. - the discontinuity being defined by an increase in P-wave velocity from 6.7 km/sec. to 7.38 km/sec. Seismic refraction profiles in the Faeroes have identified layers with velocities of 3.9 km/sec., 4.9 km/sec. and 6.4 km/sec. (Palmason, 1965). The two lower velocities have been related to stratigraphic horizons within the basalt sequence, but again the nature of the high velocity layer is unknown.
Finally, satellite results show a broad gravity high across the whole of the North Atlantic, which together with Ewing and Ewing's (1959) seismic refraction results indicate the possibility of anomalous upper mantle beneath the Norwegian and Greenland Basins and perhaps further south.

It is evident from this summary that there exist two extreme schools of thought on the structure of this area. Either Iceland, Faeroes and the intermediate rise have strong continental affinities, in which spreading within these three units must be minimal, or that the crust is closer to oceanic in character and that the topographic features are produced by anomalous material in the upper mantle. If the latter is true then one might expect normal ocean-floor spreading which should be reflected in the magnetic anomaly patterns. However, although the exposed areas of Iceland and Faeroes both exhibit Tertiary lavas it is feasible that the deep-structures of these two areas, and perhaps the rise, may all be quite different. If this is the case then obviously lateral changes in density must exist which should produce observable gravity anomalies across the transitional zones. Consequently, gravity and magnetic techniques might provide a useful means for identifying individual structural units and for studying the geological history of this area.
5.3 Interpretation

The gravity results obtained on the R.R.S. John Murray cruise are presented as a provisional contoured Free-Air anomaly, map with a contour interval of 10 mgal, Fig.5.1. Many of the anomalies are obviously related to large changes in the depth of water, and so the contouring has taken advantage of the known bathymetry as compiled by the National Institute of Oceanography. The Free-Air anomaly map shows a gravity high along the full length of the rise, but superimposed upon this high are three further features of particular interest:-

(i) The large negative anomaly centred over Iceland (Einarsson, 1954) appears to terminate along the 100 fm. line which delineates the shelf edge off eastern Iceland.

(ii) The 100 fm. line defining the edge of the Faeroes block is associated with a gravity high particularly along the northern and western margins.

(iii) The gravity features on the rise do not align themselves either parallel or perpendicular to its axis. The dominant trend on the south-western limb of the rise is N.N.W.-S.S.E., and the anomalies then swing to almost E-W on the steep north-eastern limb.
This apparent swing in structural trend across the rise is supported very clearly by the Norwegian Sea aeromagnetic results, Fig. 4.2, the direction of the magnetic lineations following very closely the direction of the gravity features. The fact that this swing in the geophysical trends is localised to the rise itself is obviously important when considering the origin and geological history of the Iceland-Faeroes Rise. The aeromagnetic results also illustrate the very different character of the magnetic anomalies either side of the rise. To the south-west of the rise the magnetic lineations are continuous although variable in width, whereas to the north-east in the Norwegian Sea the lineations form rather discontinuous features.

With regard to the Faeroes block it is now obvious that the gravity anomaly over the Faeroe Islands as identified by Saxov and Abrahamson (1964) is part of a very much larger feature effecting the whole north-western half of the block. Again this is supported by the aeromagnetic results which show high frequency anomalies in the north-west of the Faeroes block, and surprisingly long wavelength anomalies in the south-eastern part. It is of interest that these two halves of the block are separated by a series of magnetic anomalies with a strike direction of about 045° which appears to correspond with the eastern limit of the gravity low.
From this brief description of the gravity and magnetic anomalies it is apparent that the geology of the Iceland-Faeroes Rise is far more complicated than previously supposed. The gravity evidence indicates that there are fundamental differences in the deep-structures of Iceland, Faeroes and the intermediate rise, and that the gravity together with the magnetics suggest differences in the nature of the crust and perhaps the upper mantle either side of the rise as well as beneath the rise itself. Consequently, the formal interpretation of this data has concentrated on the transition from Iceland and the Faeroes onto the rise, and the structure of the Iceland-Faeroes Rise in relation to the Norwegian Basin and the eastern Atlantic.

5.3.1 Gravity

Shelf Edge off Eastern Iceland: The interpretation of the gravity anomaly observed across the shelf edge of eastern Iceland is made difficult by the lack of seismic control. However, a seismic refraction line by Palmason (personal communication) on the shelf of south-east Iceland has identified a high velocity layer of 7.15 km/sec. at a depth of 13 km. This line was shot a few miles off the coast between approximately Alvidruhamrov (18.4°W) and Breidamerkurdjup (15.8°W), and these results are
supported by a similar line on land. Båth (1960) had previously discovered a slightly higher velocity layer of 7.38 km/sec. near the centre of Iceland at a depth of 17.8 km. This suggests that the lower velocity layers, in particular the 6.4 km/sec. layer (Palmason, 1967) are perhaps being systematically phased out by the 7.15 km/sec. layer rising from the centre of Iceland towards the coast. The 7.15 km/sec. layer may be a new intermediate velocity zone, or may be interpreted as synonymous with the 7.38 km/sec. layer.

No direct density measurements have been attempted for these higher velocity layers, but the velocity - density curve published by Nafe and Drake (1963) suggest that a density contrast of 0.2 gm/cc can be expected between the seismic layers of 6.4 km/sec. and 7.15(7.38) km/sec. If the depth to this discontinuity does in fact decrease from 17.8 km. to 13 km. on the coast, then assuming a density contrast of 0.2 gm/cc this could produce a gravity anomaly of about 40 mgal. The observed Bouguer anomaly across the relevant part of Båth's line is approximately 10 mgal, whereas the observed anomaly value on the coast of south-east Iceland near Palmason's refraction line is about 45 mgal (Einarsson, 1954). The difference between these two values compares quite well with the estimated 40 mgal.
It seems feasible, therefore, that the change in depth to the base of layer 3 (6.4 km/sec.) might be the major contributor to the large negative anomaly situated over Iceland. If this hypothesis is correct then one might expect a high velocity layer near the shelf edge off eastern Iceland at a depth of about 10 km where the value of the Free-Air anomaly is about 70 mgal.

Consequently, the observed gravity anomaly across the shelf edge off eastern Iceland between latitude 65°19' N, longitude 12°45' W and latitude 65°35' N, longitude 11°10' W has been interpreted on the assumption that the anomaly is due to variations in the thickness of the lower velocity layers, and that a density contrast of 0.2 gm/cc exists with the 7.15(7.38) km/sec. layer beneath. Using an approximation of the bathymetric profile as the top surface of the model and a thickness of 10 km for the low velocity layers on the shelf edge, the inclination of the base of the model was adjusted until a good fit was obtained between the calculated and observed anomalies, see Fig. 5.2a.

It must be stressed, however, that the model proposed in this diagram should not be regarded as a quantitative interpretation.
Nevertheless, it illustrates that the shelf edge of eastern Iceland does not delineate a major, abrupt change in the deep-structure between Iceland and the Iceland-Faeroes Rise. The shelf edge may represent the termination of either an inclined low-angle discontinuity or possibly a systematic increase in density of an individual layer or layers away from the centre of Iceland.

Iceland-Faeroes Rise: The single gravity line made at right angles to the Iceland-Faeroes Rise from latitude 64°23' N longitude 5°45' W to latitude 61°38' N, longitude 13°02' W has proven the existence of a 60 mgal positive anomaly over the crest of the rise. Assuming the area is in isostatic equilibrium in accordance with Airy's hypothesis, isostatic models can be constructed using the bathymetric profile as the top crustal surface together with Ewing and Ewing's (1959) estimate of a 5 km thick crust in the Norwegian Basin as a control. The anomalies due to such models can be calculated and then compared with the observed Free-Air anomaly.

As mentioned previously there are two extreme views on the structure of the Iceland-Faeroes Rise - either the feature is due to a thickening of the crust or it is due to the effect of thin crust and anomalous upper mantle. Assuming densities of
1.03 gm/cc for sea water, 2.87 gm/cc for crust, 3.40 gm/cc for normal upper mantle and 3.30 gm/cc for anomalous upper mantle, the model representing a thickened crust produced an anomaly of about 30 mgal which is less than the observed anomaly (Fig. 5.3a), whilst the anomalous upper mantle model gave an anomaly of over 90 mgal which is far greater than the observed, (Fig.5.4a.)

In order to improve the fit between the calculated and the observed Free-Air anomaly it is necessary to alter the models without adjustments for isostatic compensation. For the model with a thickened crust the depth to the base must be decreased (Fig.5.3b), whilst in the second model the depth to the base of the anomalous upper mantle must be increased (Fig.5.4b).

Consequently, if either of these extreme models are correct then it would seem that the Iceland-Faeroes Rise may not be in isostatic equilibrium. Alternatively, if the Iceland-Faeroes Rise is in isostatic equilibrium in accordance with Airy's hypothesis then a slightly thickened crust together with a relatively thin layer of anomalous upper mantle would appear to be the most likely structure.
Fig. 5.3a. Iceland-Faeroes Rise: Isostatic Model for the Crust

Fig. 5.3b. Iceland-Faeroes Rise: Improved Model for the Crust
Fig. 4a. Iceland-Faeroes Rise: Isostatic Model for Crust and Anomalous Upper Mantle.

Fig. 5a. Iceland-Faeroes Rise: Isostatic Improved Model for Crust and Anomalous Upper Mantle.
Shelf Edge off western Faeroes: As mentioned previously a large gravity high characterises the northern and western margins of the Faeroes block. Several geophysical profiles have been made across this feature but the line selected for this interpretation is the one completed by H.M.S. Hecla between latitude 62°46' N, longitude 9°00' W and latitude 62°09' N, longitude 8°05' W, see Fig.5. The Bouguer anomaly values given in this diagram show a gravity low of 20 mgal over the rise, a gravity high of about 65 mgal over the margin and a very steep gradient of about 4 mgal/km down to about 4 mgal on the Faeroes block. The important characteristics of the magnetic anomaly profile are the far longer wavelength anomalies over the rise compared with the highly irregular anomalies on the Faeroes block.

The shortest conspicuous wavelength for the magnetic anomalies on the block is about 250 m, the corresponding peak to peak amplitude being 150 gamma. Using the general solution of Laplace's Equation in two-dimensions for estimating the maximum depth to a magnetic body (Bott and Stacey, 1967), at a depth of 250 m the peak to peak amplitude of this anomaly would be about 81000 gamma which is much larger than would be expected for the most highly magnetised rocks except iron ore. This shows that the source of the magnetic rocks must be very
close to the seabed which is here about 120 m deep. However, on the rise, although the anomalies would be attenuated because of the increase in depth of water to about 500 m, small irregularities would be expected if the highly magnetic rocks cropped out, and these are not observed. Therefore, any highly magnetic rocks that might exist beneath the seabed at the north-western end of the profile must be at some considerable depth, presumably covered by unconsolidated or semi-consolidated sediments. A thick sedimentary sequence at this end of the profile could explain the observed gravity low, but the low over the block cannot be explained by surface sediments as magnetic (igneous) rocks must be very close to the seabed.

In order to explain the steep gradient at the south-easter end of the profile the gravity anomaly has been computed across a series of models representing a change in crustal density between the rise and the Faeroes block. The depth to the base of the model has been varied and density contrasts of 0.3 to 0.5 gm/cc were assumed across a vertical interface. The results from these test models suggest that low density material must exist within the Faeroes block at a depth of less than 5km. Consequently, there appears to be a marked difference in the physical properties of the crust beneath the rise and the crust
forming the Faeroes block. It is most unlikely that the crustal structure of Faeroes is of typical oceanic type.

5.3.2 Magnetic

In the Dietz (1961) and Hess (1962) hypotheses the crest of a mid-ocean ridge is a place of injection of new crust, such that the ocean-floor is spreading away from the ridge axis. As new dykes are intruded they obtain the magnetisation of the geomagnetic field at the time they cool through the Curie temperature. However, the Earth's field has been shown to have frequently reversed its polarity during late Tertiary and Quaternary (Cox et al., 1963) and so the ocean crust has acquired strips of alternately polarised crust which give rise to a series of linear positive and negative anomalies which parallel, and are symmetrically about the ridge crest where they were created (Vine and Matthews, 1963). If this hypothesis is correct then the pattern of ocean magnetic anomalies should help considerably in evaluating the sequence of events in the development of an oceanic area.

The application of this method to the Iceland-Faeroes Rise is difficult as the rise is featured by an extremely complex pattern of magnetic anomalies that appears to be quite distinct from the anomaly patterns to the north and the south. The anomalies
over the Norwegian Basin to the north of the rise form a series of elongate, approximately parallel features which terminate along a W.N.W.-E.S.E. line at the foot of the north-east limb of the rise. The anomalies in the south are more continuous but vary considerably in width, particularly near the rise where the lineations systematically neck out off eastern Iceland. The lineations on the rise itself are complicated by high frequency variations, but it seems that the south-western half of the rise is dominated by N.N.E.-S.S.W. features, especially at the southern end, whereas the north-eastern half appears to be dominated by N.E.-S.W. features sometimes swinging to almost E-W. Each of these areas show quite distinct anomaly patterns suggesting perhaps quite different modes of formation, and certainly a very complex history for the evolution of the Iceland-Faeroes Rise.

Nevertheless, Avery et al (in press) have analysed the results of the aeromagnetic survey of the Norwegian Sea and propose that there have been three separate phases in its history of normal ocean-floor spreading. The method used by Avery for interpreting the sequence of events associated with the production of ocean crust from the Mon Ridge is based upon a model developed by Heirtzler et al (in press), Pitman et al (in press), and Dickson et al (in press) utilizing a detailed
history of magnetic field reversals. By comparing this standard model with various magnetic profiles across the Mon Ridge and Lofoten Basin it appears that the initial episode of spreading lasted from 60-49 mybp at a rate of 1.4 cm/yr. A second period of spreading seems to have lasted for 20 my assuming a spreading rate of 1.0 cm/yr. This phase may or may not have been continuous with the first spreading episode, but prior to the final period of spreading 10-15 mybp Avery suggests that a long period of quiescence occurred during which extensive sediments were deposited in the Norwegian Basin.

The magnetic anomaly pattern between Jan Mayen and Iceland, and across to Norway, presents a more complicated picture. However, it appears that ocean-floor spreading probably began between 60-70 mybp and that a distinct phase in the spreading commenced along the Iceland-Jan Mayen Ridge about 10 mybp (Vogt and Ostenso, in press)

The anomalies to the south of Iceland and Faeroes have not been compared with a standard model, but there seems to be three areas with very different anomaly patterns (Fig.4.3) To the south-west of the Iceland-Faeroes Rise as mentioned previously there exists an area of well-developed lineations of variable width
and strike. The area to the west of this is characterised by a regular series of lineations with a constant strike direction of $040^\circ$. These lineations appear similar in every respect to the lineations described by Heirtzler et al (1966) on the flanks of the Reykjanes Ridge and are considered to be both part of the same event. The third area is the axial anomaly zone along the crest of the Reykjanes Ridge thought to have been active during the last 10 my (Pitman et al, 1966).

The age of the Faeroes as mentioned previously is about 50-60 mybp and the age of Rockall is about 55-60 mybp (Miller and Mohr, 1965), and so it appears that although the anomaly patterns to the north and south of Iceland and Faeroes are in many ways very different, the possibility arises that both areas were involved in the same major events.

However, the axis of the Iceland-Jan Mayen Ridge is assymetrically located near the coast of Greenland. Johnson and Heezen (1967) attempt to explain this characteristic by assymetrical spreading combined with at least one shift in location of the axis of the mid-ocean ridge. They cite the presence of the sedimentary Southern Jan Mayen Ridge extending southward from the island of Jan Mayen as indicative of a ridge axis once located east of this ridge shifting to the west and
separating the Southern Jan Mayen Ridge from continental Greenland. A similar hypothesis was proposed by Demenitskaya (1965) suggesting that the north-south orientated Pinro volcanorium in the centre of the Norwegian Basin represents an extinct mid-ocean ridge now substituted by the seismically active belt between Iceland and Jan Mayen. Vogt and Ostenso (in press) prefer symmetrical spreading about each of several rifts succeeding each other, so that none necessarily bisect the present ocean basin.

Consequently, the area including Iceland, Faeroes and the Iceland-Faeroes Rise appears to represent the dividing line between the following geophysical features:-

(1) The well-developed lineation patterns to the south of Iceland and Faeroes differ considerably with the discontinuous anomaly features in the Norwegian Basin. This suggests that although both areas have probably been active at similar times the mode of formation of crust could vary, i.e. in the north migration of the 'mid-ocean' ridge may have occurred, whereas in the south the line of the Mid-Atlantic Ridge appears to have remained constant.

(2) If the Pinro volcanorium down the centre of the Norwegian Basin does represent an extinct mid-ocean ridge system then the
original configuration of the Mid-Atlantic Ridge must have included a large offset in the region of the Iceland-Faeroes Rise.

This implies that the approximate position of the Iceland-Faeroes Rise may have been a major line of weakness, perhaps a transform fault, dividing two oceanic areas whose formation may have resulted from two different geological processes. In the interpretation of the Iceland-Faeroes Rise it is obviously important, therefore, to gain some idea of the nature of the crust either side of the rise, particularly in the Norwegian Basin.

The total field magnetic profile that has been chosen for a detailed interpretation is across the southern end of this basin; it was recorded simultaneously with echo-sounding and seismic reflection results during the R.R.S. John Murray cruise of this area. The mid-point of this profile is at latitude 64°10' N, longitude 6°50' W and is about 150 km long on a true bearing of 137°; it is approximately perpendicular to the lineations justifying application of two-dimensional interpretation methods. The anomalies on this profile have a wavelength of about 15 km and amplitudes in the order of 500 gamma.
The seismic reflection profile demonstrates a highly irregular seismic basement involving changes in depth of 1.5 km. The material between the seabed and the strong reflecting horizon is thought to consist of unconsolidated or semi-consolidated sediments with a seismic velocity of about 1.8-2.0 km/sec. (Ewing and Ewing, 1959). It is assumed that the seismic basement is equivalent to the magnetic basement.

The first stage in the interpretation is to assess the degree in which the topography of the sub-bottom reflector might explain the observed variations in the magnetic field. The magnetic anomaly caused by the two-dimensional seismic reflection profile has been computed assuming the magnetisation is in the direction of the present Earth's field, and that the intensity of magnetisation of the basement rocks is 0.01 emu/cm$^3$. (If the age of the Norwegian Basin is less than 70 my as suggested by Vogt and Ostenso, it is justifiable to assume magnetisation in the direction of the present Earth's field, even if remnant magnetisation is important). The results of this computation (Fig.5.5) shows that there is a definite correlation between the positive and negative peaks of the observed and calculated anomalies. The amplitude of the anomalies rarely match, but certainly the amplitude of the calculated anomalies are extremely
Fig. 5.5 Magnetic Anomalies due to the Topography along a Profile across the Norwegian Basin.

- Observed
- Calculated
large suggesting that the topography has a very marked effect on the observed profile.

The second stage of the interpretation is to assess what magnetisation contrasts within the magnetic layer are necessary to provide a better fit between the calculated and observed profiles. This evaluation is made possible with the use of the two-dimensional matrix method described in Chapter 4. The sub-bottom seismic reflection profile is assumed to represent the top surface of the magnetic layer, but unfortunately neither deep reflection nor refraction control is available for defining the base of the magnetic layer. Consequently, a horizontal interface is assumed at a depth of 7 km in model 1, and at a depth of 5 km in model 2. Each model is divided into blocks 2 km wide and the observed anomaly has been digitised at 2 km intervals. The distribution of magnetisation within the magnetic layer is given in Fig.5.6, for each model together with the residuals (observed minus calculated anomalies). In model 1 where the minimum thickness of the model is 3 km the maximum magnetisation contrast necessary is about \(0.003 \text{ emu/cm}^3\), whereas in model 2 where the minimum thickness of the model is 1 km the required maximum magnetisation contrast is increased to \(0.005 \text{ emu/cm}^3\). For each model, the residuals are less than 1 gamma except at the ends of the profile.
Fig. 5.6 Distribution of Magnetisation within the Magnetic Layer of the Ocean Crust along a Profile across the Norwegian Basin.
where residuals of up to 8 gamma exist.

These results show that the contrasts in magnetisation within layer 2 must be much less than that estimated for other oceanic areas. For example, Bott's (1967) interpretation of a magnetic profile across the Juan de Fuca Ridge suggested that a total magnetisation contrast of about $0.02 \text{ emu/cm}^3$ is necessary if the magnetic rocks are within, or partially within, layer 2. As ocean basalts normally possess an intensity of magnetisation of about $0.01 \text{ emu/cm}^3$ it seems that across the Juan de Fuca Ridge reversals in the direction of magnetisation are necessary. However, the profile that has been interpreted at the southern end of the Norwegian Basin requires a much lower magnetisation contrast which suggests that magnetic reversals are not essential to explain the observed magnetic anomalies. Consequently, the structural history of the crust in this area may be quite different from normal oceanic crust. Further magnetic/seismic reflection profiles are needed across the Norwegian Basin to see if this hypothesis is correct.

If indeed a different process of crustal formation exists north of the Iceland-Faeroes Rise, then it is important to look at the structural fabric of the rise itself and perhaps the area
south-west of the rise characterised by a fan-shaped lineation pattern. As mentioned previously, the latter region is of particular interest as the N.E.-S.W. magnetic lineations in the east of this area appear to swing to almost N-S on approaching the Iceland-Faeroes Rise to be systematically terminated off eastern Iceland. In a similar way the lineations in the south also appear to narrow although the survey area needs to be extended to about latitude 58°N for confirmation of this effect. Pitman (1966) has tried to explain such non-parallelism by varying the rate of formation of oceanic crust along the axis of a mid-ocean ridge. In chapter 4 it was pointed out that this hypothesis would cause either a structural deformation of pre-existing crust or migration of the mid-ocean ridge, but if ocean crust could be produced by a process other than that proposed by Hess and Dietz perhaps a similar result might be obtained.

Thus, on the assumption that there have been no large lateral displacements within the continental blocks, then the anomaly patterns in this area suggest two possible origins for the crustal structure of the Iceland-Faeroes Rise.
(1) 'Continental Crust' (Migration of Mid-Atlantic Ridge).
The diagrams given in Fig.5.8a. illustrate the type of lineation pattern which might be created by the drifting apart of two crustal blocks together with migration of a mid-ocean ridge. The first diagram shows the position of two deep fracture zones which control the initial configuration of a mid-ocean ridge. The second diagram demonstrates the formation of 'fan-shaped' lineations caused by asymmetric production of oceanic crust each side of a median ridge. The third diagram shows the final stage of ocean crust formation after the establishment of a single straight mid-ocean ridge. This last diagram appears to be very similar to the observed lineation patterns to the south of Iceland, but such an hypothesis implies that the Iceland-Faeroes Rise is composed of crustal material that was initially adjacent to the original line of separation. If this area was primarily continental in character then it follows that the Iceland-Faeroes Rise should possess strong continental affinities. The complex anomaly patterns on the rise itself could be largely explained by a thick series of flood basalts similar to those formed in Co. Antrim.

(2) 'Oceanic Crust' (Asymmetric production of oceanic crust adjacent to area of crustal extension). The diagrams in Fig.5.7b.
Fig. 5.7 Formation of 'Fan-shaped' Ocean Magnetic Lineations
illustrate the type of lineation pattern which might be created by the drifting apart of two crustal blocks in an area where new crust is produced by two different processes. The first diagram shows the position of a deep fracture zone which controls the initial configuration of a mid-ocean ridge. The second diagram demonstrates the formation of 'fan-shaped' lineations caused by a decrease in the rate of production of ocean crust along the axis of a mid-ocean ridge due to an increase in crustal extension by some other process. In this hypothesis no attempt is made to define what mechanism of crustal extension might be involved, but simply to describe the effect on the formation of ocean crust from a mid-ocean ridge. For this hypothesis to be true the Iceland-Faeroes Rise must be equivalent to an area where crustal extension has occurred.

It is not possible to distinguish between those two ideas on magnetic data alone, but if the crust beneath the Iceland-Faeroes Rise is oceanic in character then it seems unlikely that it could have been formed from a mid-ocean ridge as proposed by Dietz and Hess - a doubt already expressed with regard to the Norwegian Basin.
With regard to the narrowing of the lineation pattern south-west of the rise and adjacent to the northern end of Rockall Bank, it seems likely that this would occur if Rockall has undergone a clockwise rotation. The diagrams given in Fig.5.7c illustrate the type of lineation pattern that might be created by the drifting apart of two major crustal blocks that has been complicated by a section of one block breaking away. The first diagram shows the position of two deep fracture zones. The second diagram illustrates the formation of 'fan-shaped' lineations caused by different rates of production of oceanic crust along two parallel fissures. The total amount of crust along any line parallel to the stress system should be constant, otherwise distortion of the mid-ocean ridge would occur. In the last diagram activity has continued along the mid-ocean ridge in the normal manner. If this idea is correct it should be possible to determine when rotation of the minor break-away section ended. It is of interest to note that the strike of the Reykjanes Ridge is 040° whereas the strike direction of the scarp delineating the western limits of Rockall Bank is about 050°. This discrepancy of 10° would be sufficient to close the deep between Rockall Bank and the main continental block of Europe.
5.4 Discussion

As a result of the gravity study of the Iceland-Faeroes Rise is appears that the deep structures of Iceland, Faeroes and the intermediate rise can be considered to be mutually different. The structure of Iceland appears to change systematically from the centre of Iceland towards the rise - this structural change may involve either a decrease in thickness of the various layers or a gradual increase in their densities. This transition is complete by the 100 fm line that delineates the edge of the shelf off eastern Iceland. The 100 fm line defining the north-western limit of the Faeroes block represents the position of an abrupt crustal change between the Iceland-Faeroes Rise and the deep structure beneath the Faeroes. It appears that low density material must exist on the Faeroes block at a depth less than 5 km. The Iceland-Faeroes Rise is difficult to account for by thick continental type crust above normal upper mantle or by typical oceanic crust above anomalous upper mantle. The feature is perhaps a result of crust that is a little thicker than normal oceanic crust above anomalous upper mantle or possible a material of slightly lower density.

With regard to the magnetic data, Avery et al. have interpreted
the Mon Ridge and Lofoten Basin in terms of normal ocean-floor spreading from a single mid-ocean ridge, but doubt has been expressed about this hypothesis concerning the Norwegian Basin and the area between Iceland and Jan Mayen. Evidence for a typical oceanic crust has been given in the detailed interpretation of a profile at the southern end of the Norwegian Basin, and it has been suggested from a study of the lineation patterns adjacent to the Iceland-Faeroes Rise that the crust beneath the rise may have close continental affinities or is perhaps a result of crustal extension perhaps similar to that envisaged by Vogt and Ostenso.

From these two geophysical studies some idea has been gained of the deep structure beneath the Iceland-Faeroes Rise and perhaps on the evolution of its crust. However, on the basis of purely lateral movement it is still very difficult to explain why the rise forms such a strong topographic feature. It has been suggested that this area may at some time have been the position of an active transform fault, but other transform faults do not produce such an extensive transformation of the upper mantle or a crust of such a thickness. Wilson's hypothesis for the formation of the Iceland-Faeroes Rise in terms of a lateral ridge produced by a line of extinct volcanoes now seems to be untenable at least in its present form, due to the sharp swing
in the magnetic lineation pattern. For this hypothesis to be correct the lineations would be expected to be somewhat complicated, but to continue across the so-called lateral ridge. Instead the lineations phase out off eastern Iceland, and many are even sub-parallel to the axis of the rise.

Perhaps features of great importance include the Hovgaard and Greenland fracture zones in the Greenland Sea (Johnson and Eckhoff, 1966), and the Jan Mayen fracture zone in the Norwegian Sea (Avery), as all appear to represent aseismic features separating abyssal plains with different depths. The Iceland-Faeroes Rise is also aseismic and divides the deep Norwegian Basin from the relatively shallow area south of the rise. All four features have similar strike directions. Consequently, the topographic character of the Iceland-Faeroes Rise may be a result of vertical processes involving epeirogenic movements rather than the more direct effects of continental drift.
6.1 Introduction

Porcupine Bank and Porcupine Bight are large topographic features representing integral parts of an apparently complex continental margin west of Ireland. The bank is characterised by a very steep continental slope from 300 fm to 1500 fm, whereas Porcupine Bight is characterised by an unusually gradual slope which extends northwards forming a deep water region between the southern end of Porcupine Bank and Ireland.

In September 1966 the Geology Departments from Durham and Bristol University took part in a joint geophysical cruise on R.R.S. Discovery. The first part of the cruise organised by Durham was designed to study the transition from continental crust to oceanic crust in this region, and if possible to gain information on the origin of Porcupine Bight. The survey consisted of several east-west gravity and magnetic lines, approximately 500 km. in length from the west coast of Ireland. The reliable gravity lines from this survey together with a gravity line along the 12° meridian by H.M.S. Vidal in 1964, and a line by Snellius in 1965 along latitude 49°, are included in a provisional Free-Air anomaly map of the continental shelf.
west of Ireland, Fig.6.1. The residual field magnetic anomaly values (Fig.6.2) have been calculated using the regional from the North-East Atlantic Ocean as deduced by Bullard et al. (1962)

The survey equipment included an Askania Gss2 surface-ship gravimeter loaned by the Department of Geodosy and Geophysics, Cambridge University, and a Proton Precession Magnetometer built by F.Gray to measure variations in the total intensity magnetic field.

6.2 Gravity Interpretation

Apart from a marine magnetic survey at the northern end of Porcupine Bank by Allen (1960) there is little detailed knowledge of the shelf area west of Ireland. However, it is indicative from the geology of Ireland that the Caledonian fold belt most probably continues to the west of Ireland and perhaps across Porcupine Bank. Strong N.E.-S.W. topographic features on the continental slope at latitude 52\(^\circ\)00' N, longitude 15\(^\circ\)10' W would support this suggestion. It is perhaps surprising, therefore, that the most striking characteristic of the Free-Air anomaly map (Fig.6.1) is the marked north-south trend which appears to cut sharply across the main Caledonian direction. Similar results have been obtained by Murphy (personal communication) in Ireland where the gravity features parallel the Caledonian trend to the east of the 8\(^\circ\) meridian, but in the west of Ireland the gravity anomalies seem
largely independent of the Caledonian direction. It would appear, therefore, that moving from central Ireland towards Porcupine Bank the north-south features become gradually more pronounced, eventually masking the Caledonian structures almost completely.

As can be seen from the isobaths in Fig.6.3 the strike of the continental slope is also north-south, and so the possibility arises that these anomalies are related to the formation of the continental margin. Consequently, Ireland and the continental shelf out to Porcupine Bank may represent an excellent area to analyse the systematic deformation of crustal material towards the edge of a continental mass. This area has the particular advantage of a continental margin at a high angle to the orogenic fold belt, which makes it easier to distinguish between the effects of the two structures – a problem that invariably exists in this type of study.

The formal interpretation of the gravity data attempts to assess the crustal transition from the continent to the ocean, and if possible to provide limitations on the physical nature of the crust beneath Porcupine Bight. On the assumption that the area is in isostatic equilibrium in accordance with Airy's hypothesis, an isostatic model for the Earth's crust can be
constructed using the bathymetric profile as the top crustal surface. The anomaly due to the resulting model can be calculated, and then compared with the observed Free-Air anomaly.

This method has been applied to three of the traverses across Porcupine Bank labelled A, B and C in Fig. 6.3., using densities of 1.03 gm/cc for sea water, 2.87 gm/cc for the crust, and 3.40 gm/cc for the upper mantle (Worzel, 1965), and assuming a normal crustal thickness beneath the west coast of Ireland of 30 km. The calculated models have crustal thicknesses of 10-15 km beneath the continental rise, about 29 km for Porcupine Bank, and a minimum crustal thickness beneath Porcupine Bight varying from 23 km in the south to 27 km in the north. The results from these models (Fig. 6.4) demonstrate a good fit between the calculated and observed anomalies along the western edge of Porcupine Bank, in particular for lines B and C. Models for these two lines also account for the linear Free-Air anomaly along the 100 fm line off the west coast of Ireland, but in line A although a positive anomaly occurs in the calculated profile, a positive residual still remains. Nevertheless, the relatively good correlation, especially along the continental margin where both the gradients and amplitudes of the anomalies match, suggests that the assumption of isostatic equilibrium based on Airy's hypothesis is valid.
Fig. 6.3 Bouguer Anomaly over Porcupine Bight. Seismic Stations and Bathymetry
Fig. 6.4 Isostatic Models for the Continental Margin west of Ireland
for this area. Such a conclusion is significant as it differs from the continental margin off the east coast of the United States as interpreted by Worzel (1965). The model that Worzel believes to be most closely representative of the continental margin along the eastern seaboard of the United States shows that the isostatic compensation is not perfect beneath the margin since the base of the model has to be moved some 20 km seawards without isostatic adjustment in order to provide satisfactory results. If this interpretation is correct then it suggests that the mode of formation of these two margins may be slightly different. (Recent deep-seismic refraction results indicate that lateral changes in P-wave velocity occur in the upper mantle beneath the continental margin of the United States, and this might account for the apparent isostatic inequilibrium in Worzel's models).

The major differences between the observed and calculated anomaly profiles across the continental margin west of Ireland occur over the deep between Rockall and Porcupine Bank, and over Porcupine Bight. With regard to the negative residuals (observed minus calculated anomalies) west of the bank it is apparent from the seismic refraction profiles by Hill (1954) that a considerable thickness of sediments might be expected in this region.
The position of these profiles are shown in Fig. 6.3 and the results he obtained are as follows:

<table>
<thead>
<tr>
<th>Sedimentary Thickness (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Station 1: 2.96</td>
</tr>
<tr>
<td>Station 2: 2.78</td>
</tr>
<tr>
<td>Station 3: 1.88</td>
</tr>
</tbody>
</table>

Such thicknesses of sediment would be sufficient to explain the discrepancy between the observed and calculated anomalies. Hill also points out that the refraction results indicate a particularly rough basement topography. Certainly the bathymetry in many places is very irregular suggestive of actual basement outcrop. If this is the case then it would explain the erratic nature of the gravity anomalies on all profiles west of Porcupine Bank. The wavelength of these variations in the gravity field is in the order of 30 km, but it is uncertain whether the structures have been crossed at right angles.

The second anomalous area, Porcupine Bight, is characterised by large positive residuals on lines B and C and a positive Bouguer anomaly, Fig. 6.3. This is perhaps surprising when one considers that a seismic reflection profile by Stride (personal communication) identified thick sediments beneath the bight
which would tend to produce a negative anomaly. It is suggested, therefore, that high density material may be present within the crust, or alternatively Porcupine Bight represents a region of relatively thin crust. A seismic refraction survey is necessary to distinguish between these two possibilities.

A further discrepancy between the observed and calculated anomalies exists on line A over Porcupine Bank. Here the observed Free-Air anomaly values are much less than the calculated, but this may be due to the presence of a granite. The magnetic survey by Allen shows a series of arcuate anomalies which have been interpreted as ring-dykes surrounding a granite intrusive centred on latitude 53°15'N, longitude 13°50'W, only a few kilometres north of line A. Bottom samples of granitic composition are also described by Allen from the same area. If such a granite extends southwards along the axis of Porcupine Bank then this might well explain the low Free-Air anomalies observed on the northern lines of the Durham survey.

Other points of interest resulting from this geophysical cruise include a negative gravity anomaly with an amplitude of 30 mgal over the Haig Fras granite, latitude 50°12'N, longitude 7°50'W; the confirmation of a gravity low in the same region as
Hersey and Whittard discovered a 'rough' surface at about 670 metres beneath the seabed, latitude 49°28' N, longitude 9°25' W; and finally another gravity low just to the west of the Isles of Scilly suggesting a continuation of the South-West England granite batholith.

6.3. Magnetic Interpretation

In the interpretation of the magnetic profiles obtained during cruise 14 of R.R.S. Discovery no attempt has been made to contour the results, although in certain areas where very long wavelength anomalies exist it may perhaps be justified. The residual magnetic anomaly profiles presented in Fig.6.2 show a large magnetic low over Porcupine Bight; a magnetic high on Porcupine Bank with high frequency anomalies at the northern end; a magnetic high associated with the 100 fm line off the west coast of Ireland, often with a high frequency component; and a series of long wavelength, high amplitude anomalies in the deep between Rockall and Porcupine Banks.

The magnetic low over the bight flanked by highs on Porcupine Bank and off the west coast of Ireland may be due to the change in depth to the basement as suggested by the seismic reflection line by Stride. The occasional presence of high
frequency anomalies in the areas of magnetic high would also suggest a shallow basement, and the complete absence of high frequency anomalies in the bight would support a relatively deep basement. The high frequency anomalies off Galway Bay coincide with a positive residual Free-Air anomaly that exists at the eastern end of line A. This may indicate the presence of a large basic intrusive or an up-faulted block of magnetic basement. Finally, it is perhaps significant that no magnetic anomalies occur along the centre of the bight.

In the gravity interpretation it was suggested that the positive Bouguer anomaly over the bight may be due either to high density material near the base of the crust or to a rise in the Mohorovicic discontinuity. If high density intrusives exist within the crust one might have expected local magnetic anomalies near the axis of Porcupine Bight similar to the elongate anomalies observed in the centre of the trough separating the Faeroes block from Shetlands.

In the deep between Rockall and Porcupine Banks the magnetic anomalies appear to have characteristics typical of the anomalies observed in oceanic areas. However, the refraction results by Hill, the bathymetry and also the gravity anomalies observed in this region suggest that the topography of the crystalline
basement may be extremely irregular. Assuming this basement to be magnetic such topographic variations would be expected to produce large magnetic anomalies. It is necessary, therefore, to obtain magnetic-seismic reflection profiles in order to distinguish between the relative contributions of the topography and the contrasts in magnetisation within the magnetic layer of the crust.

6.4 Discussion

Perhaps the major crustal problem concerning the continental shelf west of Ireland is the mode of formation of Porcupine Bight. The gravity results from this survey suggest that crustal thinning may have occurred, but the precise mechanism of such a phenomena still remains in considerable doubt. There are two schools of thought on the process of crustal thinning: (1) requires lateral movement of crustal material and (2) relies upon purely vertical transformations involving both upper mantle and the crust. Obviously more detailed information is required in order to establish any lateral displacement of Porcupine Bank relative to the main continental mass beneath Ireland, but the possibility of rotation is apparent from the computed fit of the continents around the Atlantic by Bullard (1965) where the southern end of Porcupine Bank overlaps the Canadian shelf off Newfoundland. Such rotation could help explain
the characteristic V-shaped Bouguer anomaly over Porcupine Bight and the higher positive Free-Air residuals towards the southern end of the bight. Finally, if rotation has produced a thin crust beneath the bight then perhaps this area may represent crustal thinning in varying stages of development depending on the degree of lateral displacement of the continental material.

The other rather interesting characteristic shown by the gravity results is the systematic development of Free-Air anomalies with north-south trends that progressively over-ride the effects of the Caledonian fold belt towards the continental margin. The strike of these features is not easily related to either Caledonian or Hercynian structural trends, but is an extremely common direction for the continental margin of western Europe. The masking of the Caledonian appears to begin in Western Ireland and so it is important to look at the surface geology in Ireland in an attempt to date the formation of these features. Apart from the rather confused north-south fault patterns in the north-west of Ireland the major area for structures with this trend is in the mid-west of Ireland where Lower Palaeozoic inliers separate sedimentary basins of Carboniferous age. In addition, it is worth noting that the dominant joint direction in
the Carboniferous of Ireland is also north-south. Consequently, it would seem that some degree of crustal deformation along lines parallel to the strike of the Free-Air anomalies may have started during Upper Palaeozoic times. If this is the case, then either these features are the result of late stage effects of the Caledonian orogenesis or perhaps the first phases of movement related to continental drift and the formation of a continental margin.

At present it is difficult to verify the possible explanations suggested for the geophysical and geological features described in this chapter. The survey was designed as a reconnaissance project and further gravity, magnetic and perhaps more important seismic refraction and reflection information is needed in order to solve the many problems discussed.
CHAPTER 7

THE CONTINENTAL MARGIN OF WESTERN EUROPE

7.1 Introduction

In recent years the theory of continental drift has gained a great deal in popularity largely due to research in palaeomagnetism and to the tremendous increase in our geophysical knowledge of the oceans. However, the mechanism of drift is still much disputed due to the apparent restrictions imposed by certain physical parameters of the mantle.

A mechanism is required to split an area of continental crust into one or more sections and for those sections to move apart such that the newly formed continental margins represent the lines along which the original fracture took place. It is somewhat surprising, therefore, that few geologists studying areas adjacent to the margins of the Atlantic ocean have attempted to relate observed geological features with the mode of formation of the margin. For example, if the convection hypothesis is correct whereby a convection cell rises beneath the line along which separation eventually takes place, then one might expect some degree of metamorphism or at the least a certain amount of hydrothermal activity. Similarly, a convection cell must produce certain stress conditions in the crust which presumably will be at their maximum on the margin.
Consequently, it should be possible from a purely geological basis to provide some kind of restrictions on the mechanism of continental drift. As yet very few geological features in continental areas have been attributed to the effects of drift.

It was for this purpose that a special study of Porcupine Bank and Porcupine Bight was made. However, although this survey suggested certain factors controlling their formation, it is also necessary to make a more general study of the whole margin of western Europe from Spitzbergen in the north to Spain and Portugal in the south. This continental margin is unusually complicated perhaps because of its close association with the Caledonian orogenic fold belt. Unlike the eastern seaboard of the United States which appears to contain the full width of the Caledonides, further north the Caledonides occur both in Greenland and in Europe. It is possible, therefore, that the complexity of the continental margin of western Europe may be due to its formation within an intensely fractured and deformed part of the crust. If the split had occurred through a more stable shield area, perhaps the margin would have been more regular in character. However, it is because of the existence of a large number of structural features that this margin provides an excellent area to study the stress conditions which must have been present during its formation.
In this chapter an attempt is made to isolate those features which might be related to continental drift, or which may be important in assessing the process of formation of the continental margins of western Europe.

7.2 Character of the Continental Margin of Western Europe

As indicated in the introduction a study of continental margins may provide information on the stress field and geothermal state of the crust during the initial stages of drift. In this connection it is necessary to study the morphological features of the margin, the transition from continental to oceanic crust, the effect of local geology, etc. However, the difficulty of this type of analysis is in selecting those features which reflect conditions at the time of formation, from secondary features due to the presence of a continental margin. It has been demonstrated by Bott (personal communication) for example, that where a change in crustal thickness occurs strong horizontal stress systems are set up capable of deforming the crust, i.e. once a continental margin has been formed internal stresses might well produce features parallel to the margin. Nevertheless, although such ambiguities obviously exist it is felt that various properties of the margin either suggest certain conclusions as to its origin, or at least points to perhaps fruitful lines for further research.
7.2.1 Structural control.

One of the more remarkable characteristics of the continental margin of western Europe is the degree of structural control along strike directions $352^\circ$ and $052^\circ$. Fig. 7.1 illustrates the locality of some of the major scarps of the North-East Atlantic together with their mean strike values. It is difficult to draw any definite conclusions as to the stress field which must have existed to produce such a structural pattern, but immediately one has a clue as to the type of structures to look for within the continent which may be linked with continental drift.

The strike of $052^\circ$ is closely associated with the Caledonian direction, and a $352^\circ$ strike is particularly common in Pre-Cambrian rocks of Grenville age. On the assumption that the orogenic forces which produced these two fold belts are now dormant, any subsequent movement along these directions must be of a completely independent source. Thus, if structures with these orientations have been active in Europe of post-Permo-Carboniferous age which cannot be easily related to the Tertiary Orogenesis or even the Hercynian, then the possibility arises that they may be related to continental drift. This type of
Fig. 7.1 Major scarps along the Continental Margin of Western Europe
approach is more difficult with the 052° strike as although the orogenic forces which initially produced the Caledonian fold belt are no doubt dormant, subsequent movement may well occur due to the unloading effect of erosion, Bott (1965). However, this problem does not apply to the north-south features, as the time required to attain equilibrium has been significantly longer. Consequently, a study of the distribution of structures with the 352° strike direction may be the more productive.

7.2.2. The Nature of Transition from Continental to Oceanic Crust.

Another method of estimating the physical processes involved during the formation of a continental margin is to complete a study of continental rises and slopes. From Spitzbergen to Spain there is an amazing variation in the character of the slope. Although this variation is probably largely due to the effect of local geology, the manner in which a system has taken advantage of this fact, may be critical in defining certain limits of the stress field and thermal state. In Fig.7.2 typical topographic sections are given of the continental margin of western Europe; the location of these sections are given in the inset. The profile near Spitzbergen has been taken from a publication by Johnson and Eckhoff (1966) but the other profiles have been constructed from the contoured bathymetric
Fig. 7.2 Bathymetric Profiles across the Continental Margin of Western Europe
Section 1. The Svalbard Continental Rise is typified by the uniform transition from continental rise to continental slope. However, the great interest of this region is in its close association with the Mid-Atlantic Ridge, whereby the normal flank of the ridge appears to be beneath the continental rise. The possibility exists, therefore, that here one has an area which at the present time is in the thermal state and stress condition perhaps very similar to the physical conditions of the crust at the onset of drift or at the time of formation of a continental margin. It is worth noting that at the same latitude as Spitzbergen the Mid-Atlantic Ridge makes an abrupt change in direction of about $50^\circ$. Similar changes in structural trend also occur in the continental crustal area of Spitzbergen.

Section 2. The Norwegian Plateau is defined by an east-west escarpment in the north and an approximately north-south escarpment in the west, see Fig. 7.1. The bathymetric profile illustrates the remarkably flat top to the plateau or avant-shelf at a depth of about 700 fm. Well-developed magnetic features exist.
along the scarps, but no lineations or similar anomalies occur on the plateau itself. Seismic reflection results suggest that the depth to the basement decreases across the scarp slope from the Atlantic towards the continent. It appears, therefore, that the Norwegian Plateau may have close continental affinities, and may well have been formed by subsidence of continental crust. If the area is in isostatic equilibrium it is difficult to see how such subsidence could occur without some kind of transformation of the crust-mantle boundary.

Assuming this to be the case the mechanism of formation of a continental margin must be capable of affecting at least a 200 mile width of continental crust in an apparently uniform manner. Although this uniformity seems unique to the Norwegian Plateau, it does demonstrate the possibility of quite large areas of continental crust being affected during the formation of a continental margin.

Section 3. This profile has been taken across the margin that limits the northern extension of the North Sea Basin. The profile illustrates the linear form of the slope and the low angle dip. On the assumption that the region is in isostatic equilibrium in accordance with Airy's hypothesis, the crust presumably thins gradually towards the Atlantic. However, the important features of this part of the continental margin are the
magnetic 'cluster' anomalies present across the whole area of the slope. Similar, discontinuous 'cluster' anomalies can be traced along almost the entire length of the margin between the Eurasian continent and the Arctic Basin (Demenitskaya et al 1965) off the east coast of North America (Drake et al 1959; King et al 1961; Drake et al 1963) and near Chukchi Cap (Hunkins et al 1962). It is thought that the anomalies are due to the intrusion of strongly magnetised material controlled by fissures parallel to the continental edge. In this area, however, as the thickness of the crust appears to decrease towards the ocean, in a similar way the degree of linearity of the magnetic anomalies appears to increase. Thus, there seems to be a relation between the amount of volcanic activity and the degree of thinning of the crust.

If this is in fact the case then this slope may represent an excellent area to study the transformation of continental crust at various stages of development.

Section 4. This section is taken from the southern end of the Reykjanes Ridge, across Rockall Bank and Porcupine Bank to Ireland. This profile has been chosen to demonstrate how a very large area of continent can be affected during the formation of a continental margin. The idea was suggested whilst discussing section 2, but here the area involved appears to be even larger although the crust has reacted in a somewhat different manner. The island of Rockall is composed predominantly
of aegirine-granite. Similar rock has also been dredged 19 km to the north of the island, and aegirine-granophyre at 10 km to the east. Consequently, it has been thought by many geologists that Rockall Bank is most likely to be of continental origin, but evidence to support this hypothesis was not forthcoming until Moorbath (personal communication) completed several strontium-isotope analyses. It now seems most probable that Rockall Bank is essentially of continental type. In addition, the geophysical survey of Porcupine Bank and adjacent areas, described in the previous chapter, suggests that the crust of Porcupine Bank is approaching normal continental thickness, but that the crust between Rockall and Porcupine Banks and perhaps beneath Porcupine Bight is relatively thin. Thus, on the assumption that Rockall, Porcupine Bank and Ireland were initially all part of a single continental mass and have since been separated by drift or crustal thinning, then the processes which created these crustal changes have had effect over an area some 400 miles wide.

Consequently, these four profiles indicate that considerable areas of continental crust may be effected during the formation of a continental margin, and that structures related to this event may be found well within a continental block. Also,
certain areas might provide valuable information on the
process of crustal thinning and crustal extension by multiple
intrusion which may be important for assessing the mode of
formation of adjacent ocean basins.

7.2.3 Geothermal State of the Continental Margin

The discussion so far has been limited to a description
of the type and extent of various structural features thought
to be important in assessing the mode of formation of a continental
margin. As mentioned earlier another perhaps critical approach
is a study of the geothermal history of a margin area. For
example, if convection in the mantle is a valid hypothesis
then before drift took place one would expect anomalous
thermal gradients with maximum heat flow along the line where
the continents eventually split. Local variations in heat flow
are likely to initiate centres of hydrothermal activity, particularly
where the heat flow is greatest near the region of crustal
separation. Consequently, hydrothermal deposits may provide
information on the thermal conditions during the period of
continental break up.

Unfortunately, at present the dating of such deposits
is somewhat unreliable. Only recently have reasonably satisfactory methods been developed for distinguishing epigenetic and syngenetic deposits, but the ambiguities of isotope dating due to remobilization still invariably exists. Nevertheless, accepting the difficulties of accurate age dating, knowledge of the distribution and degree of hydrothermal activity can be extremely useful.

It has been suggested by many economic geologists that the distribution of certain base metal deposits is due to variations in the thermal state of the crust caused by deep fractures within the basement. At the point where two major faults cross one another a 'hot-spot' is formed causing the convection of connate waters and the transportation of various trace elements. On the assumption that the principle of structural control in this hypothesis is correct, then the distribution of hydrothermal deposits might give a clue as to the major lines of weakness during periods of high heat flow. If in addition these lines of weakness correspond with those structures believed to be active at the time of formation of a continental margin, then perhaps some idea can be gained as to the variation in the thermal state of the crust during this period.
In this section an attempt is made firstly to relate the distribution of hydrothermal deposits in Ireland to particular deep-seated fractures, and secondly to estimate the degree in which mineralisation has been influenced by the formation of the continental margin. This investigation was made jointly with M.J. Russell.

The mineralisation in Ireland is predominantly lead-zinc, although barytes and copper are not uncommon. The larger ore bodies occur as stratiform deposits adjacent to fault planes. Almost without exception the deposits are undoubtedly of hydrothermal origin, usually in Lower Carboniferous Limestone. As in the Pennines in England mineralisation appears to have continued for a long time, but the rate of mineralisation has varied. Isotope dating has not produced conclusive results, but quite reliable evidence now exists for both syngenetic and epigenetic formations. The main approach to this study must, therefore, rely upon analyses of the structural control of mineralisation within single deposits, and also their geographical distribution.

A statistical method of representing the variation in structural trend within an individual deposit is complicated by lack of exposure. However, various authors have suggested certain apparently dominant trends in many mining areas, the following
being quite typical -

Silvermines. The mineralisation lies adjacent to a N 80°E fault, but Rhoden (1958) has brought attention to the presence of numerous north-south tributary faults, dipping both east and west and carrying ore.

Castlebayne. Small lead-zinc deposits in Silurian rocks occur with a north-south distribution which may be the northerly continuation of the Kingscourt fault.

Glendalough. Cole (1922) describes veins occurring both in a north-south and a N.E.-S.W. direction.

Avoca. Some north-south fractures contain enough chalcopyrite to have made small scale stoping worthwhile, (Murphy, 1959). This mineralisation is later than the main stratiform deposit.

It appears, therefore, that although the major lodés are orientated along N.E.-S.W. or even east-west faults, much of the mineralisation in Ireland is also affected by north-south structural trends.
The geographical distribution of mineralisation in Ireland is shown in Fig.7.3. Once again certain structural trends appear to be important, particularly the line through the four largest base metal deposits that occur in Carboniferous rocks - Gortdrum, Silvermines, Tynagh and Abbeytown. The strike of this line is 352° and is a direct continuation of the continental margin off the Hebrides of Scotland; it parallels the Free-Air anomaly off the west coast of Ireland which delineates the eastern edge of Porcupine Bight, see Fig.6.1. in previous chapter; and finally the line is also characterised by the poor correlation of gravity features from one side to the other, (Murphy, personal communication). A second line with the same strike but 30 miles to the east of the Abbeytown - Silvermines line seems to link a series of mineralisation areas between Keel and Ferbane.

Consequently, one appears to have a series of linear distributions of hydrothermal deposits with a strike direction identical with structural features to the west of Ireland, and of even greater significance a strike direction that is very similar to many of the scarp slopes defining the continental margin of western Europe.
Fig. 7.3 Geographical Distribution of Sulphide Deposits in Ireland
Therefore, as a result of detailed studies of individual deposits and their geographical distribution, it seems that mineralisation in Ireland has taken advantage of a structural trend which is not typical of either Caledonian, Hercynian or Tertiary, but corresponds with a strike direction that is extremely common along the continental margin. Although this is not conclusive, it suggests that mineralisation in Ireland may be in some way related to the formation of the margin. If this is so then this may well be of great importance economically.

7.3 Discussion

In this chapter an attempt has been made to draw attention to a variety of geological features which may help in solving the problem of the mode of formation of the continental margin of western Europe. One of the major difficulties of this particular margin is its lack of exposed land area near the continental edge. Apart from Spitzbergen there are no other areas which can be assumed to be immediately adjacent to the margin. However, this is not the case for many other continental margins which appear to be of Atlantic type, such as the Arctic seaboard of Canada, and perhaps less reliably the Red Sea.
A palaeogeographical map for the margins of the Arctic Basin has been constructed by Challinor (personal communication). The map demonstrates how the formation of sedimentary basins began in the Permian and that deformation continued throughout the Tertiary. These basins and associated structures are confined to the continental shelf and are apparently independent of the geological processes affecting other parts of the continent. In the Red Sea region, Russell (personal communication) has brought attention to the distribution of hydrothermal deposits. These deposits occur in continental crustal areas each side of the Red Sea, and parallel to its axis. On the assumption that the Red Sea represents a region at the initial stages of continental drift (Girdler, 1965), then the hydrothermal deposits are situated along what will eventually be the continental shelf. Consequently, one has independent evidence from entirely different localities of structural deformation and anomalous thermal activity adjacent to continental margins.

Finally, I would like to mention two areas of specific interest which form parts of the continental shelf of western Europe, i.e. Spitzbergen and the Shetlands-Hebrides region. Spitzbergen as pointed out earlier, is extremely close to the Mid-Atlantic Ridge. This section of the ridge is defined seismically and bathymetrically (Johnson et al, 1966),
and is characterised by an abrupt change in strike direction from 360° in the south to 310° in the north. The Svalbard Rise is limited in the west by the north-south ridge system, whilst the continental edge has a strike direction of 325°. These three structural trends are typical of the major dislocations which define the post-Carboniferous basins of Spitzbergen. With regard to the Shetlands-Hebrides region large gravity anomalies parallel to the continental margin were identified by a University of Durham geophysical cruise during May/June 1967. These geophysical trends are supported by the aeromagnetic results published by the Institute of Geological Sciences. Therefore it is suggested that any future structural interpretations of either Spitzbergen or Shetlands-Hebrides should be regarded in some degree as a continental margin problem.

In conclusion it appears that certain structural features and expressions of geothermal activity along the continental shelf of western Europe may be related to the formation of the continental margin. Structural trends of about 352° and 052° define the majority of the margin, and hydrothermal deposits apparently following similar trends occur in Ireland. By analogy with Rockall and Porcupine Banks, and the Norwegian Plateau the process involved in forming a continental margin can be expected to effect large areas of continental crust. It is suggested, therefore, that many of the geological features identified in western Europe
may be related to continental drift and the mode of formation of a continental margin, and that future studies of such features may add immensely to our knowledge as to the precise nature of the mechanism involved.
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APPENDIX A

SPECIFICATIONS AND DATA FORMATS FOR MAGNETIC REDUCTION PROGRAMME

SYSTEM A

A.1 Computer Facility Requirements

The programme is written in Algol 60 Language for an Elliott 803 computer.

Hardware requirements include:

(i) Two readers - reader 1: 8-hole and 5-hole
    - reader 2: 5-hole
(ii) Two punches - 8 hole and 5-hole
(iii) Magnetic Film Handlers
(iv) Benson-Lehner X-Y Plotter
(v) D-Mac Pen-follower with 5-hole punch
(vi) Flexowriter - Elliott 8-hole
(vii) Creed - Elliott 5-hole

Software requirements include:

(i) Film Package
(ii) Plotter Package
(iii) Algol Translation Tape
A.2 Preparation of Data Tapes

It has been mentioned in chapter 2 that due to the small storage capacity of the Elliott 803 the programme has been divided into four separate programmes plus a trigger programme at the beginning. This does not mean that the amount of data the computer can handle is badly restricted as only discrete sections of data are processed at one time. Nevertheless, to obtain the maximum efficiency from this programme the data must be organised with some care. The data formats for each programme are listed below, together with relevant notes, definitions and operating instructions.

A.2.1 Magnetic Reduction Programme, Trigger

Data format: No data tape required

Operating Instructions: Load Film Handler. Write Permit.
Read Film Package. Read Programme
Change F2 digit.

Notes: This programme sets the words in block 49 to zero.

A.2.2 Magnetic Reduction Programme, Part 1.

Data format: (a) Reader 1: 8-hole
zerolat zerolong maxlat range xscale yscale
R phiO lamO r anscale zero sfac FON
FOE blno
(b) Reader 1: 5-hole (magnetic readings)
tt(i) aa(i)
(c) Reader 2: 5-hole (navigational readings)

F(1) G(1)
F(2) G(2)
F(3) G(3)
x(i) y(i)

10000 space space

Operating Instructions: Load Film Handler. Write Permit
Read Film Package. Read Programme

After the 8-hole data tape has been read, a data wait allows
the sets of 5-hole data to be loaded. The programme is restarted
by changing the F2 digit.

Definitions: \( tt(i) \) and \( aa(i) \) represent the digital version of the
magnetic analogue record, see Fig.A.1.

\[ \text{anscale} = \text{Scale factor equivalent to width of analogue record in} \]
\[ \quad \text{gamma}. \]

\[ \text{sfac} = \quad \text{Scale factor equivalent to width of analogue record in} \]
\[ \quad \text{pen-follower co-ordinates}. \]

\[ \text{zero} = \quad \text{Base line value in pen-follower co-ordinates}. \]

With reference to Fig.A.2, F(1), G(1) and F(2), G(2) must be on
the latitude for which the 1:1,000,000 scale is quoted. It is
advisable to have the two positions as far apart as possible.
F(3), G(3) should be chosen several degrees away from the latitude
for which the scale is quoted and on the same meridian as F(1), G(1).
Fig. A.1 Digitisation of Magnetic Analogue Record

Fig. A.2 Digitisation of Ship's Track

Fig. A.3 Latitude and Radius of Curvature of the Earth
x(i), y(i) represents the digitised ship's track co-ordinates.

10000 followed by two spaces is a terminator.

zerolat = latitude of 1:1,000,000 scale in degrees.

zerolong = longitude of F(1), G(1) in degrees

maxlat = latitude of F(3), G(3) in degrees.

range = Number of degrees of longitude between F(1), G(1) and F(2), G(2).

xscale and yscale = Number of pen-follower digits per foot in x and y directions. (Should both be the same value).

R = Radius of curvature in feet perpendicular to the meridian at the latitude for which the 1:1,000,000 scale is quoted. The value of R is relative to the scaled model, not the true radius of curvature of the Earth.

\[ R = \frac{\text{radius of curvature in feet at latitude } \phi}{1,000,000} \]

With reference to Fig.A.3., assume that in cross-section the earth has the shape of an ellipse.

\[ R = \frac{a}{(1-e^2 \sin^2 \phi)^{\frac{1}{2}}} \]

where \( a = \text{major semi-axis}; \ b = \text{minor semi-axis}; \ \phi = \text{latitude}; \)

\[ e^2 = \frac{a^2 - b^2}{a^2} \]
phi0 = Latitude of true origin for square grid; usually chosen at southern end of survey area.

lam0 = Longitude of true origin for square grid in seconds; best longitude is line through centre of survey area.

r = Number of magnetic readings per block on magnetic film; maximum of 12.

FON = Position of false origin in terms of number of meters north of true origin.

FOE = Position of false origin in terms of number of meters west of true origin.

blno = Number of first block to be written on film; suggest block 50.

Notes:  
(a) It is recommended that when preparing navigational co-ordinates, the lines are digitised from west to east or north to south as the analogue output Part 3 corresponds to the order in which this data is prepared.

(b) The number of navigational co-ordinates less one for each line (not including F(i), G(i)) should equal the number of magnetic readings divided by r.

(c) The maximum number of magnetic readings per block on film, r, is 12. Therefore, if the magnetic record is digitised every 5 mins., then the ship's track should be digitised every hour. If the magnetic record is digitised every 2.5 mins., then the ship's track should be digitised every half hour.
(d) If the first navigational co-ordinate x(l), y(l) is on the hour, and the magnetic record is to be digitised every 5 mins, then the first magnetic reading to be digitised tt(i), aa(l) should be 5 mins. past the hour.

(e) tt(l) is the range on which the magnetic record begins e.g. 50000 gamma. If tt(i) > 20000 then the value of tt(i) represents the new range in gamma.

If tt(i) = 0 then anscale is altered to 100 gamma.
If tt(i) = 1 then anscale is altered to 1000 gamma.

(f) The only values of tt(i) that are used are the ones mentioned in (e). Thus, when digitising a magnetic record the paper can be moved across the table, but ensure the base line, the value of zero is kept constant.

(g) Do not move 1:1,000,000 chart after F(i), G(i) values have been digitised.

(h) If 12 magnetic readings are used for each block on the magnetic film, then it is recommended that the total number of blocks used for each line is limited to 24 due to restrictions in Part 3 of the programme.

A.2.3 Magnetic Reduction Programme, Part 2

This part is used for assessing the regional gradients based on the survey data collected. The results are written on block 48. If the regional has already been calculated then this programme is not necessary, and the known regional parameters
should be written on block 48 instead.

Data format: No data tape required.

Operating Instructions: Load Film Handler. Write Permit
                    Read Film Package. Read Programme.
                    Change F2 digit.

A.2.4 Magnetic Reduction Programme, Part 3

Data format: (a) Reader 1: 8-hole
             length(j) ht(j) xmax(j) xmin(j)
             ymax(j) ymin(j)

(b) Reader 1: 8-hole
     m n

Operating Instructions: Load Film Handler. Write Permit
                    Read Plotter Package. Read Programme

After first data tape has been read, a data wait will allow the
loading of the second data tape.

Definitions: The following represent the various parameters necessary
for defining the positions of axes for the X-Y Plotter output:-

length (j) = length of x axis for each line in inches
ht(j) = length of y axis for each line in inches
xmax(j) = Distance in kilometres from origin
xmin(j) = Distance in kilometres from origin

N.B. xmax(j)-xmin(j) is the equivalent length of x axis in kilometres.
(Usually convenient to have xmin(j)=0).
ymax(j) = Value in gamma required at top of y axis.

ymin(j) = Value in gamma required at origin.

m = Number of first block in which data has been written on film (Usually block 50).

n = Number of the survey line at which the programme is required to start.

Note: If a fault occurs in this programme, simply re-enter the data tapes, but alter the value of n to the number of the survey line at which the failure occurred.

A.2.5 Magnetic Reduction Programme, Part 4

Data format: No data tape required

Operating Instructions: Load Film Handler. Write Permit

Load Film Package. Read Programme

Change F2 digit.
APPENDIX B

SPECIFICATIONS AND DATA FORMATS FOR MXOCEAN MK 2

B.1 MXOCEAN MK 2, Part 1

IMPORTANT: Label magnetic tape - 'MAGNETIC'

Data format: nsta; nmag; nmx; IM; IE; ALFM; ALFE;

\[ \text{xsta}(i); \text{zt}(i); \text{zb}(i); \]

where \( i = 1 \) to \( \text{nsta} + 1 \).

Definitions (see Fig.B.1):

\[ \text{nsta} = \text{total number of blocks} \]

\[ \text{nmag} = \text{total number of blocks each side of any station} \]
which can be considered to affect the anomaly at that station.

\[ \text{nmx} = \text{number of blocks each side of any station which} \]
are to be considered as two-dimensional blocks.

Blocks between \( \text{nmx} \) and \( \text{nmag} \) will be approximated to line dipoles.

\[ \text{IM} = \text{inclination of the magnetisation within the body} \]
in the plane of magnetisation.

\[ \text{IE} = \text{inclination of the Earth's magnetic field in} \]
the magnetic meridian.

\[ \text{ALFM} = \text{angle measured in an anticlockwise sense from the} \]
strike of the body to the azimuth of the plane of magnetisation.
Fig. B.1 Definitions for MxOCEAN MK 2
ALFE = angle measured in an anticlockwise sense from the strike of the body to the magnetic north-south line.

(IIM = resolution of IM into plane of profile perpendicular to strike of body.)

(IIE = resolution of IE into plane of profile perpendicular to strike of body.)

xsta(i) = distance of the stations in kilometres from the origin. Each station being on the datum above the centre of a block.

zt(i) = depth in kilometres to the top surface of the model vertically beneath the mid-point between two stations.

zb(i) = depth in kilometres to the bottom surface of the model vertically beneath the mid-point between two stations.

B.2 Mxocean Mk.2, Part 2

Data format: nsta; nmag; nmx;

aobs(i);

where i = 1 to nsta

Definitions: nsta, nmag and nmx are defined as above.

aobs(i) = the observed magnetic anomaly above the centre of each block.