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Interpretation of gravity and magnetic anomalies in the N.E. Atlantic

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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

CONTENTS

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.

(v)

ACKNOWLEDGEMENTS

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

PHYSIOGRAPHIC

MAP

OF   THE

N. E. ATLANTIC

JAN
MAYEN

MON RIDGE

S. JAN MAYEN
RIDGE

LOFOTEN

BASIN

LOWER SVALBARD RISE

UPPER SVALBARD RISE

NORWEGIAN

PLATEAU

CONTINENTAL

SHELF

PINRO VOLCANORIUM

LOWER CONTINENTAL
RISE

UPPER CONTINENTAL
RISE

CONTINENTAL SLOPE

ICELAND

ICELAND-FAEROES RISE

FAEROES

NORWAY

REYKJANES RIDGE

ABYSSAL

PLAIN

ROCKALL BANK

CONTINENTAL

SHELF

PORCUPINE
BANK

IRELAND

BRITAIN

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 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
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 s outh-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 $49^{\circ}28'$ N, longitude $9^{\circ}25'$ W and the Haig Fras granite at
latitude $50^{\circ}12'$ N, longitude $7^{\circ}50'$ 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 Geodosy 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 on normal erection an automatic cut-off during course alterations when the angle and rate of turn exceeds 5° and 0.3° per second, respectively.
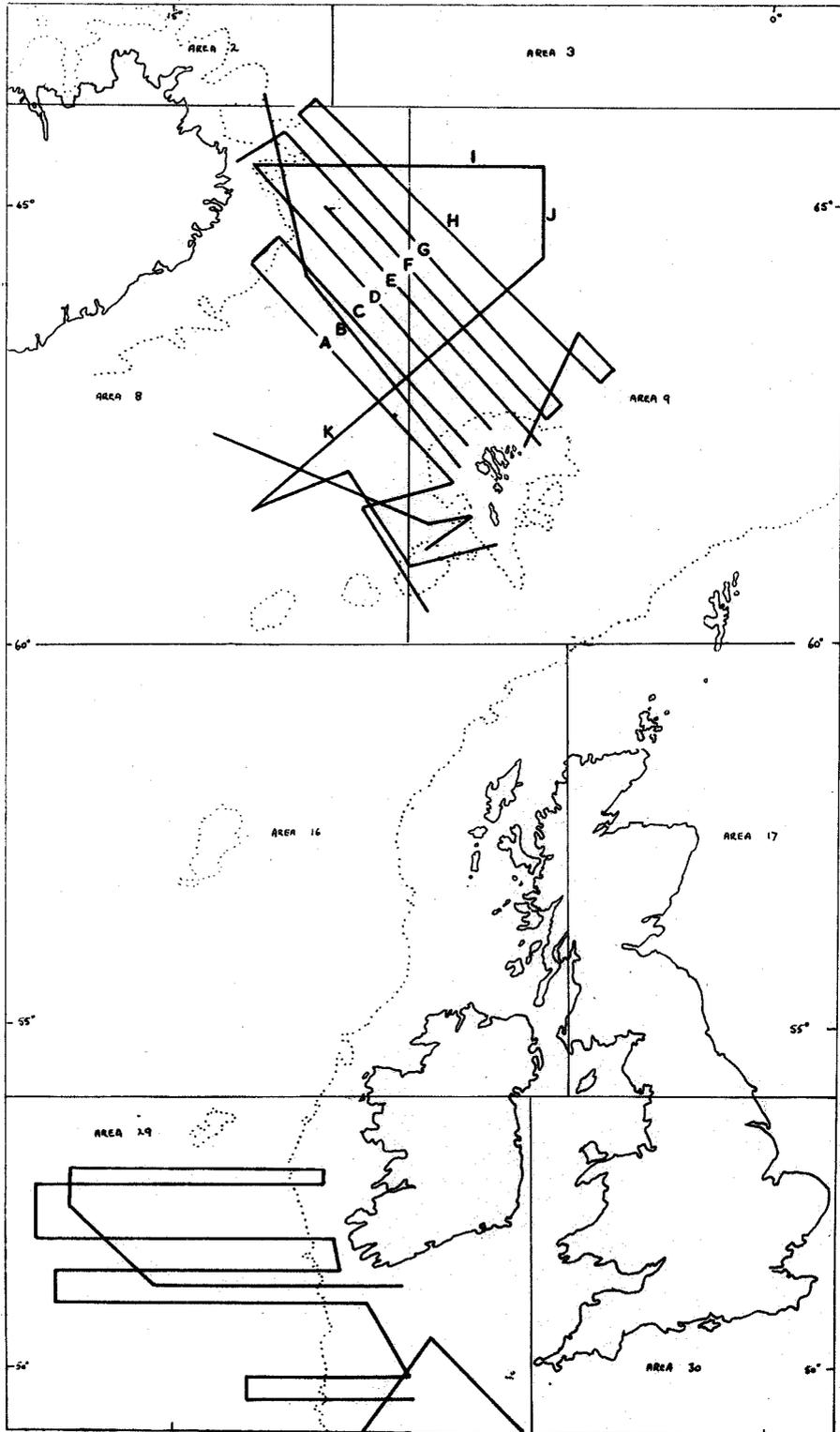
Fig.2.1 Ship's track for Porcupine Bank and Iceland-
Faeroes Rise Surveys

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 Anschutz 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 mgal) on 1 September 1966, and on
the quay at Cork (g_o = 981,244.89 mgal) on 16 September.
The upper spring calibration factor used was F = 64.47 mgal/
(measuring spring division) as supplied by the manufacturer,
and the enograph analogue chart calibration was calculated
as 1.286 mgal/(chart division).   The total drift between
Plymouth and Cork was -3.86 mgal, equivalent to a linear
drift rate of -0.26 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.

Time	Swell w.r.t. ship	Error (m gal)
0255-0345	030°	+8.9 $\pm$ 3.9
0420-0505	210°	-1.6 $\pm$ 3.3
0520-0605	320°	+5.7 $\pm$ 1.3
0645-0750	120°	+2.4 $\pm$ 1.3
0820-0920	300°	+6.4 $\pm$ 1.7

Time	Wind		Swell		
	Dir.	Vel(knots)	Dir.	Period (secs)	Ht.(ft.)
2400	234°	4	230°	-	1
0400	265°	18	-	-	-
0800	270°	13	260	7	6
1200	212	8	210	-	-

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 6mgal.

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,

$$\triangle g = 7.487V \, \sin\phi \, \cos\lambda + .00415V^2 \quad (1)$$

where V = speed of ship in knots

ϕ = true course made good

λ = latitude

The significance of the first term to gravity measurements
at sea was first pointed out by Eötvos and the correlation,
actually the vertical component of Coriolis, is referred to
as the Eötvos 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 Eötvos 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 Eötvos 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°,

$$d(\Delta g) = 52.5(\cos \phi d\phi + \sin \phi \frac{dV}{V}) \qquad (2)$$

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 Eötvos correction of about $\pm$ 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 $\pm$ 8 mgal may exist at the western ends of the lines,

and about $\pm$ 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 (g_o = 981,830.3 mgal) on 27 May 1967 and at Thorshavn, Faeroes

(Lighthouse, g_o = 982,105.33 mgal , King's Monument, g_o = 982,101.10 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 Geodosy and Geophysics, Cambridge University. The upper spring calibration factor used was F = 64.47 mgal/ (measuring spring division) as supplied by the manufacturer, and the enograph analogue chart calibration was calculated to be 1.264 mgal./ (chart division). The drift between Stornoway and Thorshavn (27 May - 7 June) was calculated as a total of -3.1 mgal., a drift rate of -0.29 mgal./day. The drift between Thorshavn on 8 June and Thorshavn on 17 June was calculated as a total of 0 mgal , a drift rate of 0 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 Geodosy and Geophysics, Cambridge University (unpublished report).

| Time | Swell w.r.t. ship | | | Vel (knots) | Cross-coupling Error |
	Dir.	Ht.(ft.)	Period (secs)		(mgal)
2040/153	315°	5	5	8	+8
0930/154	010°	7-10	6	10	+8
1850/154	000°	9	6	6	+3
1855/154	170°	9	6	6	-3
1900/154	170°	9	6	10	-2
1150/155	220°	9	7	10	-15

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 Eötvos 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 Eötvos 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 propellor pitch. Normally the propellor 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 <u>Magnetics</u>

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

recenfly 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.

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                          Digital Record
      |                                        |
      |                                        |
      |                                        |
Digitise                                 Editing
Analogue using
pen-follower
      |                                        |
      |                                        |
      |                                        |
Computer conversion                      Computer conversion
from p-f co-ords                         from readings to
to gamma                                 gamma
      |                                        |
      ↓                                        ↓

Total magnetic field                     Total magnetic field
in gamma                                 in gamma
```
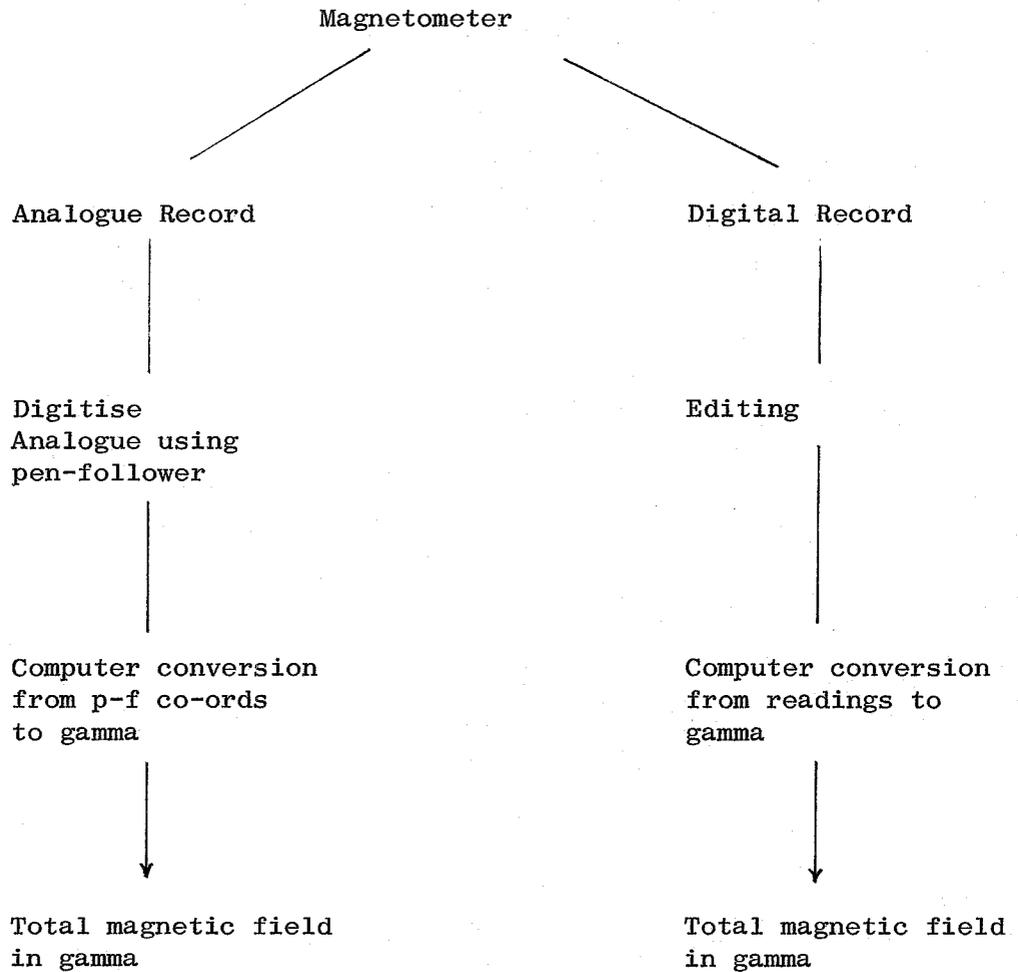
Fig.2.3 Reduction of Magnetic Data

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 centres 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.

Regional gradients
if required

Lat./Long.

Total Mag. field

Estimate of
reg. gradients
east/north if
required

Magnetic data
tape for
automatic
contouring

Magnetic Reduction
Programme

Analogue record
of Res. field
against
distance

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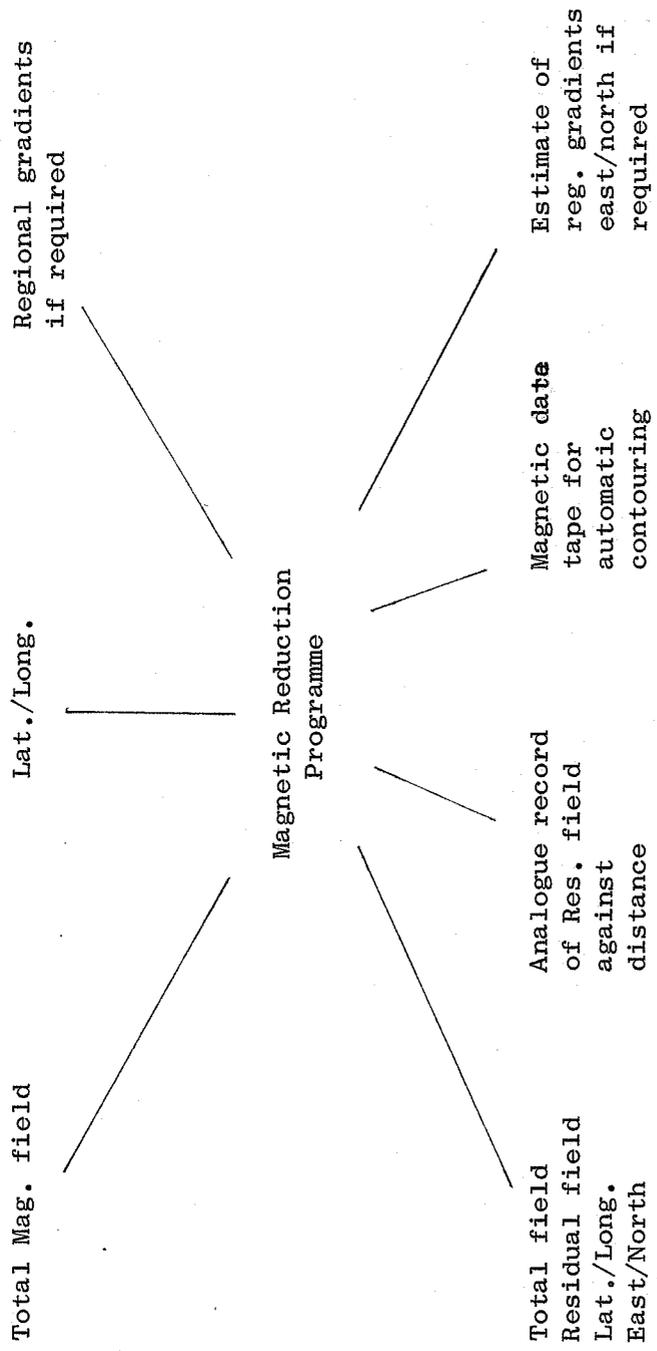Lat./Long.
East/North

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 $xT/x0$ for the x
direction, and $yT/y0$ for the y direction.

xT = Theoretical distance in feet between two meridians on the

same latitude.

xO = Observed distance in feet.

yT = Theoretical distance in feet between two lines of latitude

on the same meridian.

yO = Observed distance in feet.

xT is based upon the equation,

One degree of longitude on latitude $\phi = .017453\ R\cos\phi$

where ϕ 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.

yT is based upon the formula which expresses the distance of

any parallel on a mercator projection map from the equator.

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

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:

Latitude in degrees $= 2\ \tan^{-1}(e^{y'}/R\cos\phi\ -45)$

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 words 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
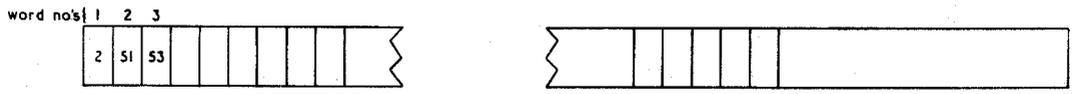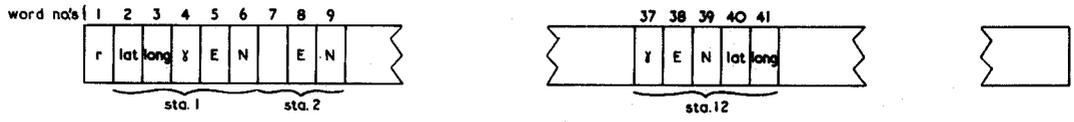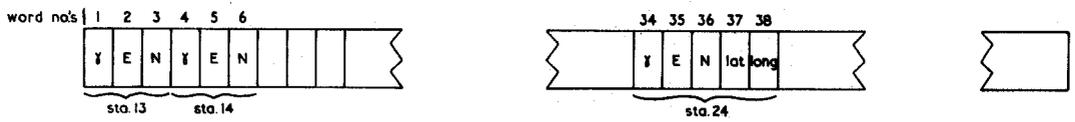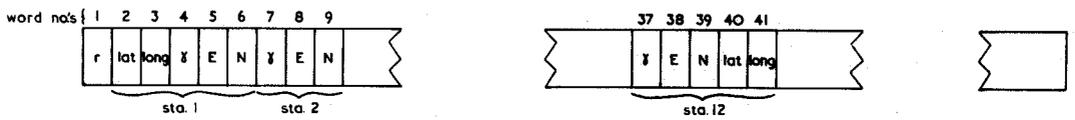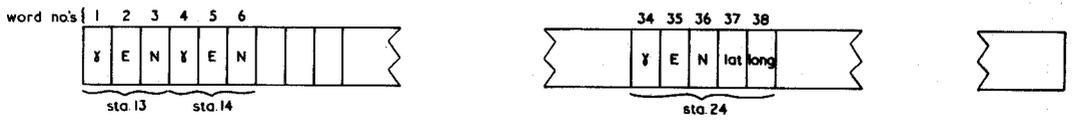
Fig.2.5 Storage of Results on Magnetic Film

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,

Latitude   Longitude   Observed Gamma   Residual Gamma

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 100km.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,

$$A_i = \sum_{j=1}^{m} k_{ij} J_j \quad (i = 1, 2 \ldots n) \quad (1)$$

where the anomaly $A_i(x,z)$ is known at n points and there are

n blocks.   Assuming unit magnetisation, the anomaly at the

ith field point caused by the jth 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,

$$J = k^{-1} A \qquad\qquad (2)$$

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.
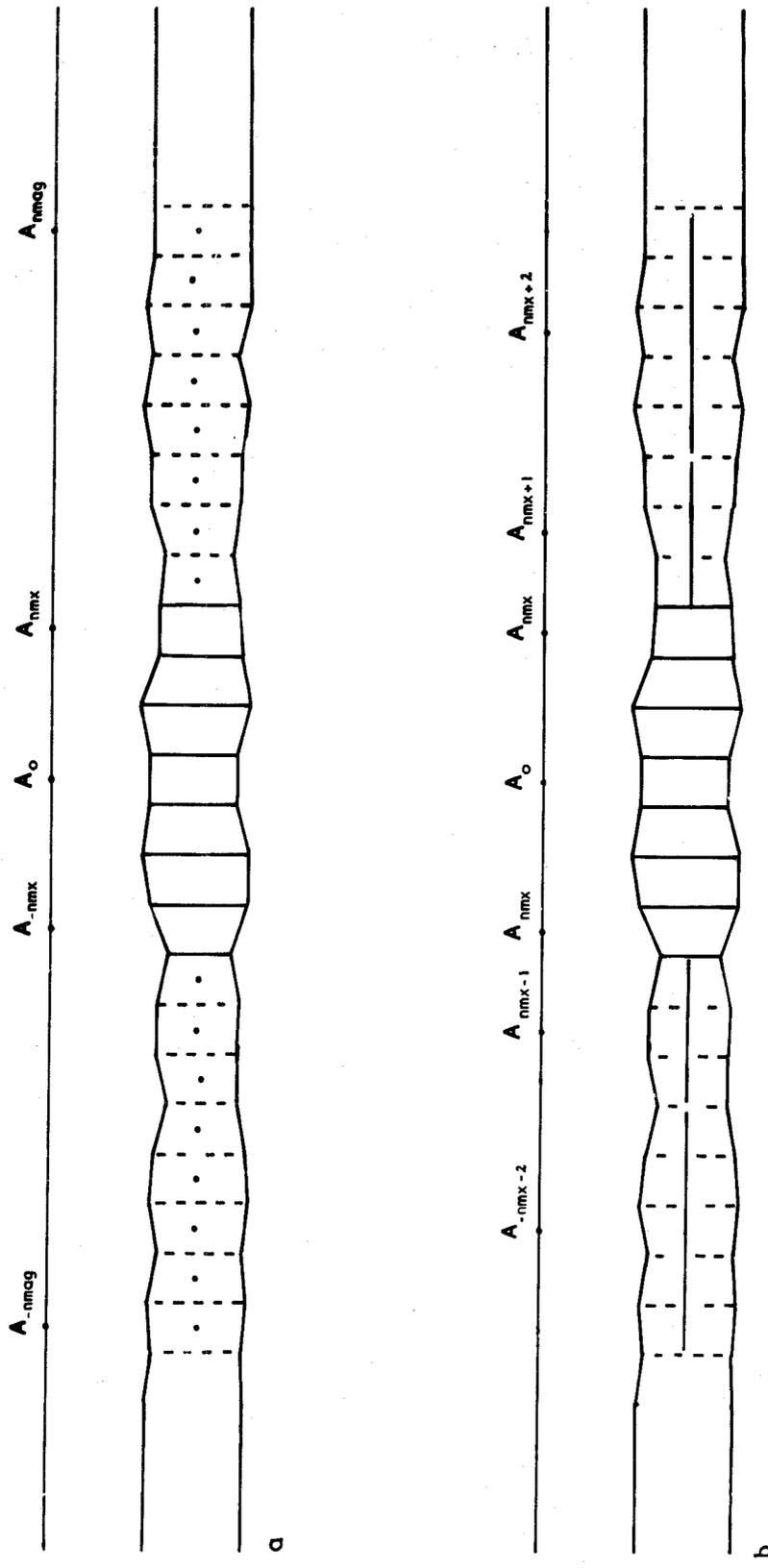
Fig.3.1 Approximation of Blocks : (a) To line dipoles (b) To Magnetic Sheets

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,

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

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_i' (the central row of the inverted matrix W_i). The values of W'_i act as weighting factors in the evaluation of the intensity of magnetisation such that,

$$J = \sum W'_i A_i \qquad (4)$$

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 field from 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,
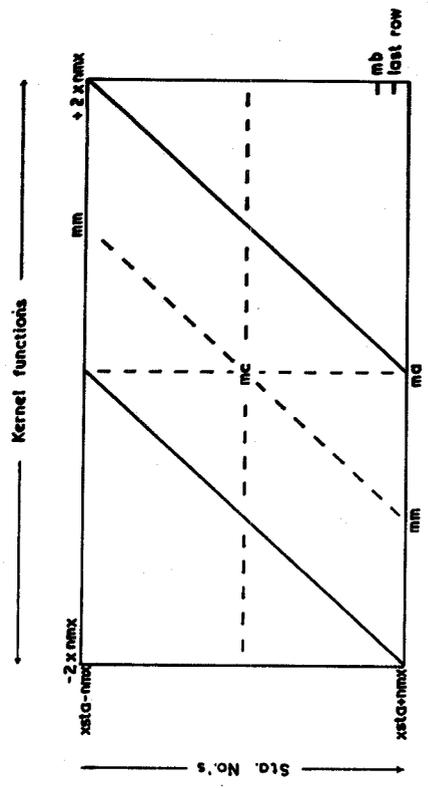
Fig.3.3 Construction of Rectangular Matrix

Fig.3.2 End Corrections
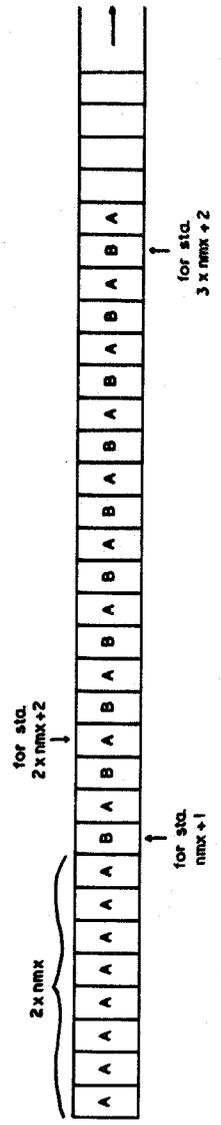
Fig.3.4 Results of Part I on Tape assuming nmx = 4

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 - '$\underline{if}$ count$\leqslant$nmag + 1'

and '$\underline{if}$ 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 ith 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 x nmx + 1 by 2 x 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 x nmx + 1 by 2 x 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 x nmx + 1 by 2 x 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 x nmx+1)X

        (2 x 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 ($p[i]: = p[i+m]$, 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 contruct 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 2xnmx + 7 by 2xnmx + 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 2xnmx + 1 loops of the programme have been completed
the first matrix inversion can be made. The matrix to be
inverted is now the larger 2xnmx + 7 by 2xnmx + 7 square
matrix with the smaller 2xnmx + 1 by 2xnmx + 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 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 nmx + 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 nmx + 1 to 2xnmx + 1 and from nsta - 2xnmx -1 to

nsta-nmx as a reasonable estimate of an anomaly can only be

obtained on the basis of nmx two-dimensional blocks each side

of a field point. This criterion is not satisfied for the first

and last 2xnmx + 1 field points, and so the residual anomaly

is evaluated at field points within the range 2xnmx + 2 to

nsta-2xnmx -1. By a similar argument the iterative corrections

to the intensity of magnetisation for blocks from 2xnmx + 2 to

3xnmx + 2 and from nsta-3xnmx-1 to nsta-2xnmx-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 2xnmx + 2 to nsta-2xnmx - 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 .02 e.m.u./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

diminuition 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 diminuition 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
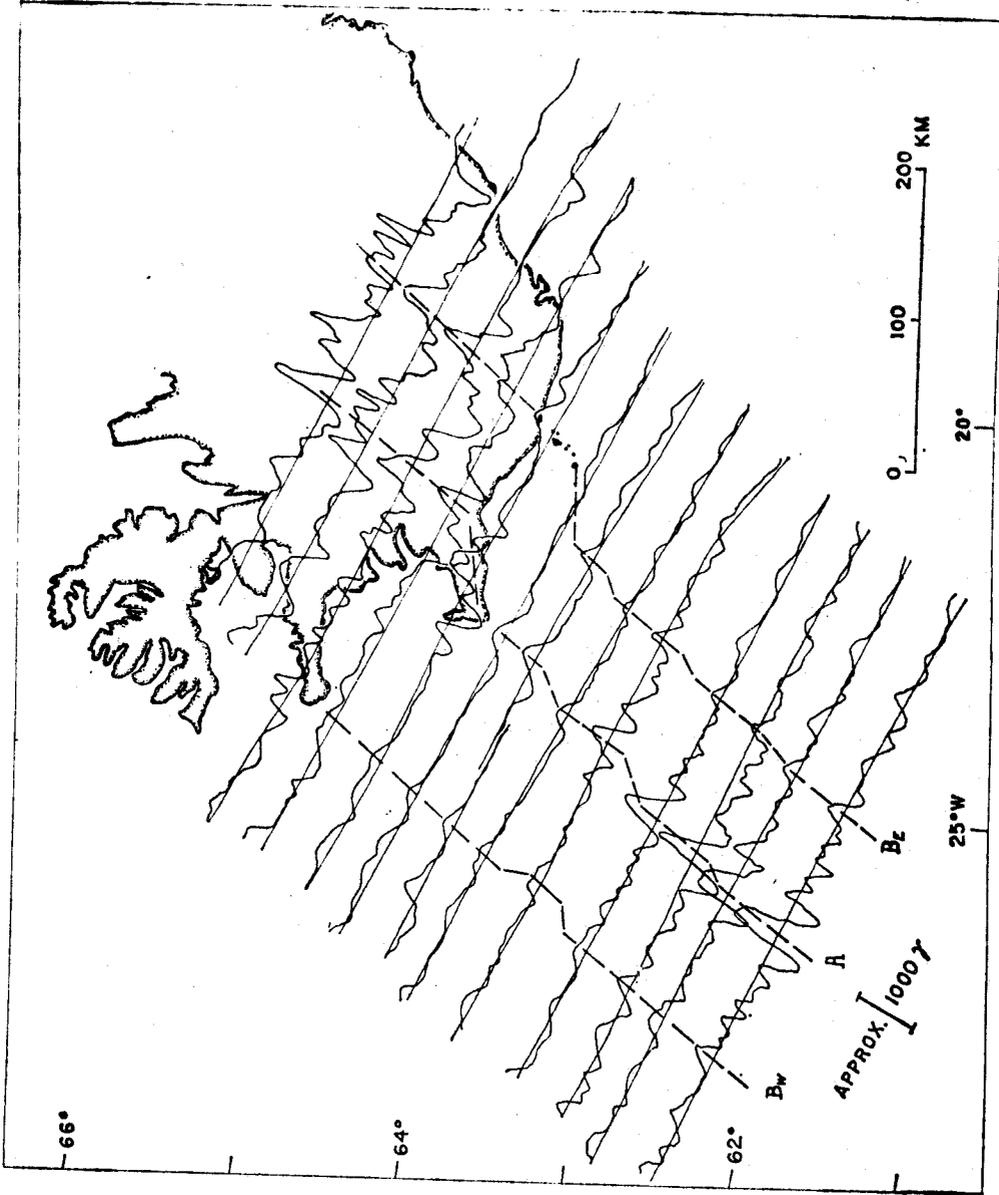
Fig.4.1 Magnetic Anomalies in and S.W. of Ireland (Serson et al.1966)
The Correlations of Anomalies A and B are by Einarsson (1967)

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 ± 2.0 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.

4.2. The Variety of Ocean Magnetic Anomalies: A Criticism of the
     Vine and Matthews Hypothesis.

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

RESIDUAL MAGNETIC INTENSITY CHART OF THE NORWEGIAN SEA
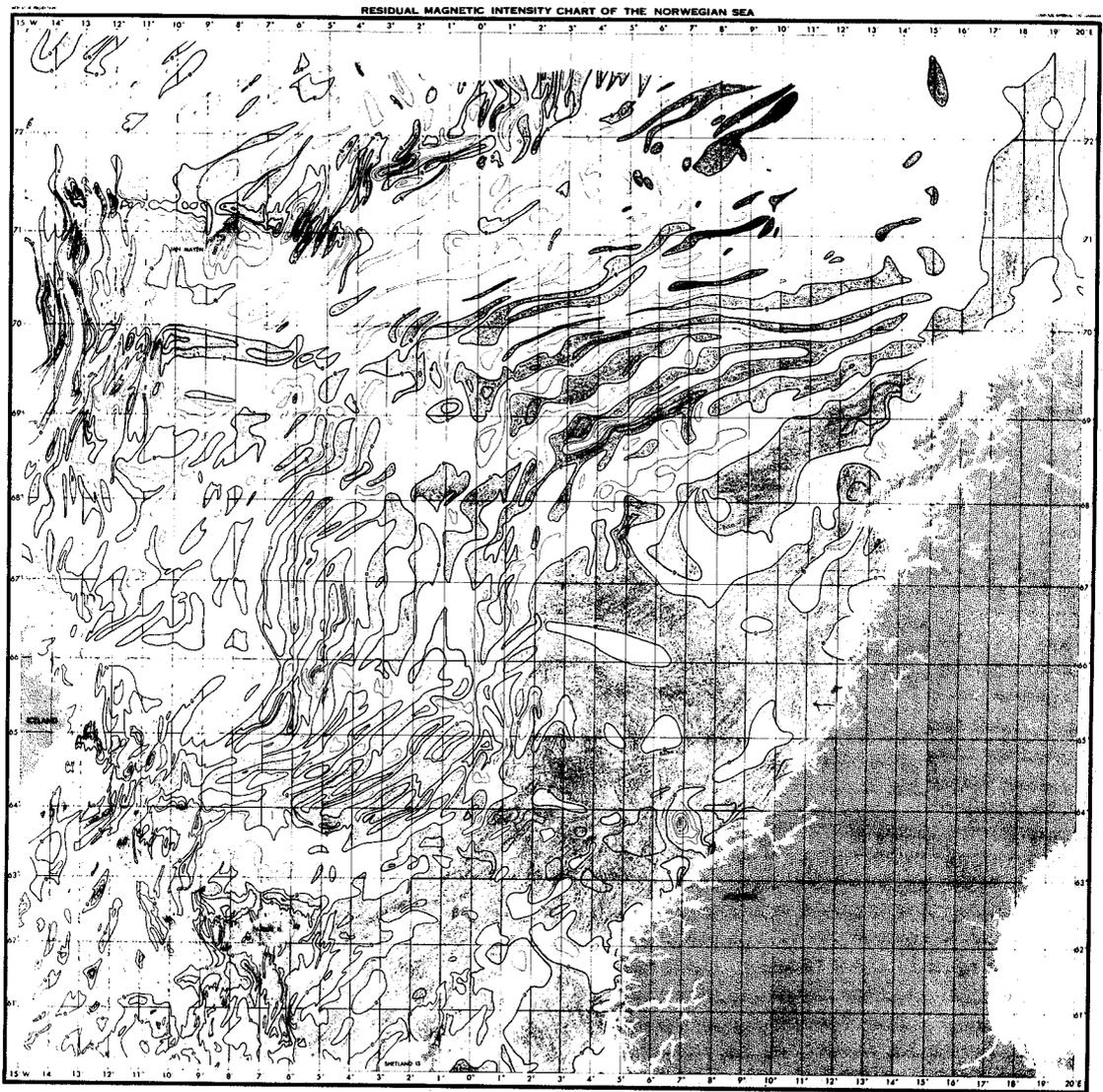
Fig.4.2 Magnetic anomalies over the Norwegian Sea (U.S. Naval
Oceanographic Office)

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
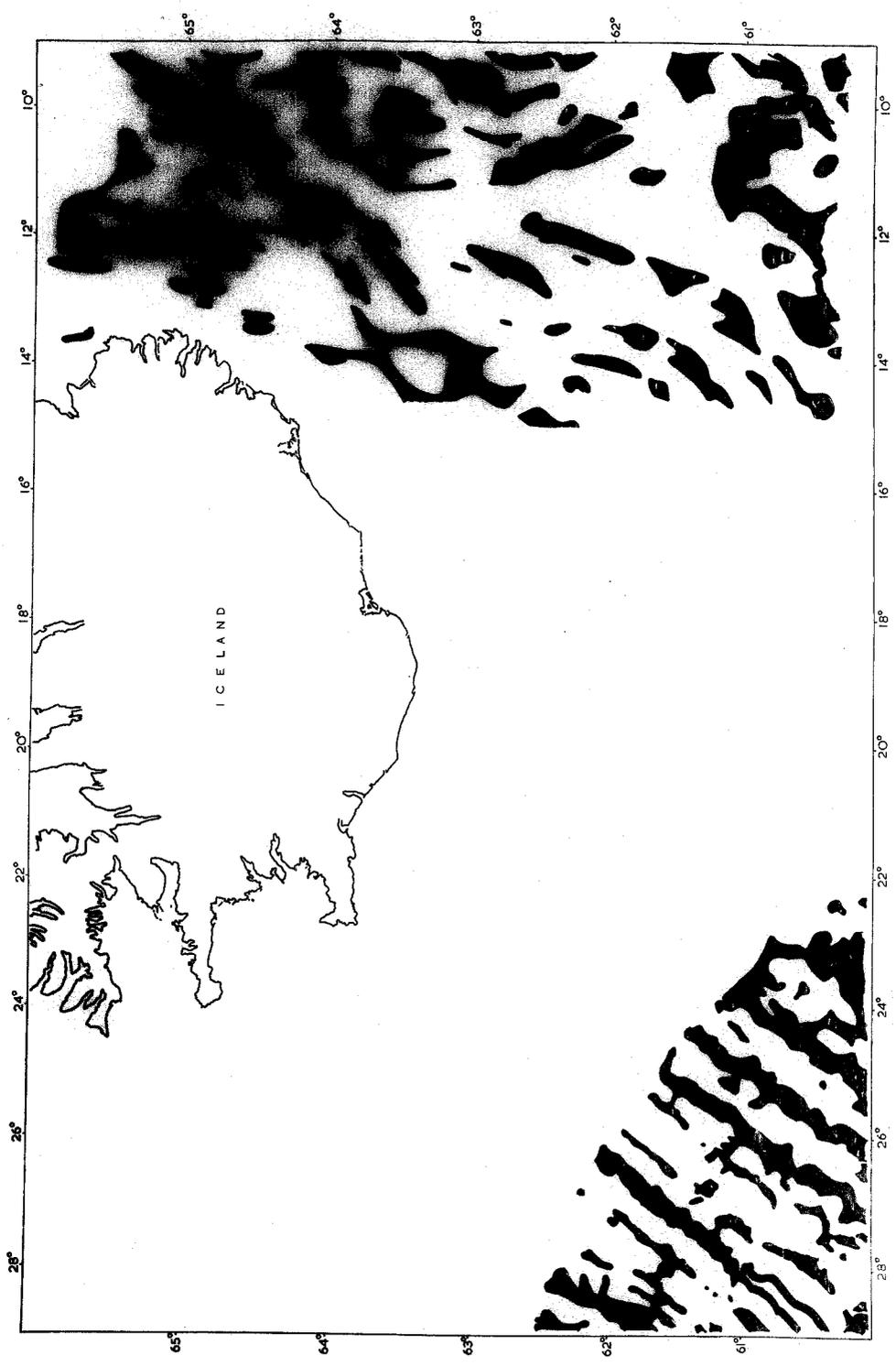
Fig.4.3 Magnetic anomalies associated with the Reykjanes Ridge and the
Iceland-Faeroes Rise

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 Svalboard 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 ac ross 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. *(in press)* 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
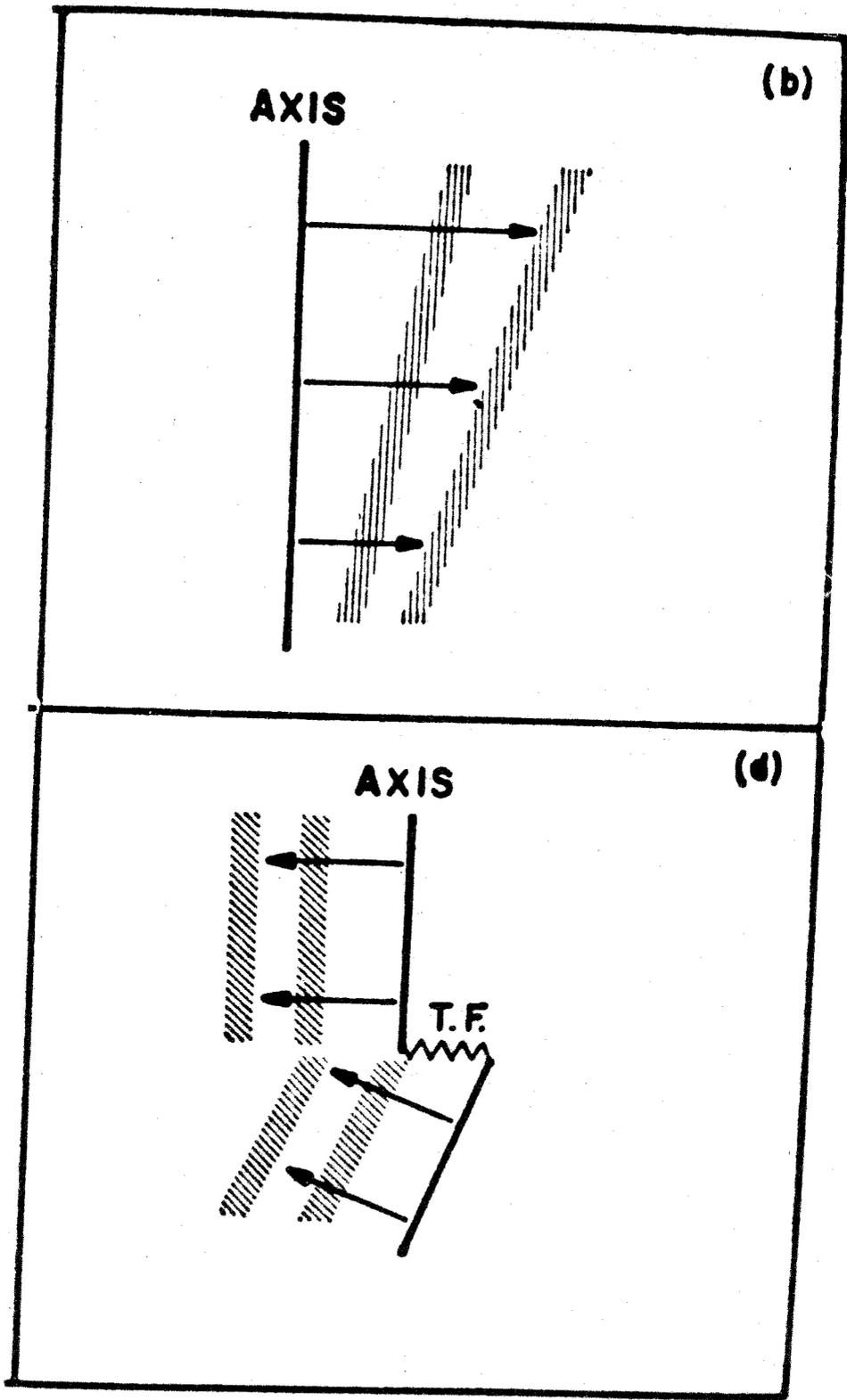
Fig.4.4 Formation of Non-parallel Magnetic Lineations
according to Pitman (1966)

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° 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 intermittant 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
assymetric 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.Thorodsson (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, scoriae 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 Sr^{87}/Sr^{86} 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 exists 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 countour 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.
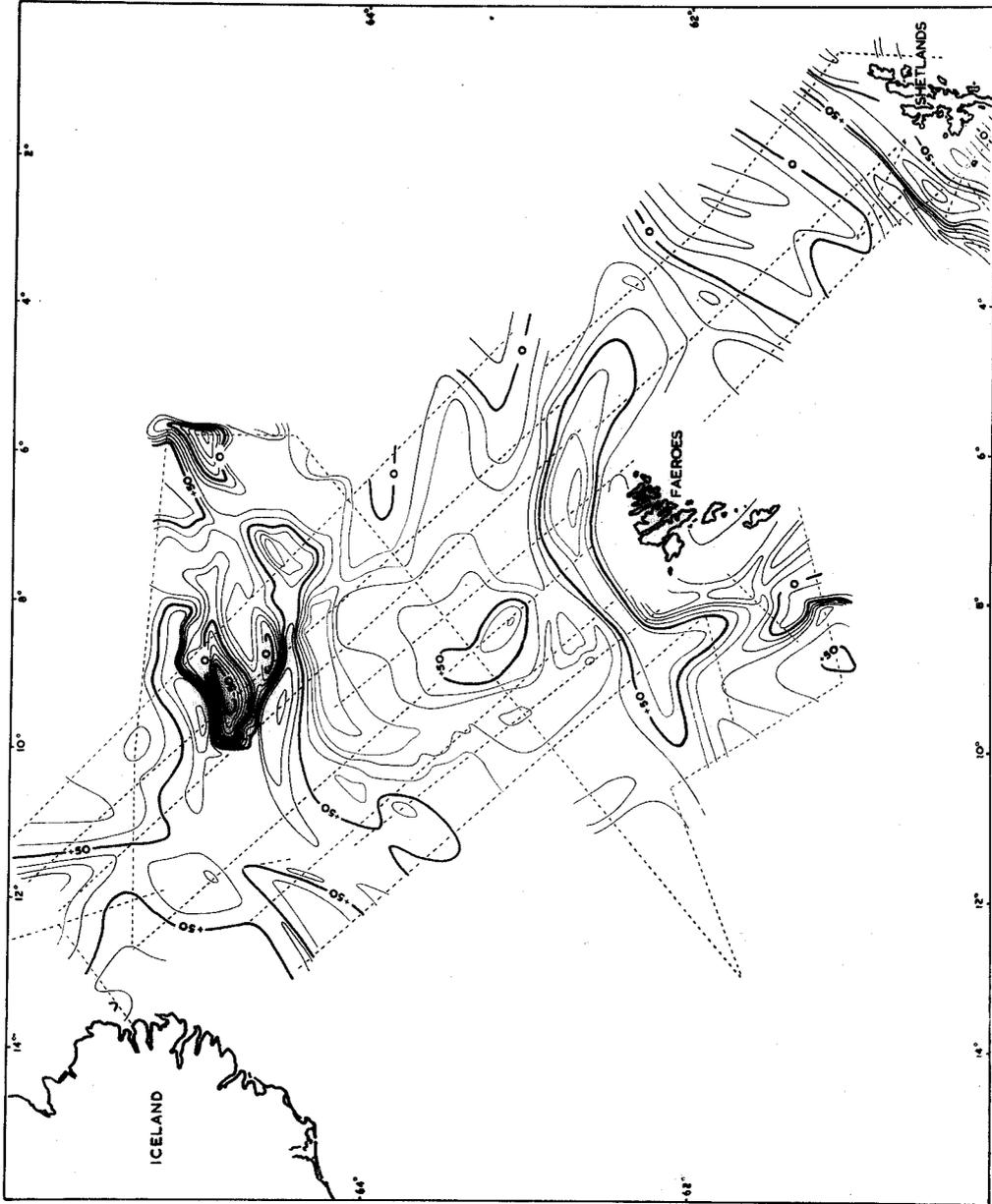
Fig. 5.1 Contoured Free-Air Anomaly Map of the Iceland-Faeroes Rise

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^{O}W) and Breidamerkurdjup (15.8^{O}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 $65^{\circ}19'$ N, longitude
$12^{\circ}45$W and latitude $65^{\circ}35'$ N, longitude $11^{\circ}10'$ 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.
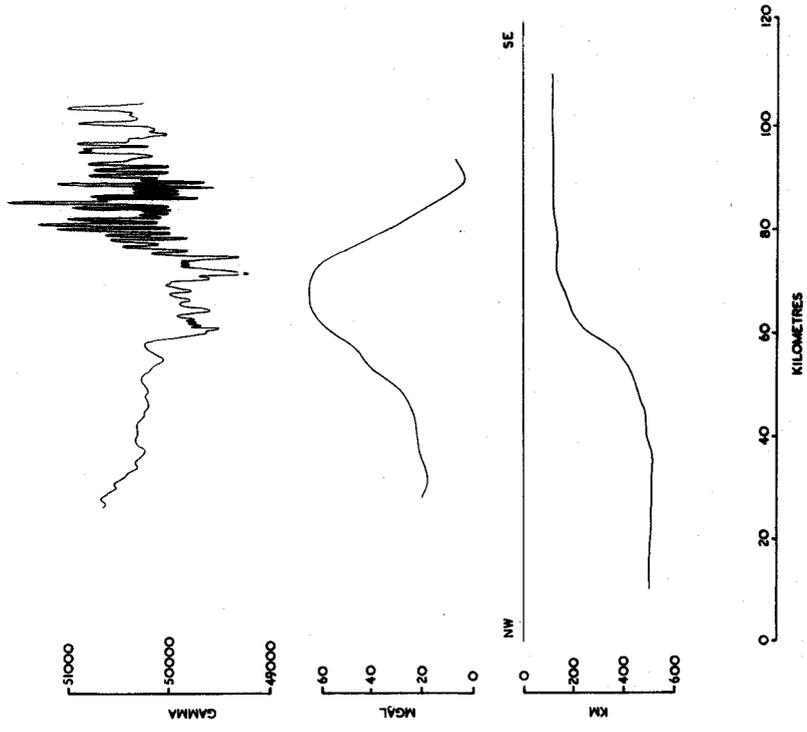
Fig.52b. Shelf Edge off western Faeroes
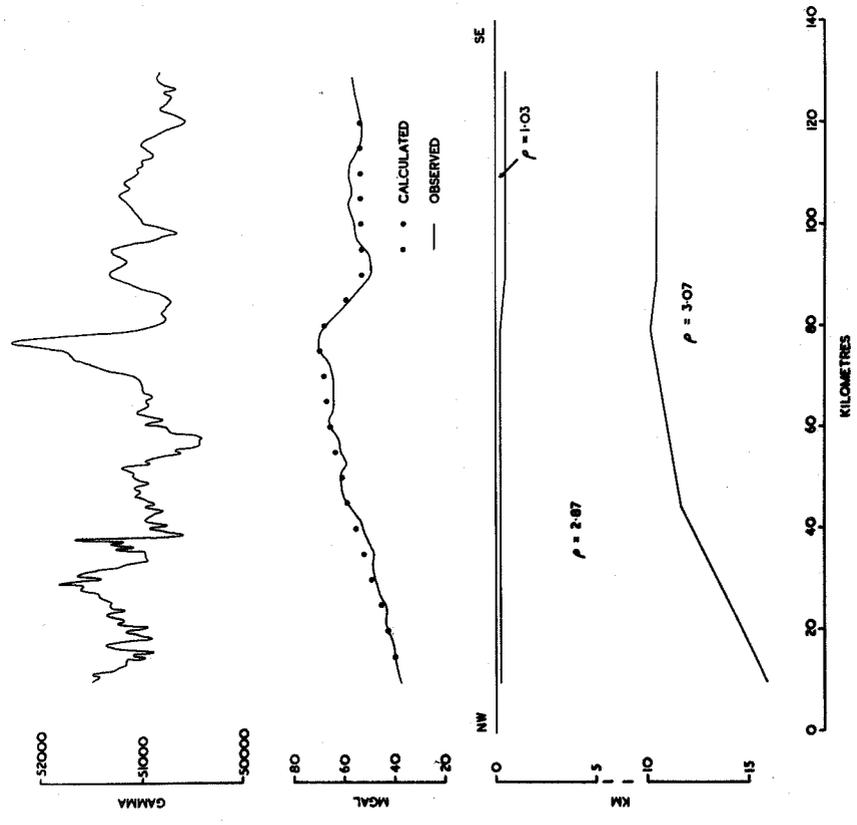
Fig.52a. Shelf Edge off Eastern Iceland

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 $64^{\circ}23'$ N

longitude $5^{\circ}45'$ W to latitude $61^{\circ}38'$ N, longitude $13^{\circ}02'$ 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.
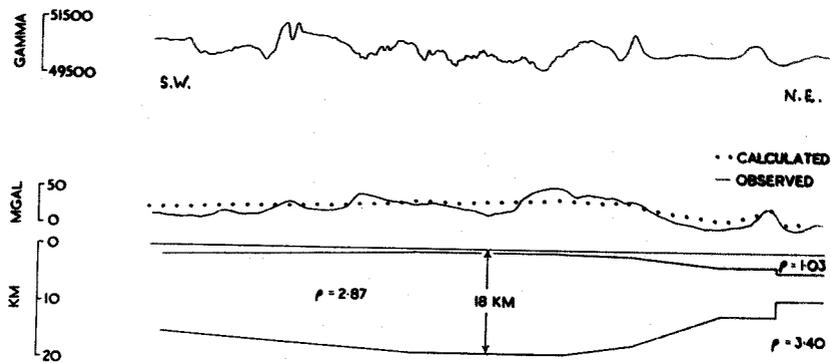
Fig.5.3a. Iceland-Faeroes Rise: Isostatic Model for the Crust
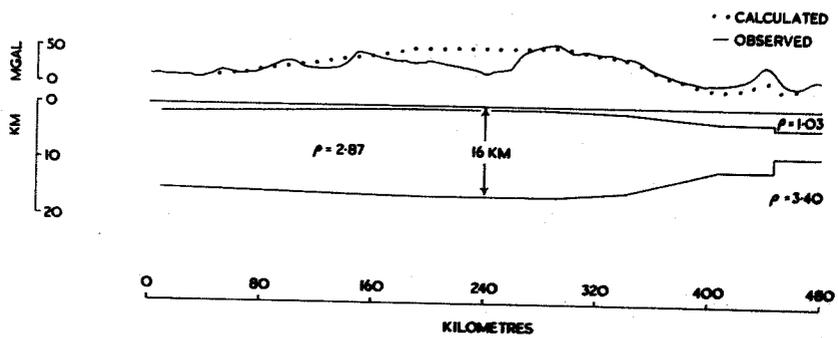
Fig.5.3b. Iceland-Faeroes Rise: Improved Model for the Crust
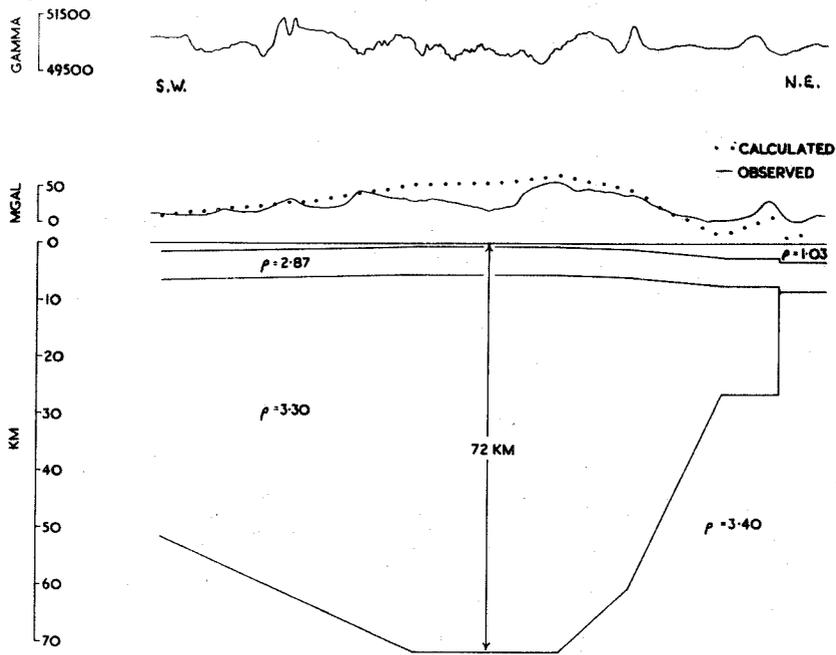
Fig.5.4a. Iceland-Faeroes Rise: Isostatic Model for Crust
and Anomalous Upper Mantle.
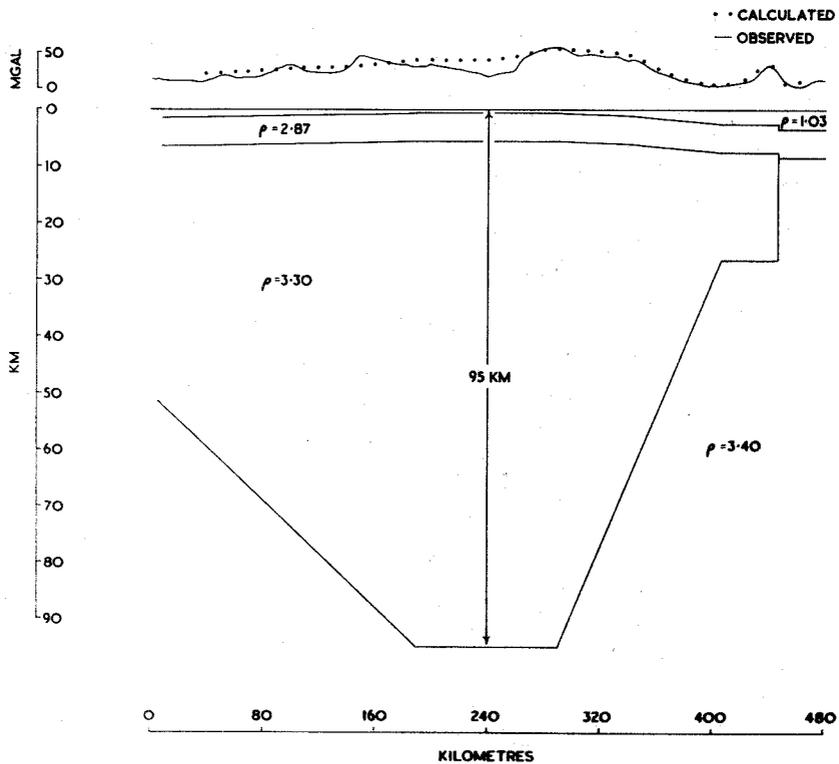
Fig.5.4b. Iceland-Faeroes Rise: Isotatic Improved Model
for Crust and Anomalous Upper Mantle.

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 $62^{o}46'$ N, longitude $9^{o}00'$ W and latitude

$62^{o}09'$ N, longitude $8^{o}05'$ W, see Fig.5.2b. 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-eastern

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°. 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 s eismic reflection results during the R.R.S. John Murray

cruise of this area.   The mid-point of this profile is at latitude

$64^o 10' N$, longitude $6^o 50' W$ 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
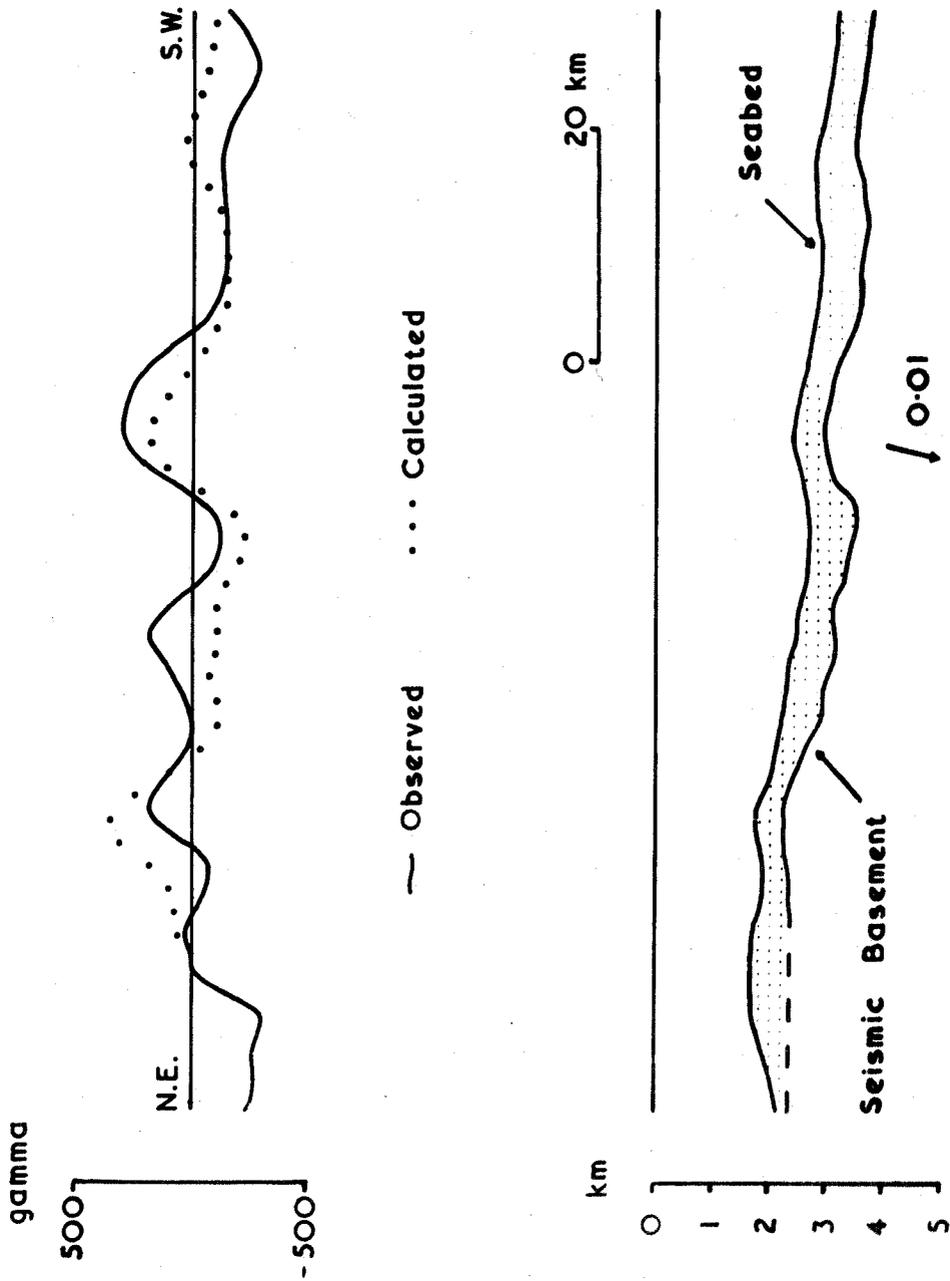
Fig.5.5 Magnetic Anomalies due to the Topography along a Profile across the Norwegian Basin

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 .003 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 .005 emu/cm^3. For each model, the

residuals are less than 1 gamma except at the ends of the profile

gamma

500

N.W.   S.E.

O   20 km

-500

km

O

1

2

3   ← layer 1

4   ← layer 2

5   Base of model 2

6

7   Base of model 1

gamma

10

                                                          residuals

-10

e.m.u./cm³   Model 1

0·01

-0·01

10

                                                          residuals

-10

                              Model 2

0·01

-0·01
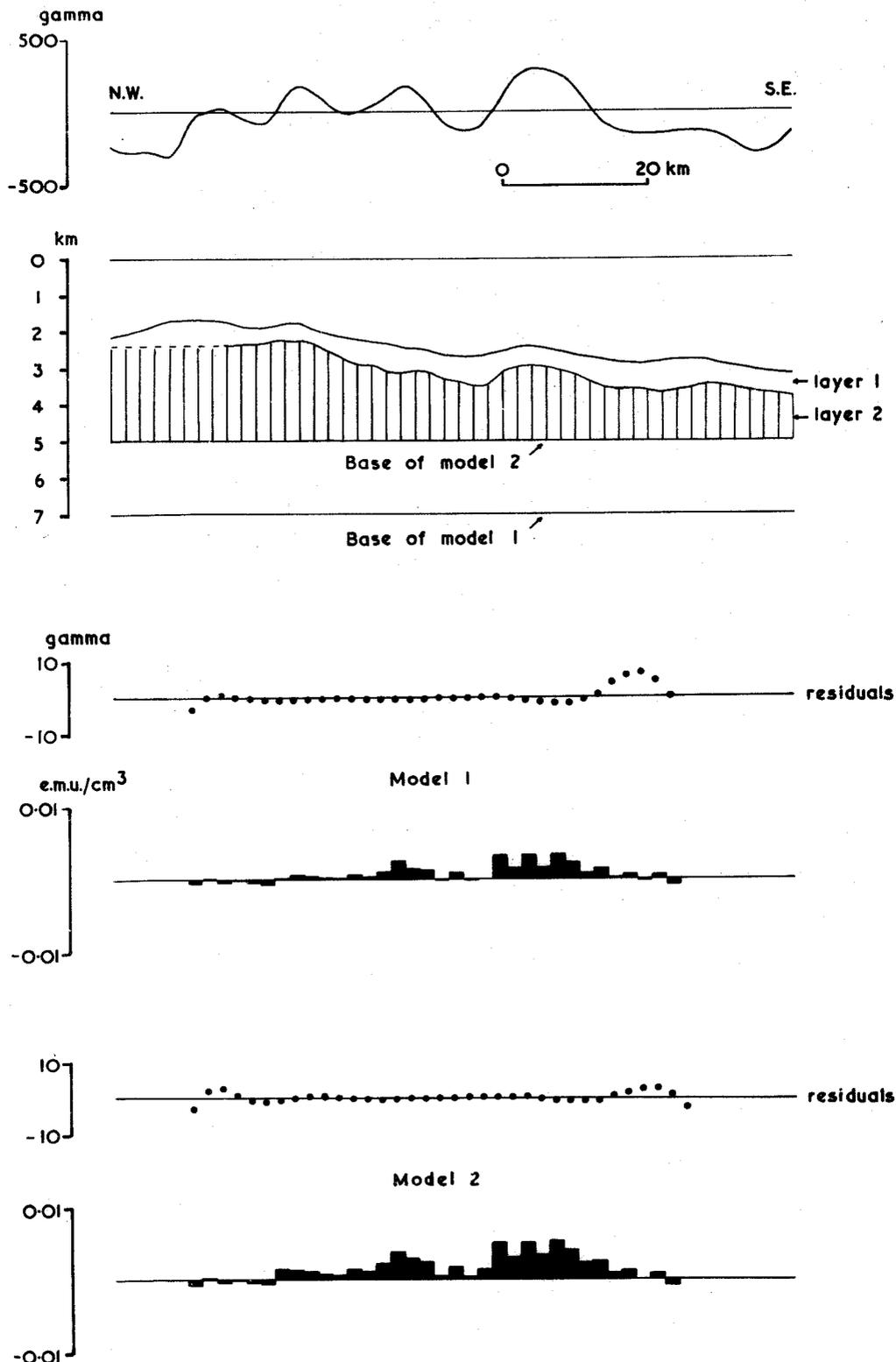
Fig.5.6 Distribution of Magnetisation within the Magnetic Layer
       of the Ocean Crust along a Profile across the Norwegian Basin

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 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 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 assymetric 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' (Assymetric production of oceanic crust

adjacent to area of crustal extension).   The diagrams in Fig.5.7b.
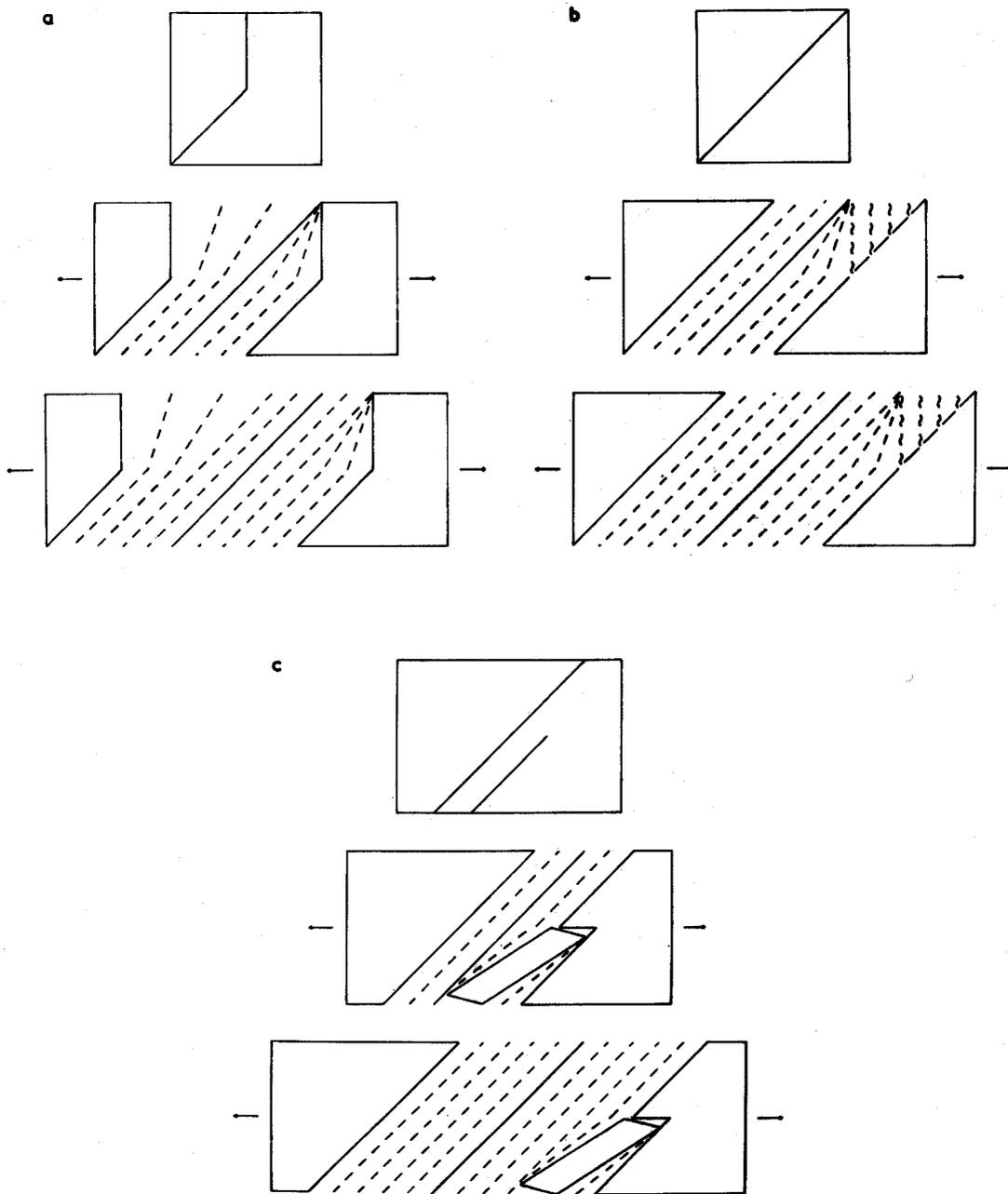
Fig.5.7 Formation of 'Fan-shaped' Ocean Magnetic Lineations

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 is 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.

CHAPTER 6

GRAVITY AND MAGNETIC INTERPRETATION OF PORCUPINE BANK AND PORCUPINE BIGHT

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 oceaniccrust 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°

meridian, but in the west of Ireland the gravity anomalies seem
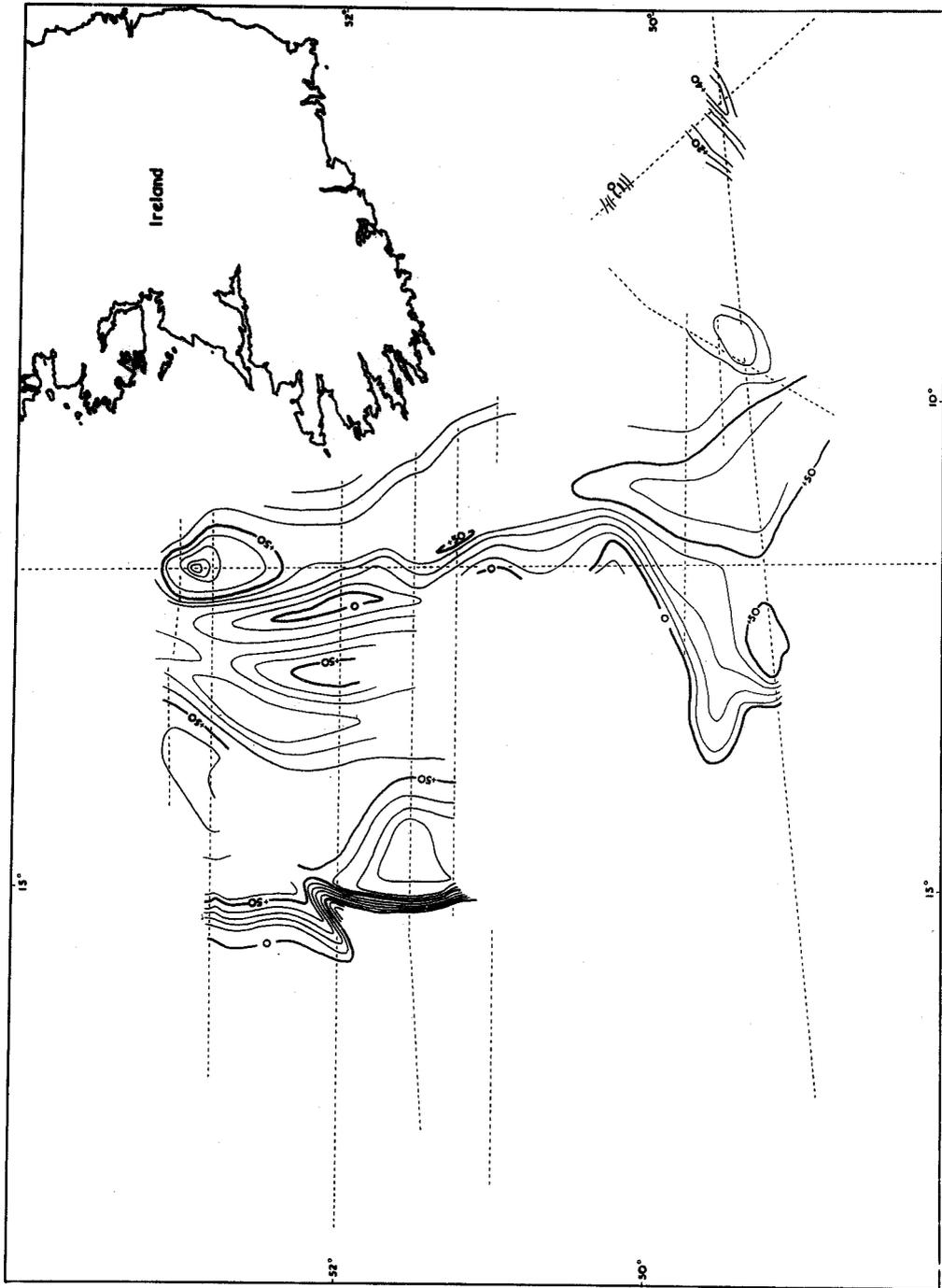
Fig.6.1 Contoured Free-Air Anomaly Map of the Continental Shelf to the South-
west of Ireland
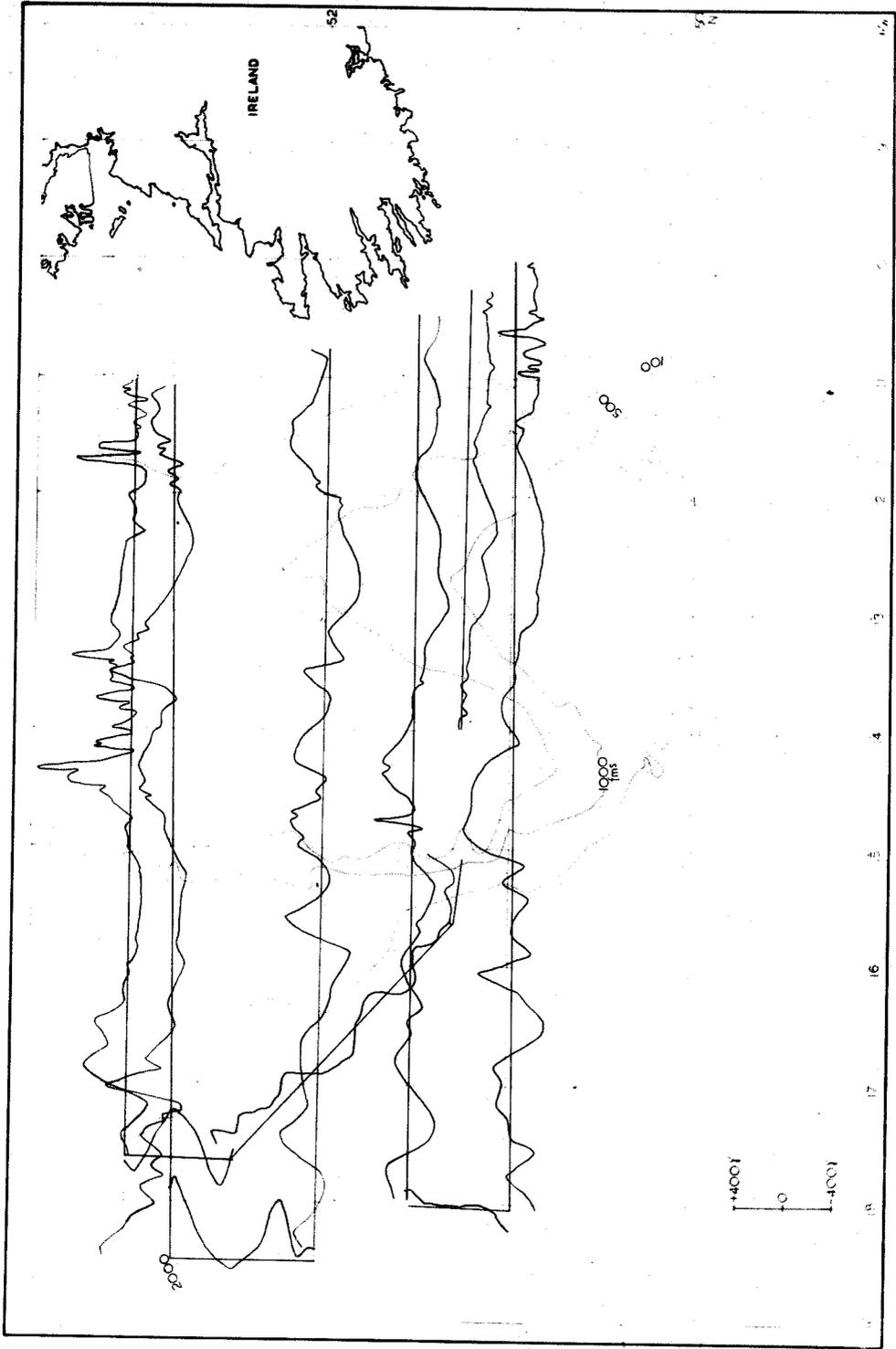
Fig.6.2 Residual Magnetic Anomaly Profiles South-West of Ireland

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
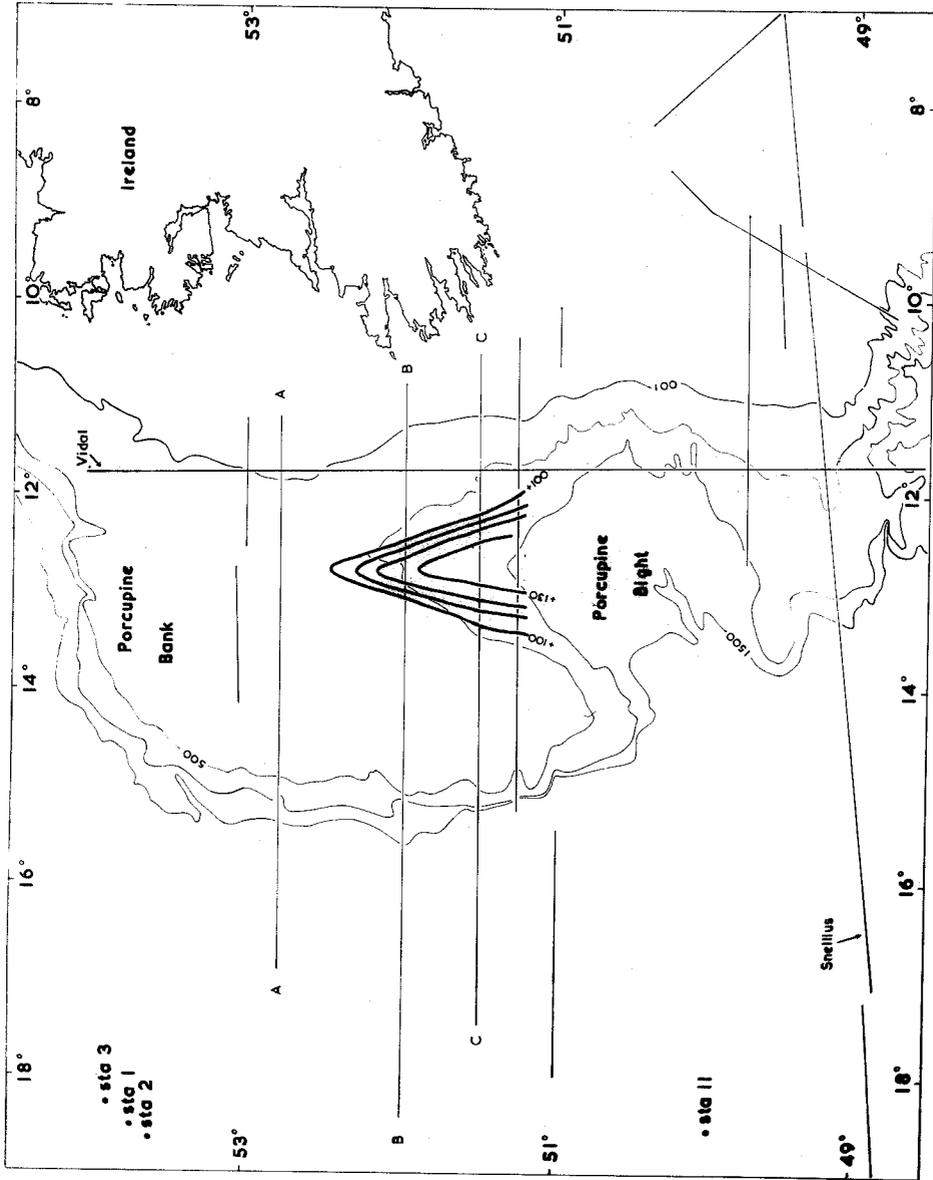
— Bouguer anomaly in milligals; —1500— Bathymetry in fathoms; —— Gravity survey lines.

Fig.6.3 Bouguer Anomaly over Porcupine Bight. Seismic Stations and Bathymetry
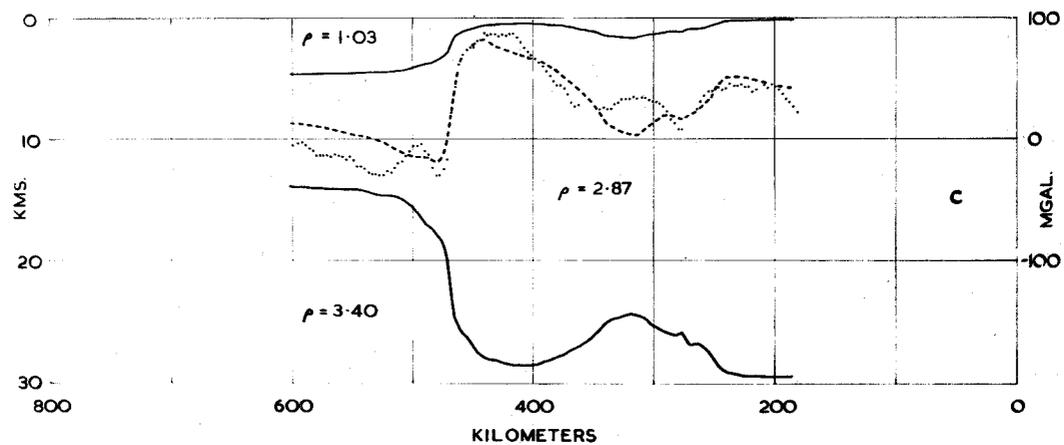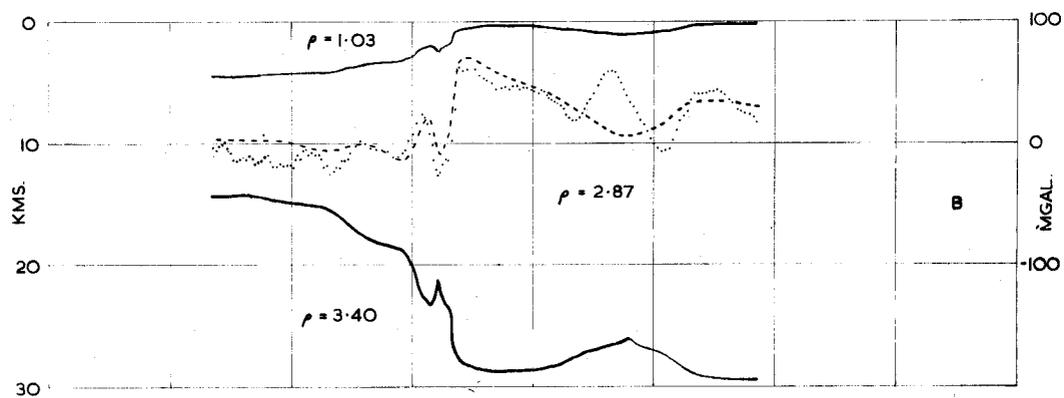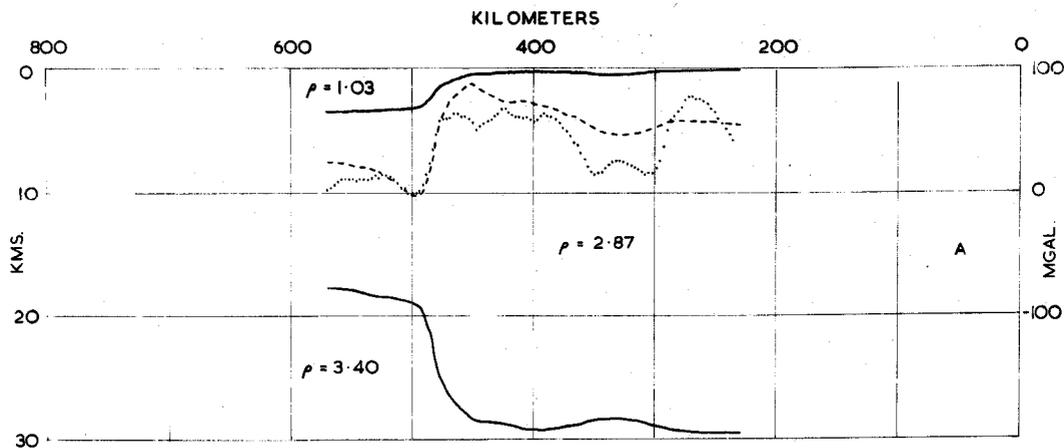
Fig.6.4 Isostatic Models for the Continental Margin west of Ireland

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:-

	Sedimentary Thickness (km)
Station 1	2.96
Station 2	2.78
Station 3	1.88

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 wave length 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 $53^{\circ}15'$ N, longitude $13^{\circ}50'$ 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 $50^{\circ}12'$ N, longitude

$7^{\circ}50'$ 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 $49^{\circ}28'$ N, longitude

$9^{\circ}25'$ 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 ver tical 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 chracteristics of the continental margin of western Europe is the degree of structural control along strike directions 352° and 052°. 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° is closely associated with the Caledonian direction, and a 352° 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 ac tive 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
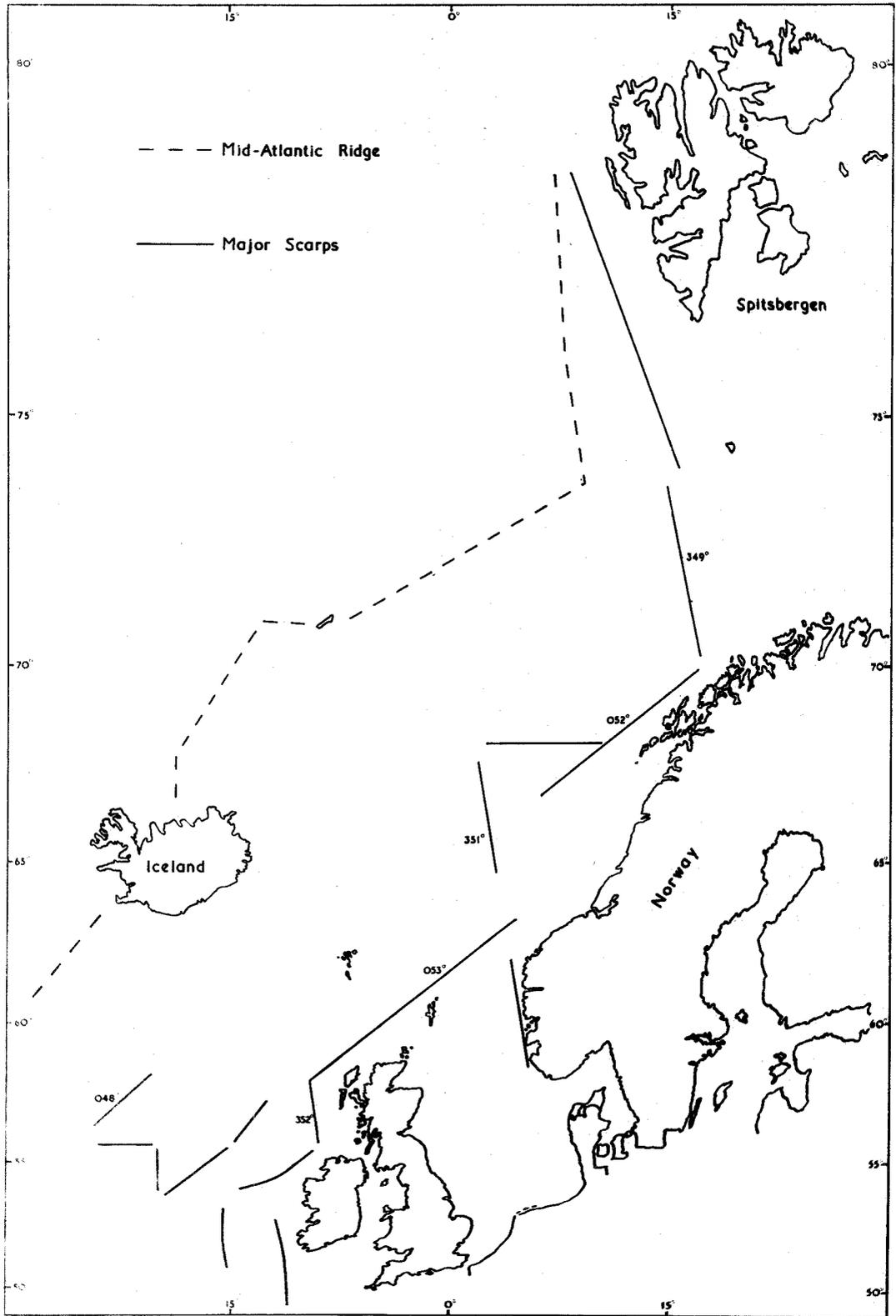
Fig.7.1 Major scarps along the Continental Margin of Western Europe

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 variations 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

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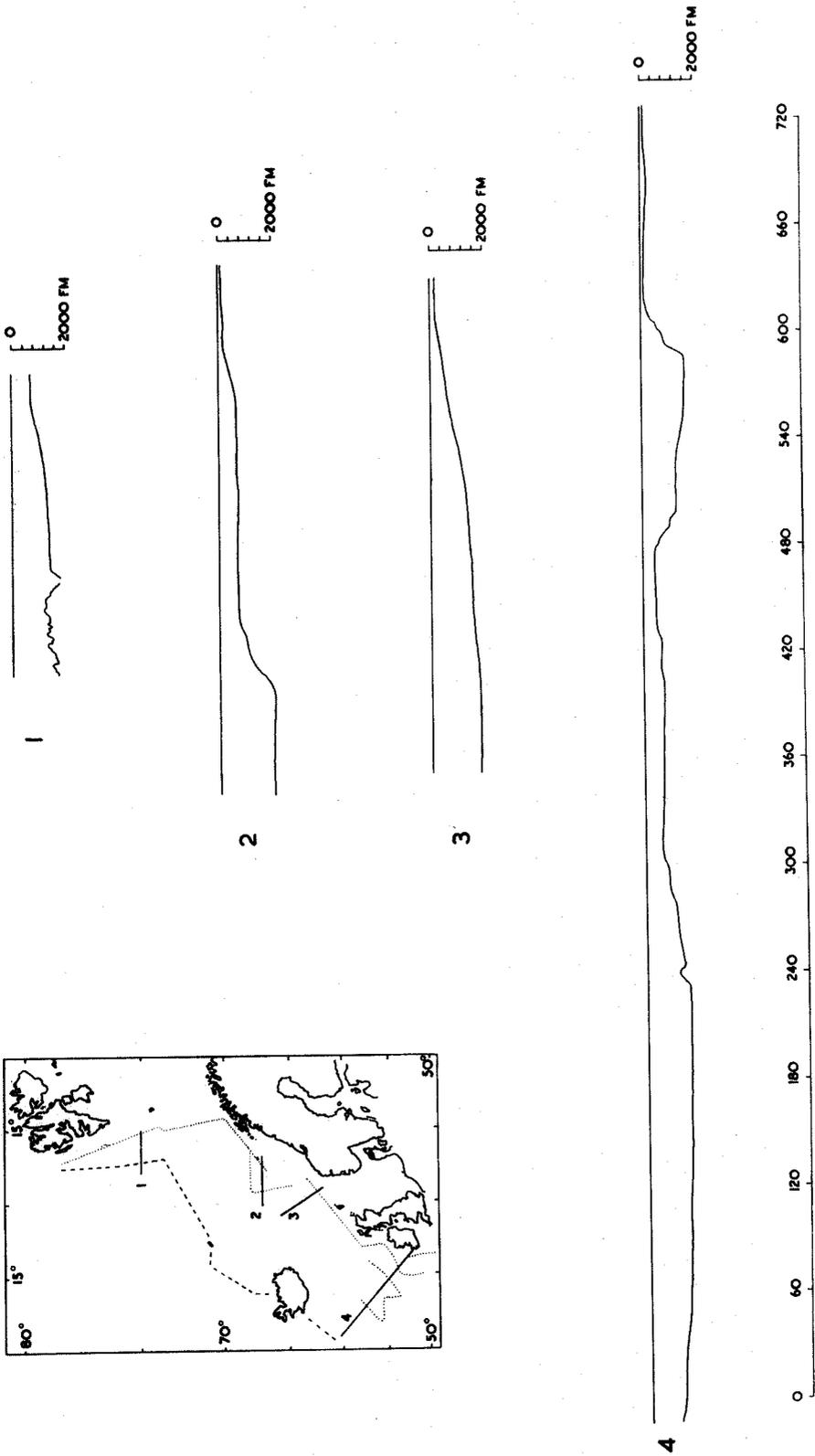
Fig.7.2 Bathymetric Profiles across the Continental Margin of Western Europe

charts produced by the National Institute of Oceanography and the U.S. Naval Oceanographic Office. This is not normally a good method for assessing the nature of the continental slope, but is sufficient to demonstrate the variation in general character.

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°. 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 continenal 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 carespond 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 hydro-
thermal 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 lodes 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.
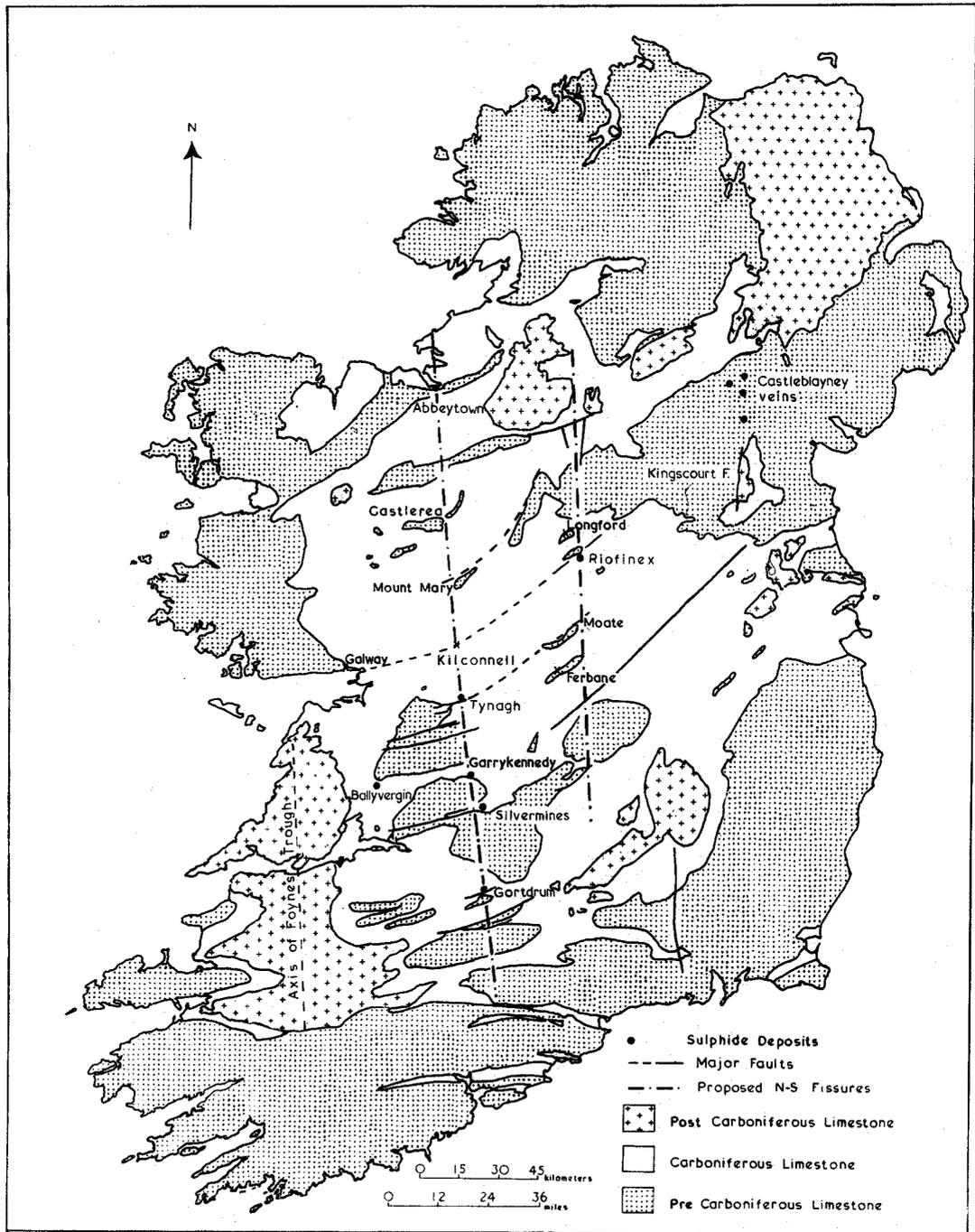
Fig.7.3 Geographical Distribution of Sulphide Deposits
in Ireland

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 contructed 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.

anscale = Scale factor equivalent to width of analogue record in

gamma.

sfac =   Scale factor equivalent to width of analogue record in

pen-follower co-ordinates.

zero =   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).
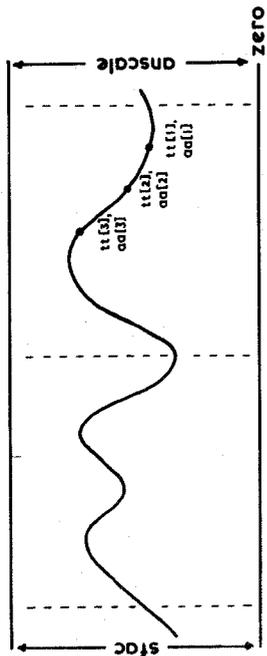
Fig.A.1 Digitisation of Magnetic
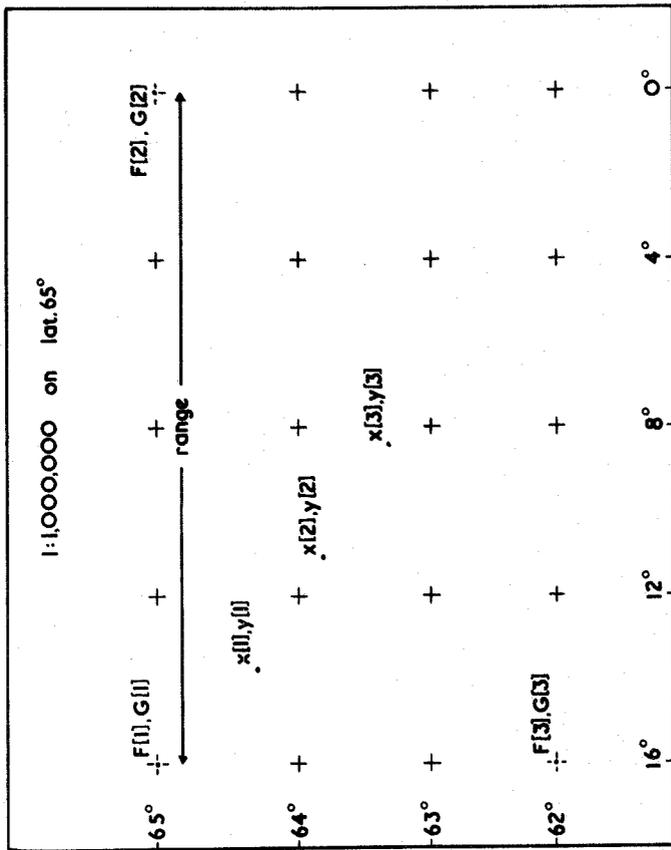Analogue Record
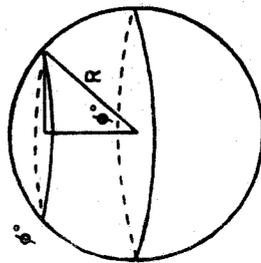

Fig.A.2 Digitisation of Ship's Track

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 = major semi-axis; b = minor semi-axis; ϕ = latitude;

$$e^2 = \frac{a^2-b^2}{a^2}$$

phiO   = Latitude of true origin for square grid; usually chosen

at southern end of survey area.

lamO   = 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(1), y(1) 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(1) should be 5 mins. past the hour.

(e) tt(1) 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 requiredattop 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;

xsta(i); zt(i); zb(i);

where i = 1 to nsta + 1.

Definitions (see Fig.B.1):

|	
nsta =	total number of blocks
nmag =	total number of blocks each side of any station which can be considered to affect the anomaly at that station.
nmx =	number of blocks each side of any station which are to be considered as two-dimensional blocks. Blocks between nmx and nmag will be approximated to line dipoles.
IM =	inclination of the magnetisation within the body in the plane of magnetisation.
IE =	inclination of the Earth's magnetic field in the magnetic meridian
ALFM =	angle measured in an anticlockwise sense from the strike of the body to the azimuth of the plane of magnetisation.
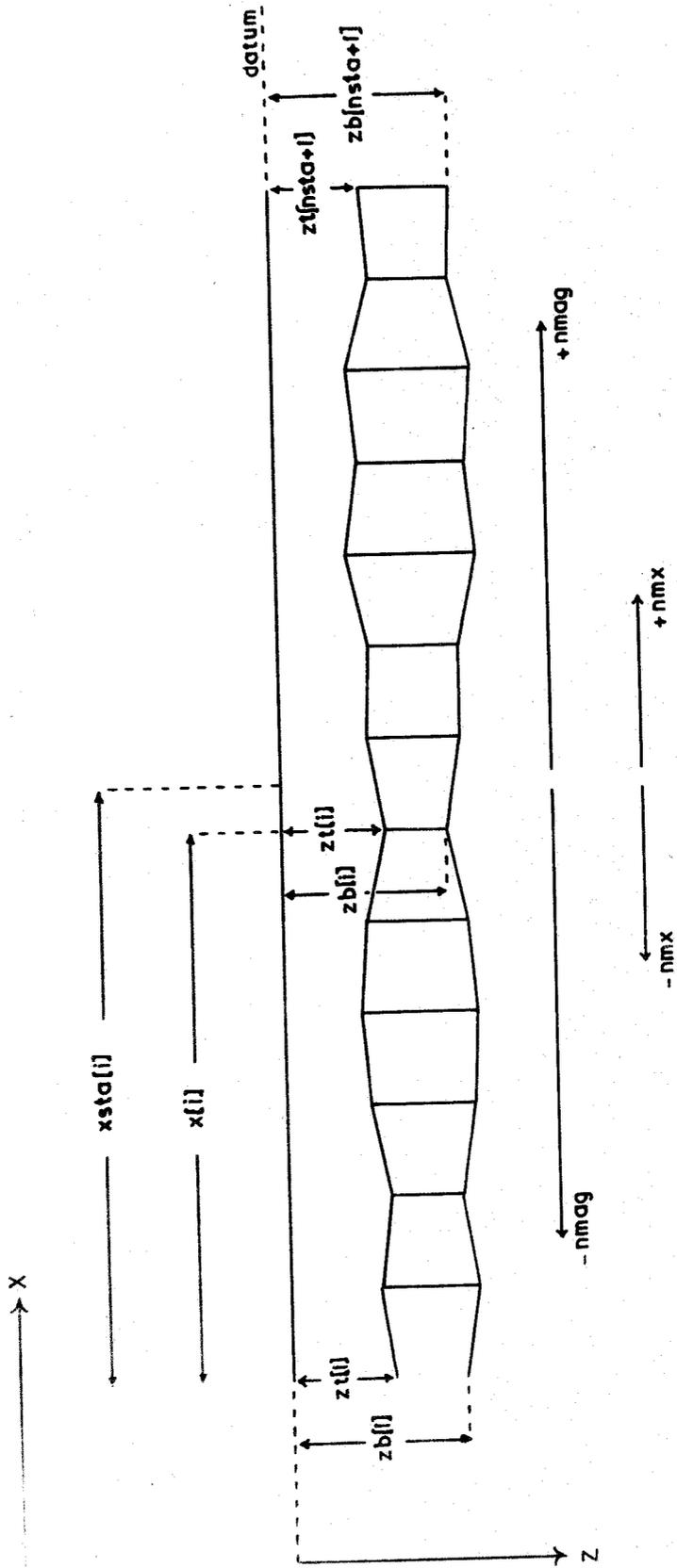
Fig.B.1 Definitions for MXOCEAN MK 2

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.

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