A geophysical investigation of the tertiary volcanic districts of western Scotland

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A GEOPHYSICAL INVESTIGATION OF THE TERTIARY VOLCANIC DISTRICTS

A GEOPHYSICAL INVESTIGATION OF THE TERTIARY VOLCANIC DISTRICTS OF WESTERN SCOTLAND

being

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

by

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Bede College

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Summary

During the period 1955-58, 582 new gravity stations were established in the Western Isles using Worden and Frost gravity meters. The results showed that the Tertiary Plutonic Centres are characterised by high positive Bouguer anomalies, the anomalies over the Skye and Mull centres - +73 mgals. - being the highest yet recorded in the British Isles.

Three main premises were adopted in the geological interpretation of the gravity anomalies:

1. That the similarities between the gravity field over the Tertiary Centres, and those found over active and extinct volcanoes elsewhere, are significant, and imply a similarity of origin and geometry.
2. That the most likely space form, both geologically and gravimetrically, of the subjacent magma chamber is a vertical cylinder widening towards the base and extending downwards into the intermediate layer.
3. That departures from the normal gravity field associated with a vertical cylinder are due to i) the complicating effects of the lighter granitic masses seen at the surface and ii) an over simplification in the original model.

It seems likely that the anomalous mass would be more accurately represented by a series of interacting vertical cylinders situated beneath the individual centres within a

plutonic complex, rather than by a single cylinder.

A theoretical model consistent with the magnitude of either the Skye, or the Mull anomaly, has a diameter of 11 miles and a similar depth. Obviously the presence of these large basic masses within the granitic layer creates a large, and hitherto unsuspected, 'basaltic space problem' which can only be resolved by assuming a stoping type of mechanism.

The associated granites and granophyres have little effect on the main positive anomaly and are generally less than a mile in thickness. Their space form is laccolithic rather than batholithic and serves to emphasise the difference between the Tertiary granites and the post tectonic granites.

A gravity low in North Skye is interpreted as a Triassic trough some 2000 feet deep underlying the Jurassic. Another 'low' in Sleat is believed to be the result of a thickening of the lighter Torridonian above the Kishorn Thrust. The gravity field over the Ross of Mull granite is unlike that normally associated with either Tertiary or Caledonian granites, and a suggested interpretation is that the granite is in the form of a wedge terminating to the west along the line of the Moine Thrust.

Finally, the origin of the Tertiary basalts is discussed as the result of major rifting of the crust and a phase change within the mantle.

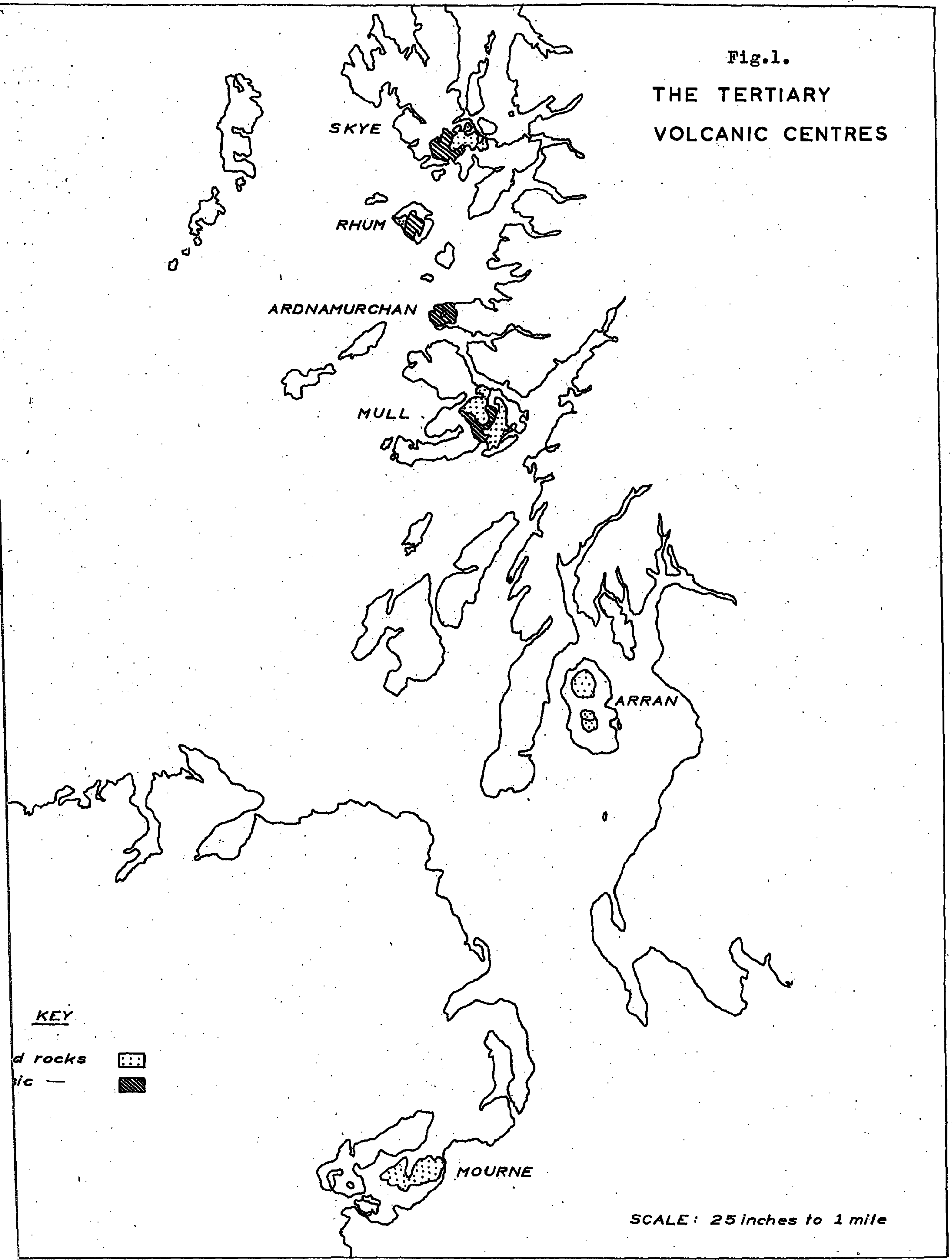


Fig.1.

THE TERTIARY VOLCANIC CENTRES

Chapter 1

GRAVITY ANOMALIES AND VULCANISM

The evidence of things unseen is the principal characteristic of our science (Jaggar).

The majority of the information about both modern and extinct volcanoes has resulted from geological field studies and laboratory experiments. Of necessity, this study has been confined to the limited vertical section exposed at the surface, and of the underlying magma chambers comparatively little is known. This fact was emphasized by Williams (1954) who in a paper on the problems facing volcanology wrote: 'Much light might be thrown on this question of the shape and depth of reservoirs by geophysical exploration, especially in volcanic fields that rest on foundations whose structure is simple and whose stratigraphy is known.' Whilst Professor Williams probably had active volcanoes in mind, the gravity results already obtained by Cook and Murphy over the extinct Tertiary volcanoes of Slieve Gullion and Carlingford, suggested that a gravity survey of the Tertiary Volcanic Centres of Western Scotland could have considerable interest. And so the present work was undertaken in order to investigate the shape and depth of the postulated magma chambers beneath the Tertiary centres. The half-hope was also entertained that the results might help to elucidate certain problems of petrogenesis and origin. Unfortunately, the study appears to have created several new problems in addition to those which it has solved.

Although much of the stratigraphy of the Inner Hebrides is known, the structure could not be said to be simple, and of the geophysical methods available gravity alone is a practical proposition. The seismic method is expensive and, owing to the complexity of the basement structure, it is doubtful if the results could be interpreted when obtained. Magnetic measurements could be of value in Arran, but in the other centres, the strong magnetic field associated with both the basalts and the gabbros would preclude the use of any instrument more sensitive than a compass. Airborne magnetic survey may be of value.

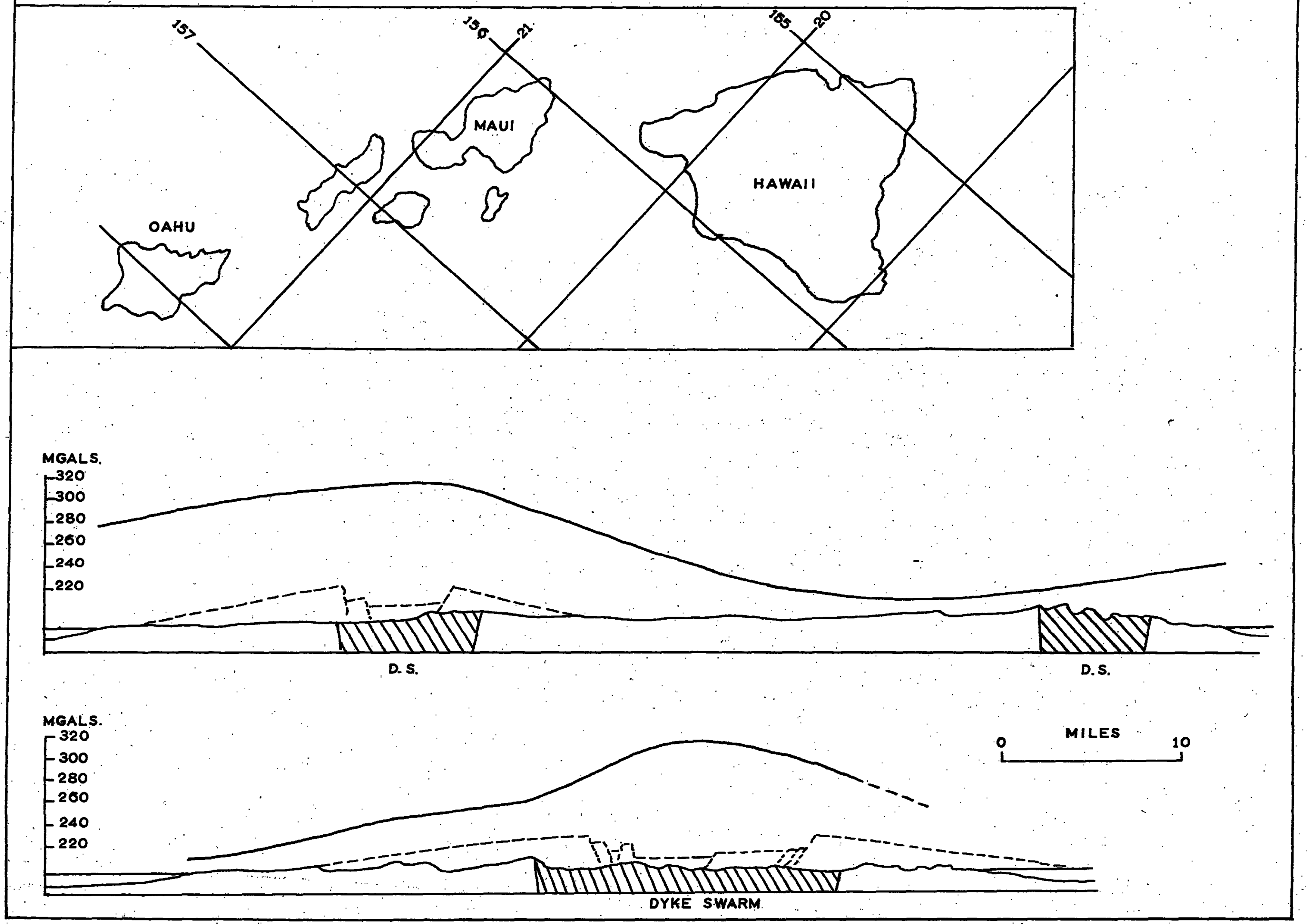
If the Tertiary Plutonic Centres are - as Judd suspected - the basal wrecks of great central volcanoes, then their gravity field should resemble the gravity field over recent and modern volcanoes. The application of this rough geophysical uniformitarianism leads to the corollary that, if the observed gravity fields are similar both in the size of the anomaly and its disposition, then the causes of the field are similar, and the interpretation can proceed on similar lines. Thus, an examination of the gravity field over modern and recently extinct volcanoes could have considerable value for the present work. Unfortunately, evidence is scanty, and as is so often the case, the results are in the form of the isostatic anomaly; and the effects which might reasonably be attributed to the geology have tended to become lost in the mathematical manipulations.

General association of gravity anomalies and vulcanism

Regions other than Great Britain

It has long been axiomatic that the inner volcanic island

ANOMALIES


157
156
21
155
20
MAUI
HAWAII
OAHU
MGALS.
320
300
280
260
240
220
D. S.
D. S.
MGALS.
320
300
280
260
240
220
DYKE SWARM
0
MILES
10

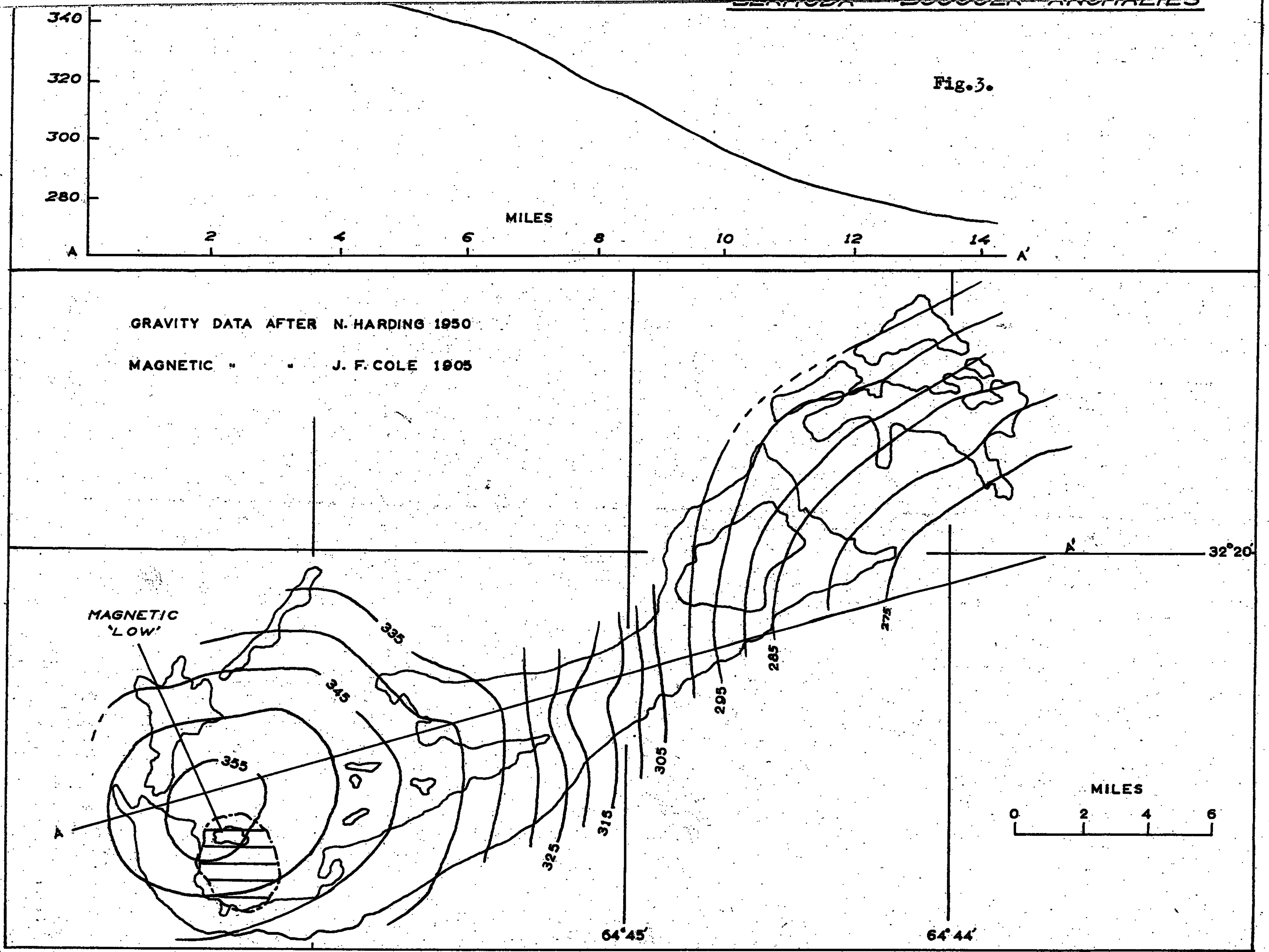
arcs have positive Bouguer anomalies. The volcanic line is one of maximum gravity; crustal warping bringing the higher density lower layers nearer to the surface. Generally the evidence is insufficient to determine the form of the magma chambers.

<u>Hawaii</u>

Much of the geophysical controversy which has ranged around the Hawaiian volcanoes has been concerned with the testing of the various isostatic hypotheses and determining the strength of the crust beneath the Pacific. Of the form of the underlying magma chamber little is known gravimetrically. Seismic evidence indicates the existence of a magma chamber at a depth of some 60 kilometres (Jones 1938). This is well below the Mohorovicic discontinuity and presumably represents the ultimate source of the basaltic magma before it rises into higher level sub crustal magma chambers. This, perhaps, supports Kuno's contention that a basaltic magma can be derived only by a partial melting of the sub-Mohorovicic peridotite layer.

The neighbouring island of Oahu has been investigated in some detail by Vening Meinesz (1934) and Woollard (1954). The geology is fairly simple, the island having been formed by the coalescence of basaltic material from two volcanic domes.

The Bouguer anomaly profiles (Fig. 2) show a close correlation with the geology, two gravity highs of 110 mgals each, corresponding with the ancient volcanoes of Waianae and Koolau. There is, however, no noticeable distortion of the gravity field over the later and smaller centres of volcanic eruption.



340
320
300
280
MILES
2
4
6
8
10
12
14
A
A'
GRAVITY DATA AFTER N. HARDING 1950
MAGNETIC " " J. F. COLE 1905
MAGNETIC 'LOW'
335
345
355
325
315
305
295
285
275
32°20'
64°45'
64°44'
MILES
0
2
4
6

Fig.3.

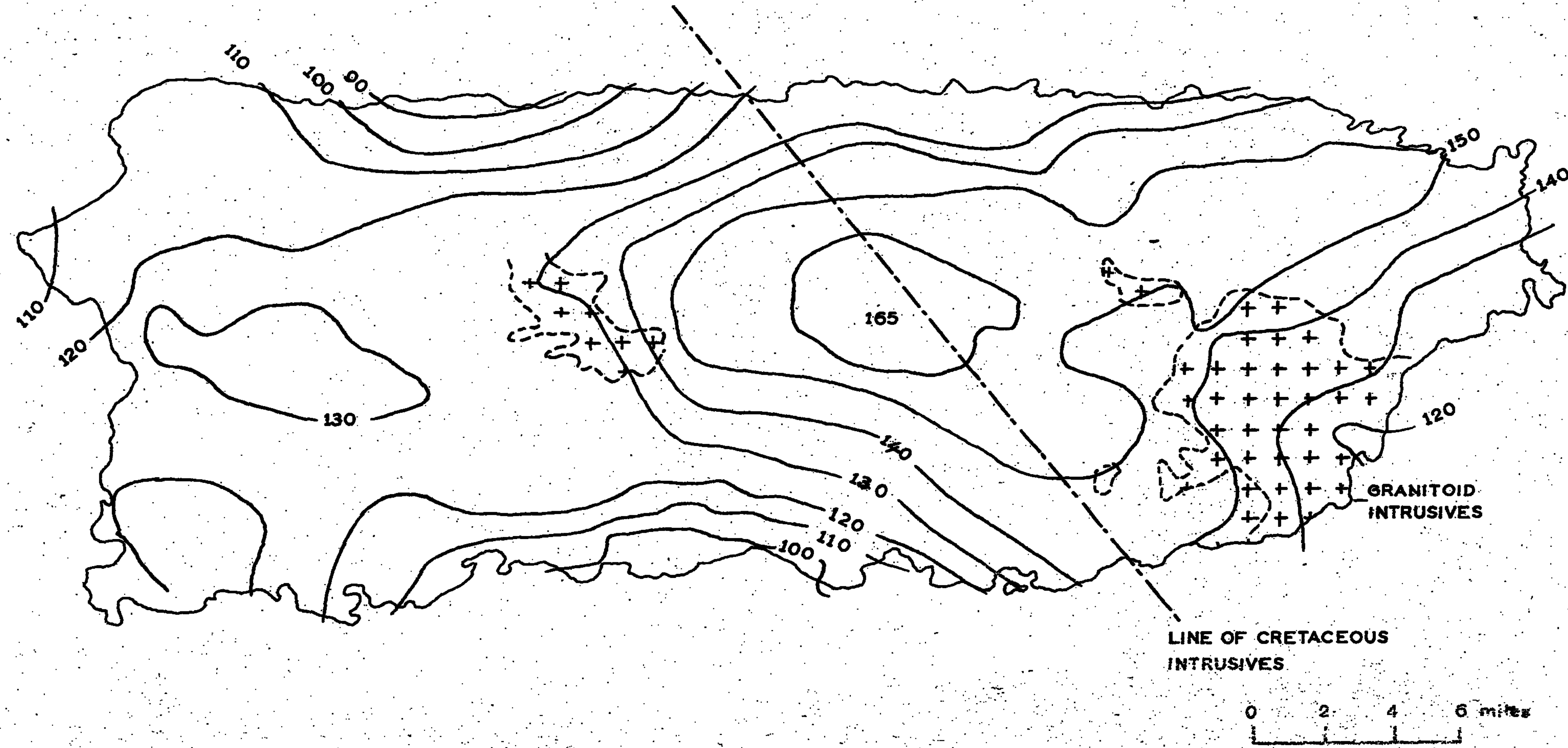
The interpretation of the anomaly - mainly due to Woollard - was based on the effects of a vertical cylinder whose diameter was that of the surface caldera (4 miles) and a density contrast of 0.6 gms/cc. On this basis a cylinder 7.9 Kms. long was indicated. This value is a minimum since such a high density contrast is not likely to be maintained at depth.

Bermuda

Bermuda is a less obvious volcanic example, the volcano having been long extinct and peneplaned to sea level. Yet the gravity field is remarkably similar to that already noted over the Hawaiian volcanoes. Such geological evidence as is available suggests that the volcanoes of the late Cretaceous age, and borings through the surface capping of Oligocene and recent limestones have proved the volcanic nature of the basement. At its greatest development during the Cenozoic, the volcano may well have stood 10000' above sea level.

Figure 3 shows the Bouguer anomalies over the island. The maximum anomaly of 55 milligals coincides with a magnetic 'low' and it is almost certain that this is related to one of the major volcanic pipes which supplied the island. On the basis of the gravity evidence the diameter of the pipe would appear to be 2.5 miles. The remainder of the anomaly has been interpreted in terms of a crustal flexure displacing the 'Moho' together with a regional magma chamber 200 kms. wide at a depth of 60 Kms. Other mass distributions will obviously produce the same anomaly, but as in the case of Oahu, the authors believe this interpretation to be consistent with the seismic evidence. (vide Woollard, 1954)

PUERTO RICO – BOUGUER ANOMALIES



Puerto Rico

Puerto Rico (Fig. 4) provides more geological evidence than Bermuda for its volcanic origin, but is less typical in that the main lavas are andesitic rather than basaltic. From the stratigraphy - summarised by Schuchert (1934) - it appears that explosive volcanic activity prevailed through the island's early development. Eruptive activity was followed by intense folding and plutonic intrusion. The four known volcanoes were subsequently buried beneath Oligocene and Miocene limestones.

The Bouguer anomalies (Shurbet and Ewing, 1956) are curious in that they do not correspond with the surface geology. An area of maximum positive anomaly - some 65 milligals - is associated with hydrothermally altered and silicified lavas, and it seems probable that both the anomaly and the metamorphism are related to dioritic intrusion along a N.W. - S.E. line. (This has been indicated on the text figure). As is the case with the Tertiary granites of Western Scotland, local gravity minima are found over granitoid intrusives which are believed to be related to the original Cretaceous vulcanism. Hess (1955, p.431) has suggested that the andesitic lavas of the West Indies are derived by melting of the gabbroic material forming a downward bulge of the crust; a structure which is consistent with the geophysical evidence.

The Mediterranean area

Gravity measurements in the Aegean made by Cassinis, revealed a large positive anomaly of 100 mgals over the volcano of Santorin. Other measurements in the eastern Mediterranean by

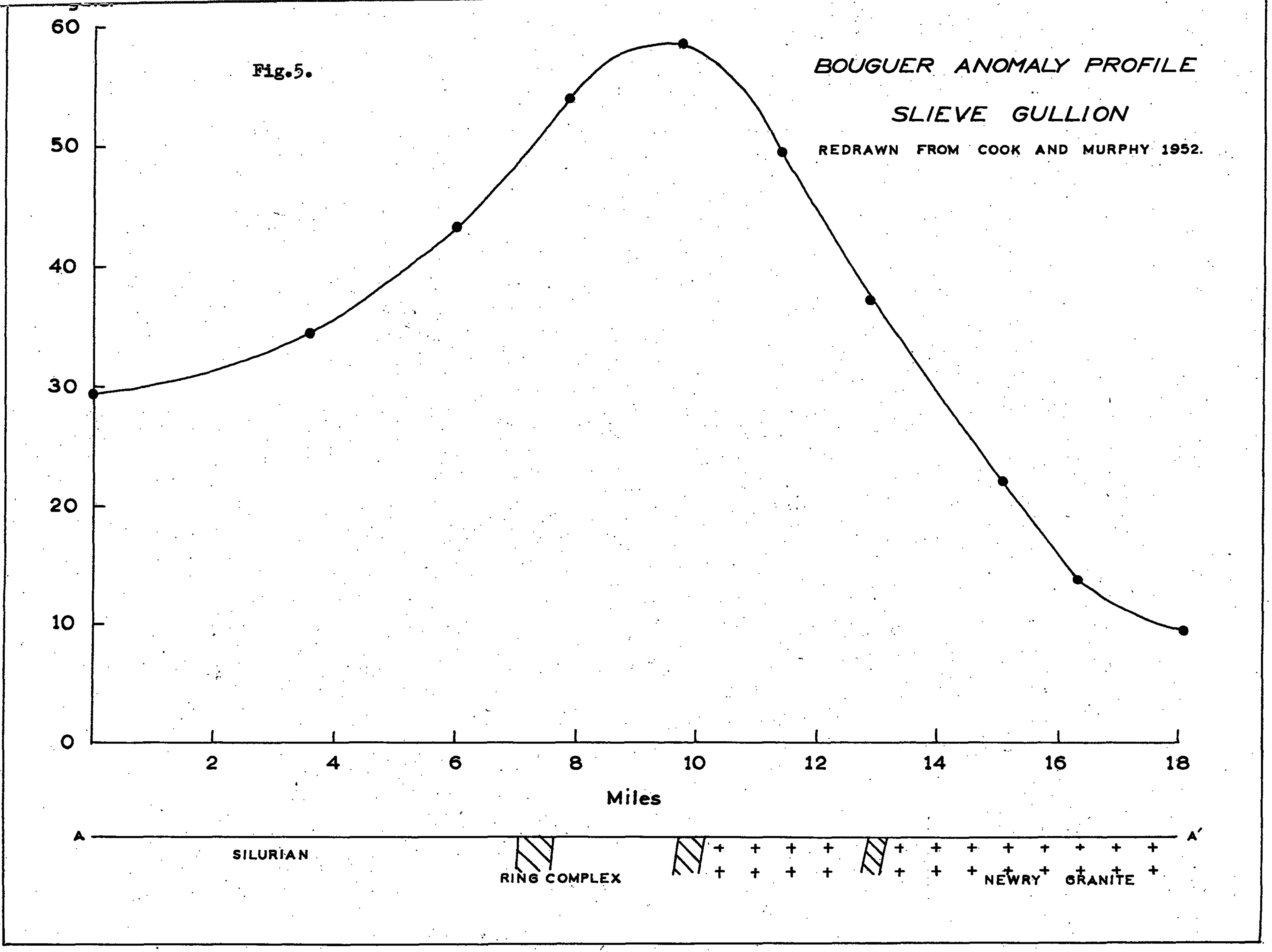
Cooper and others (1952) indicated positive anomalies over Malta and the active volcanoes of Pantellaria. The largest positive anomaly in the world - 193 mgals - is found in western Cyprus. Even assuming a density contrast of 0.6 mgals the thickness of basic material consistent with the anomaly is of the order of thickness of the granitic layer. The origin of the anomaly is tectonic rather than volcanic, but the interesting feature relevant to the present work is that despite the enormous mass surplus, the island has risen rather than subsided since the Pleistocene.

Iceland

Iceland is the last active remnant of the Tertiary vulcanicity which originally extended throughout Western Scotland and Northern Ireland northwards to Jan Mayen and Spitsbergen. The Bouguer anomalies are comparatively simple: a negative central area contrasting with a belt of positive anomalies around the coast. The interpretation is both complex and incomplete, and leaving aside any detailed considerations, the negative anomaly over the centre - whatever its cause - is presumably responsible for the continuous uplift of the island since the Tertiary.(Einarsson, 1954)

The North West peninsula is characterised by a series of ring fractures similar to those developed in other Tertiary regions (Bailey 1919). Cauldron type subsidences at both Faxa Flow and Breidi Fiord show high positive Bouguer anomalies of 50 and 60 milligals (Einarsson, 1954)

Fig.5.


BOUGUER ANOMALY PROFILE
SLIEVE GULLION
REDRAWN FROM COOK AND MURPHY 1952.
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
Miles
A
A′
SILURIAN
RING COMPLEX
NEWRY GRANITE

General Association of Gravity Anomalies and Vulcanism Great Britain and Ireland

The Irish Tertiary Complex

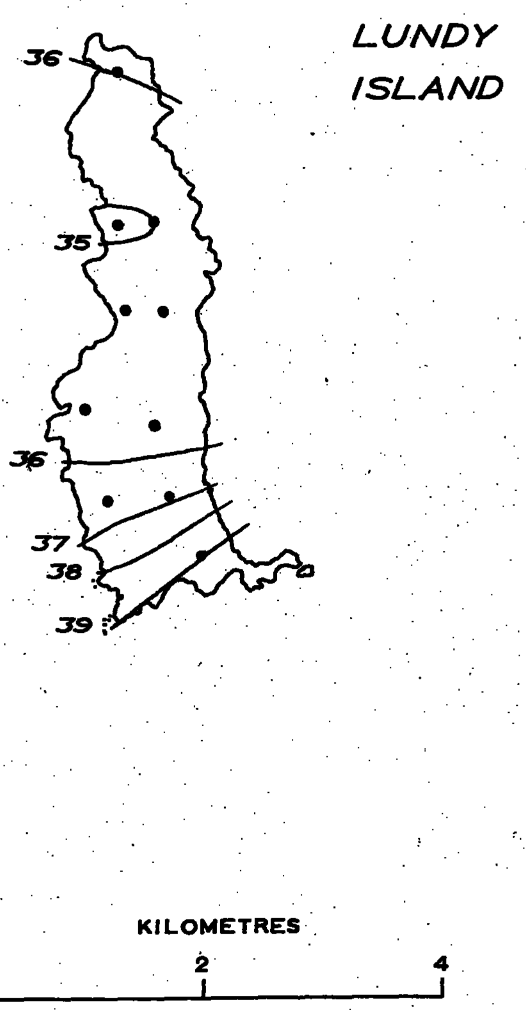
In 1952, Cook and Murphy published an account of a series of gravity measurements over the Tertiary centres of Mourne, Carlingford and Slieve Gullion. These four centres (there are two centres in the Mournes) are ring complexes similar to the Tertiary Ring Complexes of Western Scotland. Like these they are characterised by an approximately circular form, by arcuate boundary fractures and by the subsidence of the country rock making room for the intrusions. They lie at the southern end of a line joining the Scottish centres (vide Fig. 1).

The Bouguer Anomalies are highly positive (Plate 4) rising to a maximum value of 59 mgals over the Slieve Gullion centre (Fig. 5), the presumed site of a Tertiary volcano. It is apparent from the map that the Tertiary acid rocks have little effect on the main positive anomaly and that they must therefore be thin.

For the purpose of the interpretation, it was assumed that the mass indicated by the gravity data is the magma reservoir postulated by Anderson (1924, 1936) in his theory of the formation of cone sheets and ring dykes. The simplest geometrical solid corresponding with the anomaly is that of a horizontal cylinder of basic composition with its upper surface 6000 feet below sea level.

The authors admit that the horizontal cylinder is not the most likely form geologically, but it does satisfy some of the

Fig.6.



AFTER BOTT, DAY, AND MASSON SMITH.

Bouguer anomaly in milligals, ref. to I.G.F.

characteristics of the gravity field and it is a simple form for calculation purposes. A cupola extending downwards to a great depth is favoured on geological grounds.

Petrogenetically the results are of considerable interest, for whereas at the surface there is a preponderance of acid rocks in the ratio of $5\frac{1}{2}$ to 1, the Bouguer anomalies indicate that the mass of basic rock below must be 100 times that of the acidic rocks exposed at the surface. The obvious implication is that these granites could easily be derived by differentiation from the enormous bulk of underlying magma, or by refusion of the sialic crust. In either case the anomalies emphasise the difference in space form between the Tertiary granites and the post or syntectonic granites (Bott, 1953, 1956).

Lundy Island

Lundy Island is included in this section on account of its suspected Tertiary affiliations. A gravity survey (Bott et al. 1958) revealed a Bouguer anomaly of 36 mgals over the Lundy granite, rising to 42 mgals over the adjacent slates. From the Bouguer anomalies a laccolithic space form was deduced, the granite having a probable thickness of 1.6 Kms. Both the regionally (or locally) positive gravity field and the laccolithic space form are quite unlike those normally associated with British post-tectonic granites, and their closest parallel would appear to be with the Tertiary Mourne granites which are less than 1.2 Kms. thick.

Conclusion

The above accounts of the gravity fields over active and extinct volcanoes are much contracted, and for further details reference should be made to the original works. However, from these accounts certain tentative conclusions can be drawn. In passing, it is worth noting that none of the volcanoes described are pre-Cretaceous in age.

1. Volcanoes would appear to be characterised by high positive Bouguer anomalies, ranging from 50 to 110 mgals.
2. The magnitude of the anomalies coupled with the Bouguer gradients suggests that the masses responsible are intra-crustal and that they have a considerable extension in depth.
3. Whilst an intra-crustal magma chamber is indicated by the anomalies, the ultimate source of the magma appears to be located below the Mohorovicic discontinuity, and is detected by seismic rather than gravitational methods. For example, the total gravitational effect of the postulated regional magma chamber beneath Bermuda is only 2.5 mgals (Woollard, 1954).
4. Where acid intrusives are associated with the basic masses they produce local gravity minima.
5. Later and smaller centres of volcanic activity connected with a major volcano have little or no effect on the main anomaly.
6. The lines of equal Bouguer anomaly over the volcanoes are roughly circular implying a symmetrical origin. Previous interpretations have, however, been mainly concerned with depth estimations rather than attempts to fit a theoretical model to the observed anomalies.

The rest of the work is concerned with a detailed description of a gravity survey of the Tertiary volcanic districts of Western Scotland - the basal wrecks of Judd's central volcanoes. Chapters 2 and 3 are concerned with the more routine aspects of the survey. Chapters 5 - 8 are devoted to an account of the gravity field over the main Plutonic Centres, and attempts to find a series of theoretical models consistent with both the observed gravity field and the structural pattern deduced from the geology.

Chapter 11

THE GRAVITY OBSERVATIONS AND THEIR ADJUSTMENT

Introduction

The gravity surveys of the Tertiary Volcanic Districts were begun in September 1955 using a Worden gravimeter loaned by the Imperial College. A preliminary series of gravity measurements on Skye, established the existence of a large and previously unsuspected positive Bouguer Anomaly over Central Skye, and a gravity low over North Skye and Sleat. In the Summer of 1956 the survey was extended into Mull and Ardnamurchan, using the newly acquired Frost gravimeter, and the same pattern of positive anomalies was again observed. During 1957, the island of Arran was included in the survey and another positive anomaly discovered over the Central Complex. Unfortunately, the usual equinoctial gales prevented us from extending the survey to the remaining Tertiary centre of Rhum, as was originally planned.

A further series of observations were made in Skye in September 1957 so as to confirm the size and disposition of the gravity low in the north of the island. The gravity field over the central area was more accurately delineated by measurements made on the adjacent off shore islands, and the island of Raasay was included in the survey. Observations on the islands were of necessity sparse owing to the difficulty of moving the Frost gravimeter by small boat.

The major gaps in the previous surveys were filled in during the Christmas of 1957 with the aid of the Geological Survey's Worden gravimeter. This entailed a series of foot

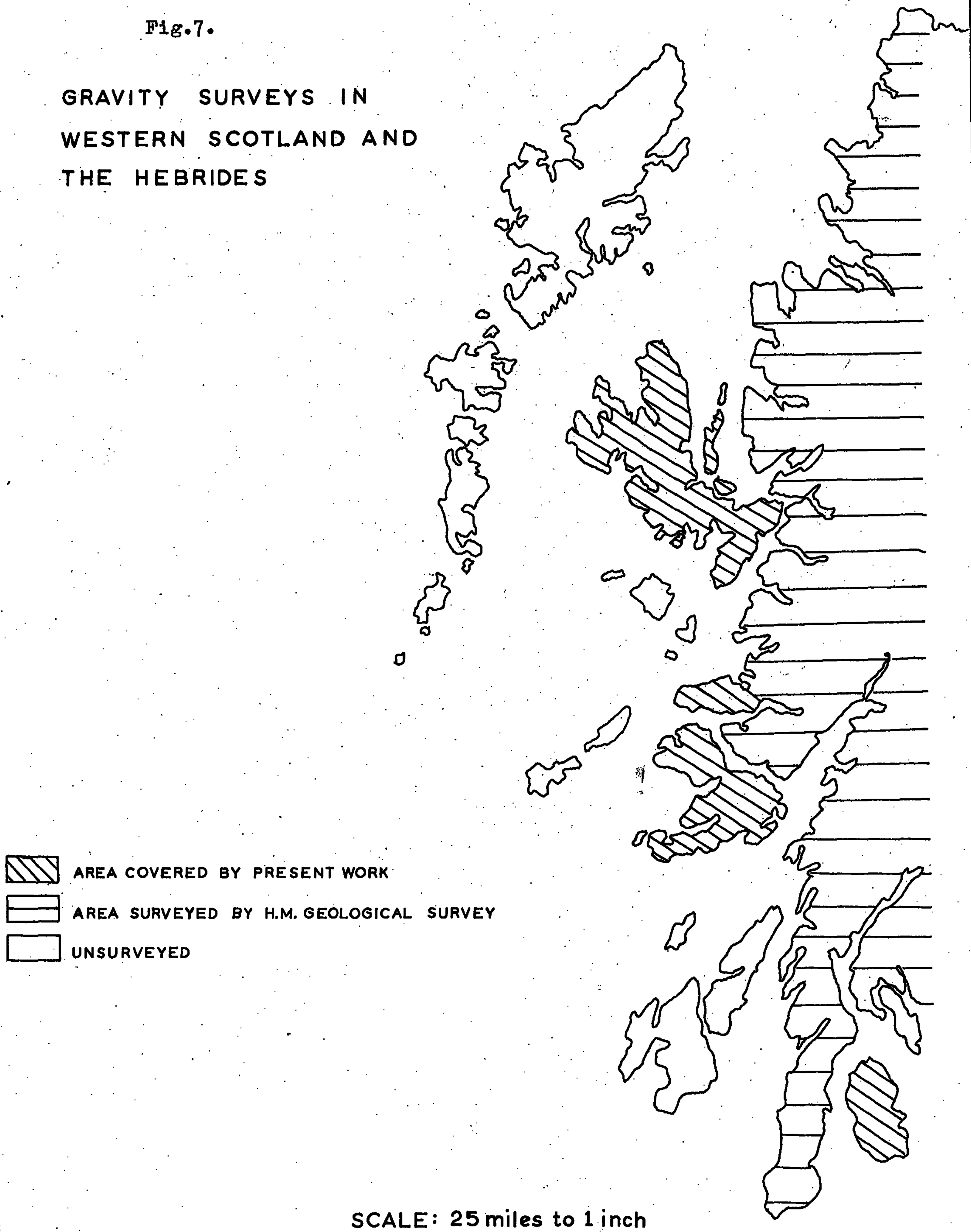
Summary of Field Work

Date	Period of Work	Nature of Work.	Instruments	Observers	Results
Sept-Oct 1955	4 weeks	Gravity Survey of Skye	Worden Gravimeter	M.H.P. Bott J. Tuson	246 gravity stations
May-June 1956	3 weeks	Gravity Survey Mull and Ardnamurchan	Frost Gravimeter	M.H.P. Bott J. Tuson	186 gravity stations
September 1956	2 weeks	Samples for density determinations	-	J. Tuson	600 rock specimens
July 1957	10 days	Gravity Survey Arran	Frost Gravimeter	M.H.P. Bott J. Tuson	72 gravity stations
September 1957	12 days	Gravity Survey Skye and adjacent islands	Frost Gravimeter	J. Tuson	43 gravity stations
December 1957	2 weeks	Gravity Survey Arran and Mull	Worden Gravimeter	M.H.P. Bott J. Tuson	35 gravity stations

Totals: 582 gravity stations. 600 rock specimens

Fig.7.

GRAVITY SURVEYS IN WESTERN SCOTLAND AND THE HEBRIDES



traverses across the more inaccessible parts of Arran and Mull which had been omitted from previous surveys on account of transportation troubles with the Frost gravimeter.

The total area covered by the surveys is shown on Figure 7, and a summary of the field work given in Table 1.

The instruments

None of the gravimeters used in the survey was recalibrated. Frost Meter 54 had previously been calibrated by Tomaschek (K.H.G. Rept. No. 44, 1953) against Worden Meter 45 over the Kirklington Gravity bases and later in Westminster Cathedral. The final calibration factor adopted was 0.0837 mgals/D.D. ± 0.0004. Calibration changes with temperature are insignificant but the meter is very sensitive to high ambient temperatures, the latter producing erratic drift of up to 2 mgals. There would appear to be an appreciable pressure effect.

The calibration of Worden Geodetic model No. 241 was obtained direct from the makers and was given as 0.11496 mgals/D.D. This was subsequently confirmed by the owners - Imperial College.

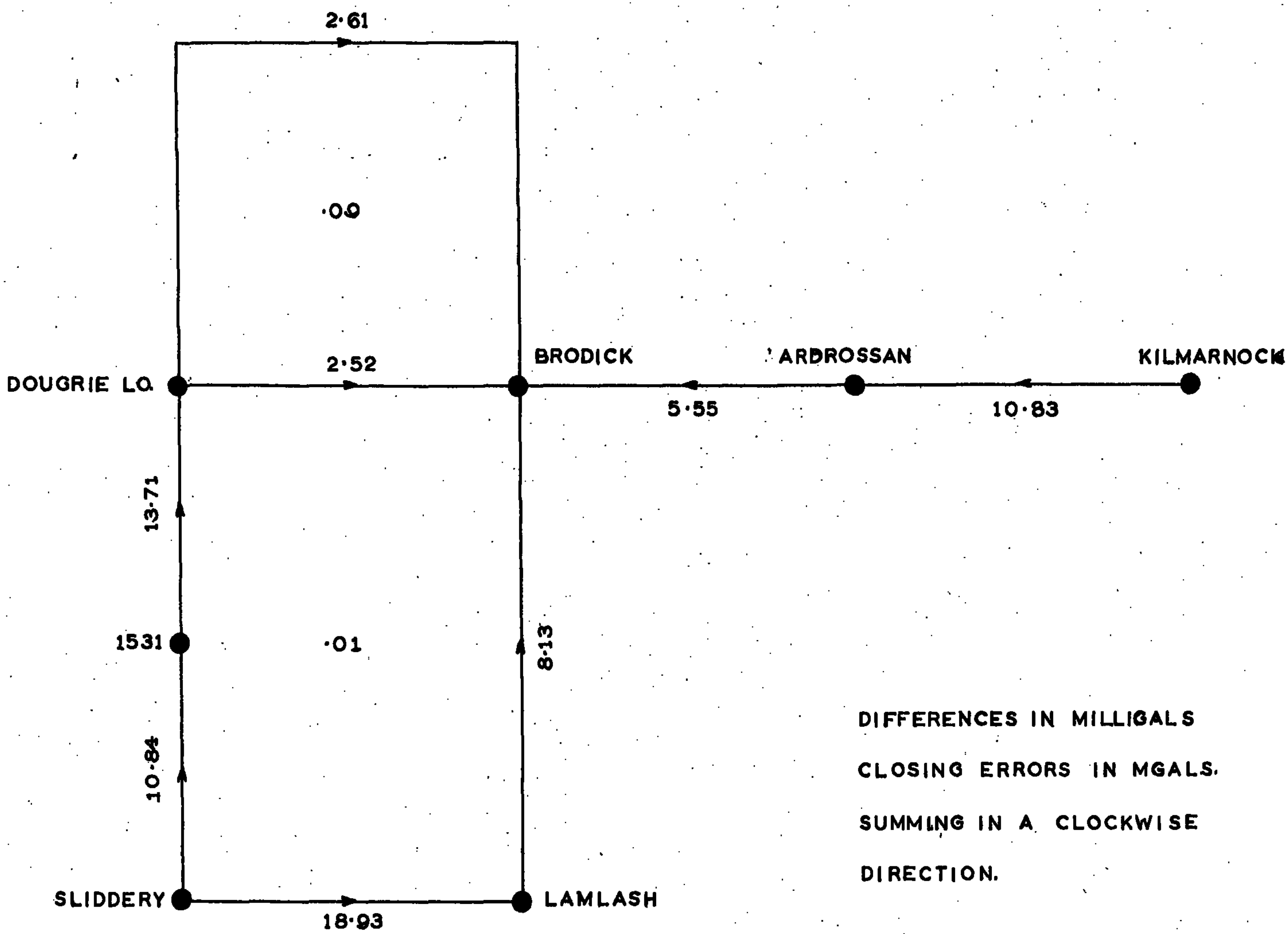
The Geological Survey's Worden Gravimeter W345 is regularly calibrated over the Macclesfield Gravity bases and the figure given (0.12653 mgals/D.D.) was correct at the time of use.

Base Connections

All the surveys were connected to the gravity base network established on the Scottish mainland by Bullerwell (unpublished) and so ultimately to Pendulum House, Cambridge. Details of these connections, and of the base networks set up on each island, are shown on the text figures 8, 9 and 10. For convenience, the majority of the bases are sited on roads and, where possible in sheltered spots. The bases are plotted on both the 6 inch and

Fig.8.

FROST BASE CONNECTIONS - ARRAN



NOT TO SCALE

the 1 inch maps, and a set of diagrams showing the detailed positions of the bases will be deposited in the Durham Colleges Geology Department.

The Skye surveys were connected to the Geological Survey's gravity base station at Spean Bridge through a series of intermediate bases. This linkage - Kyle of Lochalsh to Spean Bridge - was subsequently repeated by Bullerwell; his value for the gravity difference between the two bases differing from ours by 0.03 milligals.

The Mull surveys were linked to the mainland through Ardnamurchan, and so eventually to the Geological Survey base at Carnach in Argyll. Connections between Mull (Tobermory) and Ardnamurchan (Mingary) were carried out with Frost Meter 54, observations being made in the order T M T T M T. Rough seas proved too much for the gravimeter and the final link was ruined by an instrumental 'jump' of 1.7 mgals. Fortunately, drift on the previous links had been small, and the quoted value of the gravity difference (11.87 mgls.) is considered reliable. The recorded value of gravity at Tobermory differs from Bullard's 1936 pendulum observation by 5.75 mgals.

Base stations in northern Arran were established using the forward looping method (Nettleton, 1940) with intervals between successive readings of approximately one hour. The method and its errors are more fully set out in Murphy (1957). Other bases in the south were established by the conventional method and the Arran survey eventually tied into the Geological Survey base at Kilmarnock through Brodick and Ardrossan.

Closure errors in the observed linkages were so small that

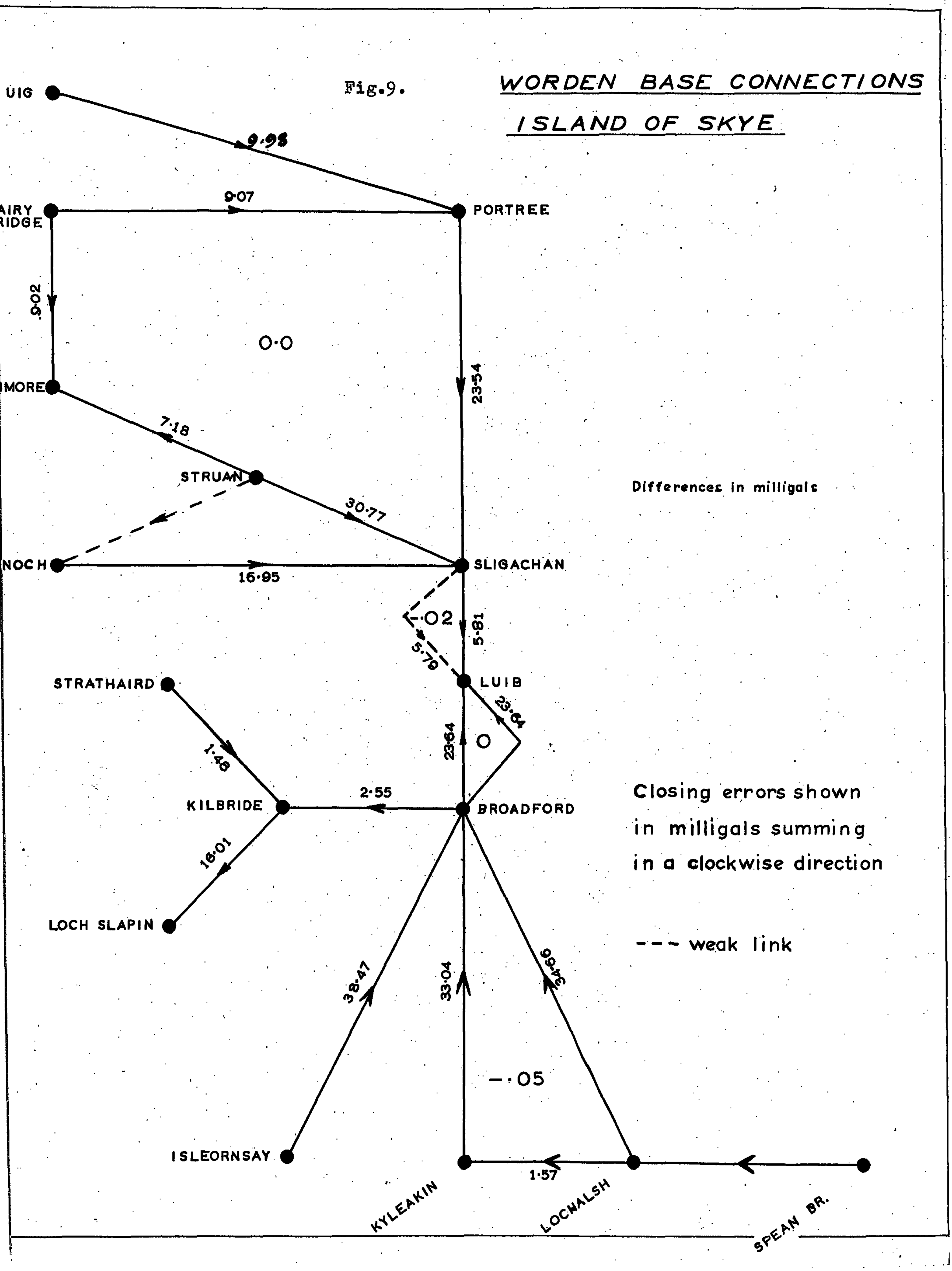


Fig.9.

WORDEN BASE CONNECTIONS

ISLAND OF SKYE

rigorous adjustment was not justified and the values given by the linkages to the primary Geological Survey bases were accepted.

Gravity measurements on the small islands adjacent to Skye - such as Soay, Crowlin and Scalpay - are less reliable than those on the mainland owing to lack of adequate drift control. Practical considerations required periods of up to seven hours between base observations, and whilst the recorded drift was small and assumed to be linear, the actual drift was probably much greater and non-linear. Even so the errors from this source are unlikely to exceed 0.15 mgals. The measurements on Raasay are more reliable, estimates of the drift having been obtained by repeating stations at regular intervals.

The Bouguer Anomaly

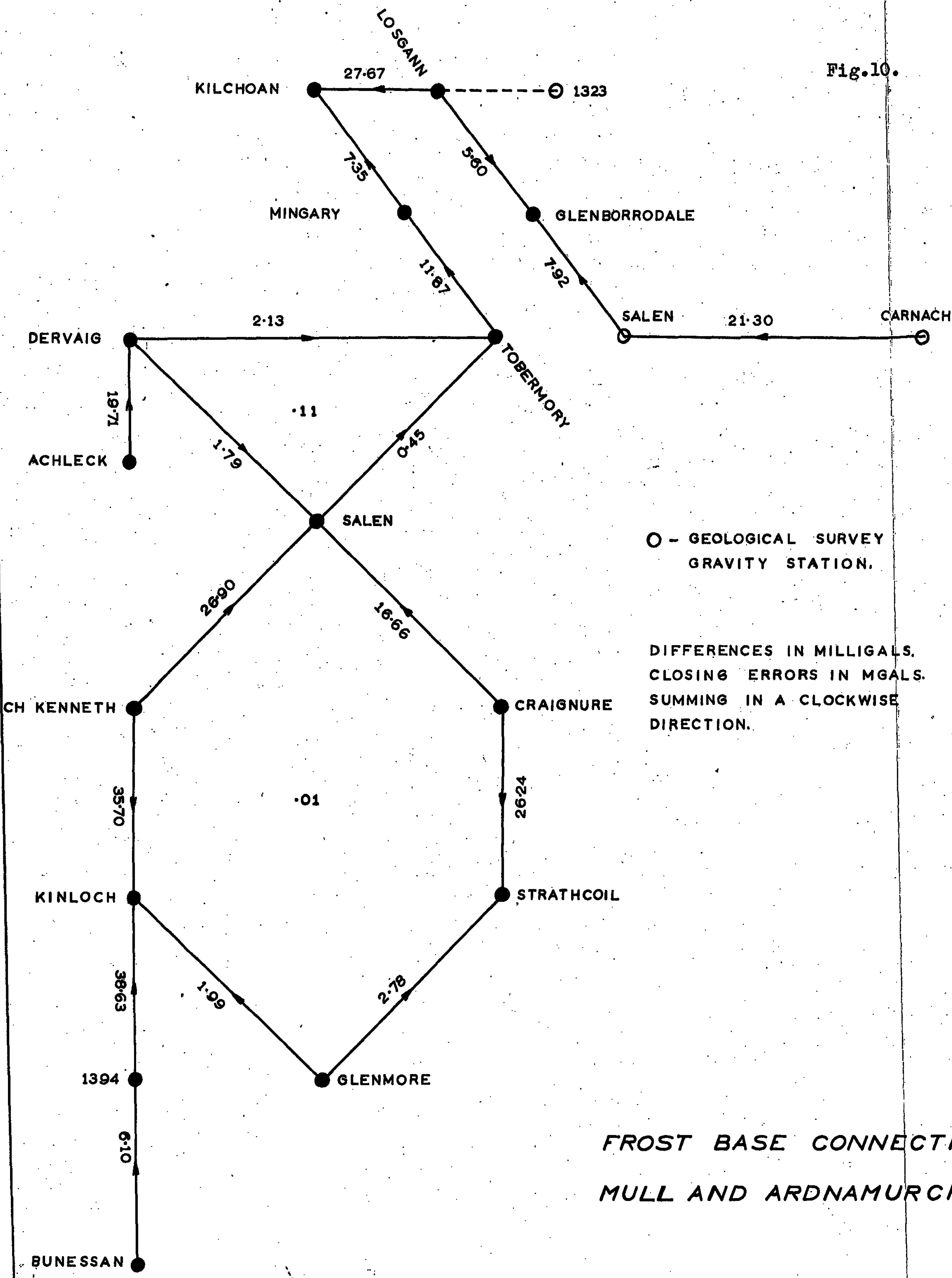
A gravity anomaly is usually defined as the difference between the observed value of gravity on an absolute basis, and the theoretical value calculated for that particular station from the International Gravity Formula of 1930. The Bouguer Anomaly used in this work is defined as:-

$$(g_{sta} - g_{PH}) + (g_{PH} - \gamma) - (0.09406 - 0.01277p)h + T$$

where g_{sta} is the observed value
g_{PH} .. value at Pendulum House
γ is the theoretical value
p is the density
h is the height in feet above sea-level
T is the Terrain Correction

This corresponds with an isostatic anomaly in which the crustal thickness equals infinity, but unlike the isostatic anomaly makes no assumptions about sub-crustal mass distributions, or as to the nature of the compensation at depth.

Fig.10.



FROST BASE CONNECTIONS

MULL AND ARDNAMURCHAN

In the text 'Bouguer Anomaly' refers to the actual value of the Bouguer Anomaly on an absolute basis calculated from the above formula, whereas the term 'anomaly' is used to describe the difference between the Bouguer anomaly at a station and some arbitrary background value.

The Bouguer Reduction

The elevation term - (0.09406 - 0.01277p)h is the correction to be applied to the observed gravity to reduce it to the value at sea level if the station is assumed to be at a height h on an infinite sheet of rock of thickness h and density p. The two parts of the correction are of opposite sign and are normally combined into a single correction involving a height and a density.

Densities used in the Bouguer Reduction

The following density values were adopted for the reduction:

Granite	2.60 gms/cc	Jurassic	2.60 gms/cc
Gabbro	3.00 "	Triassic	2.50 "
Basalt	2.85 "	Old Red Sandstone	2.60 "
Lewisian	2.76 "	Cambrian	2.69 "
Dalradian	2.75 "	Torridonian	2.65 "
Moine	2.75 "		

Not all these values agree with those given in Chapter 3 since many of the reductions were carried out before the final laboratory figures were available. The differences are unimportant at the heights involved.

The Jurassic density is an average value obtained by estimating the lithological proportions of the typical succession in North Skye. These are

Shale	730 feet	density	2.58 gms/cc.
Limestone	260 "	"	2.70 "
Sandstone	1160 "	"	2.54 "

This yields an average value of 2.58 gms/cc which was subsequently rounded off to 2.60 gms/cc.

<u>Terrain Corrections</u>

The ordinary Bouguer reduction described above assumes that the topography is in the form of a plane of infinite extent. This is clearly not so in an area of high and rugged relief, so a further correction has to be applied to allow for the departures of the topography from the plane. This is by far the most tedious and time consuming part of a gravity survey, though essential in an area such as Central Skye where the terrain correction frequently exceeds five milligals.

The standard method (Hammer, 1939; Nettleton, 1940) subdivides the area around each station into a series of zones and sectors of arbitrary azimuth. The average height within each compartment is then estimated with the aid of graticules and the correction read off from the tables. This procedure is repeated for each compartment in turn and the total effect found by summation. Other methods have been evolved using either planimeters or computation charts - see for example Monnet (1956) - and all allegedly save time.

A more recent development involved the use of a suitably programmed electronic computer (Bott, 1959). In essence the method depends on dividing the region into a series of kilometre grid squares and estimating the average height of each square. The grid is normally made sufficiently large to include all but the outermost zones of the conventional zone chart. The correction is then determined for each gravity station by allowing the computor to continuously solve the equation:

$$\delta g = G\rho A\left[\frac{1}{r} - \frac{1}{(r^2+h^2)^{\frac{1}{2}}}\right] \cdots\cdots\cdots$$

where δg is the terrain correction
h is the height difference between square and the station
r is the distance from the station to the centre of the square
A is the area of the square
ρ is the density
G is the gravitational constant

for each square in turn and then summing to find the total correction.

The mass of each square is assumed to lie along a vertical central line whose height is the average height of the square. The errors are large for small values of r and the programme is adapted so that all squares whose centres are within 0.99 Kms. of the station are rejected. These rejected squares are then computed using the conventional method. Computer time can be saved by combining single squares which are a considerable distance from the station and treating them as a single square of say 16 Km. side.

Once the main programme has been prepared - this took several months - the preparation of the information from each area for the computer is comparatively simple. One data tape is devoted to the average heights of the kilometre squares and their grid references: the heights and grid references of the stations are then punched onto another tape. After processing, the computer prints the results in the form of a grid reference, height, and terrain correction for each station, together with the grid references of the unprocessed squares.

Terrain correction for Skye and Ardnamurchan were carried out using the conventional method. Those for Mull and Arran were carried out on the Durham University Ferranti Pegasus Computer - Ferdinand.

Errors

Errors in a gravity survey are of two types: systematic errors in such things as the calibration of the gravimeter and the density factor; and random errors in g resulting from the gravity measurements themselves. The probable calibration errors of both the Frost and the Worden gravimeters are 0.05% and 0.05% respectively, and are unimportant. Errors in density, whilst the principal source of error in a gravity survey, are unlikely to exceed 0.05 gms/cc or 0.6 mgals/1000 feet. Since the majority of the stations are at heights of less than 150 feet, the error is unlikely to exceed 0.10 mgals.

Random errors in the gravity observations can be determined from base linkages, drift curves and comparisons between base runs with different gravity meters. The average closing error in the Frost base network is 0.06 mgals., and in the Worden network 0.02 mgals. Several stations do not lie in closed linkages, but errors of the same order are indicated by the drift curves.

Latitudes were estimated from the six inch maps and have an uncertainty of ± 1 sec. or ± 0.02 mgals. Where possible, the heights of the stations were related to Bench Marks and have a possible error of ± 0.5 feet of ± 0.06 mgals. Elsewhere Spot Heights had to be used and the consequent uncertainty rises to ± 2 feet or ± 0.12 mgals.

Terrain corrections are accurate to ± 0.1 mgals except in a few areas of high relief where uncertainties in the average heights of the terrain may increase the error to ± 0.4 mgals.

A comparison between the terrain corrections for ten stations as determined by both the computer and the zone chart are given in Bott's paper (op. cit). The results suggest a probable error of 5% in the computed values.

The overall uncertainty of the anomaly is about 0.4 mgals.

The absolute value of the Bouguer Anomaly is dependent upon factors extraneous to this particular survey, such as the accuracy of the Pendulum ties to Potsdam. Following standard British practice, the surveys have been linked to Pendulum House Cambridge using a value of 981.2650 gals. More recent determinations suggest that the absolute value at Cambridge is 981.2685 gals. (Cook, 1953).

Chapter III.

ROCK DENSITY DETERMINATIONS

Introduction

The densities of the rocks in an area covered by a gravity survey are required for two purposes: the calculation of the Bouguer Anomaly, and the interpretation of that anomaly. For the former purpose rough values of the densities will suffice, unless the stations are at a great height, as a change of 0.1 gms/cc in the density produces a change of only 1.28 milligals/1000 feet, Even so, this is still the greatest source of error in a gravimeter survey. In interpretation, the importance of an accurate knowledge of the bulk densities of rocks cannot be over emphasised, since the density contrast below the surface is a primary factor in the interpretation of the gravity anomaly caused by any given geological structure.

Techniques

A common method of determining bulk densities is to determine the gravitational attraction of a known thickness of a formation (Nettleton, 1939; Parasnis, 1952). This is achieved by measuring 'g' across some erosional feature such as a scarp. The method presupposes that there is no horizontal gravity gradient, or that this gradient can be eliminated, and that the changes observed are due to elevation and density. For this reason the method proved impractical in the Western Isles; a suitable scarp and an absence of horizontal Bouguer gradient never occurring in the same place.

To determine the bulk densities, a representative collection of rock samples was made in the Summer of 1957.

Wherever possible specimens were collected from quarries excavated for road metal and good unweathered specimens of igneous and metamorphic rocks were obtained by this means. There are few quarries in the sedimentary formations, and the majority of the Mesozoic specimens come from either cliff sections or small road cuttings and consequently show some weathering. Although the reliability of the mean and the standard deviation increase with number, there is clearly a practical limit on the number of specimens which can be collected from each exposure. Masson-Smith (unpublished) has shown that the average standard deviation and the range of standard deviation is apparently independent of the number of specimens and that five or, at the most, ten, specimens per exposure is sufficient. An average of seven specimens was collected at each exposure. ‖One in a hundred specimens have an abnormal density, and at least three specimens are required to ensure recognizing the abnormality. This, however, does not eliminate the difficulty of knowing the true proportion of specimens of abnormal density.‖

Delete

<u>Apparatus and procedure</u>

The laboratory method used does not differ radically from the normal physical method of determining density, and is similar to that used by Moore in 1902 and Holmes in 1921. The specimens are saturated with water under vacuum, weighed in water, weighed in air, dried in an oven, and finally re-weighed dry.

To saturate the rocks the specimens were first evacuated in a vacuum chamber for ten minutes - in this case a modified autoclave - and water admitted slowly. ~~at a rate of 1 pint per minute.~~ (This ensures that the water is completely de-aerated before coming into contact with the specimens). Evacuation was continued until air bubbles ceased to rise from the specimens, and in some cases this required several hours. With the vacuum chamber and water pump used, a vacuum equivalent to 2 cms.Hg. was obtained and at this pressure 3% - 5% of the pore space may still be occupied by trapped air bubbles.

A chemical balance was modified by having the usual weight pan on one arm, and two pans, one above the other, on the other arm. The lower of these pans was immersed beneath 3 inches of water and used for determining the weight in water. Since changes in water level would affect the upthrust on the balance beam, and so alter the weight, this effect was kept to a minimum by using a large tank. A tank 6" x 20" x 20" was used and changes in water level were negligible.

Great accuracy in weighing is unnecessary, since an error of 0.01 grams in the weight will only give an error of 0.006 - 0.0006 gms/cc in the final density (Masson-Smith).

A summary of the results together with their standard deviations are presented in Tables 2, 3 and 4. For comparative purposes another table (Table 5) has been prepared showing previous density determinations. In the majority of cases the authors give no indication as to whether the specimens were dry or saturated. The difference between the two densities in the case of igneous rocks is comparatively unimportant.

<u>Discussion</u>

In the interpretation of a gravity survey the excess or deficiency of density of the disturbing body over that of its surroundings has to be assumed. The value of this density contrast is based on specimens collected from the upper layers,

Table 2

SATURATED DENSITIES OF METAMORPHIC ROCKS

System	Type	Density gms/cc with S.D.	No. of samples	Locality
	Hornblende gneiss	2.96 ± 0.16	6	Sleat, Skye
LEWISIAN	Granulitic	2.66 ± .01	7	
		2.76 ± .02	5	
		2.79 ± .07	7	
		2.82 ± .03	6	
TORRIDONIAN	Sandstone	2.64 ± .01	7	Sleat, Skye
	"	2.65 ± .02	6	
	"	2.63 ± .03	5	
	Quartzite	2.65 ± .01	7	
	Sandstone	2.63 ± .01	7	
	"	2.64 ± .01		
CAMBRIAN		2.72 ± .02	6	Broadford, Skye
	Limestone	2.69 ± .01	8	
	"	2.70 ± .01	5	
	"	2.65 ± .02	9	
	Marble	2.83 ± .01	5	
TARSCAVAIG MOINE		2.75 ± .03	10	Sleat, Skye
DALRADIAN	Phyllites	2.70 ± .02	7	North Arran
	Schistoze Grit	2.66 ± .01	3	

Table 3

SATURATED DENSITIES OF IGNEOUS ROCKS

Age		Density (gms/cc.) with S.D.		
TERTIARY	Granite	2.57 ± .01	8	
		2.60 ± .04	6	Beinnan Dubhaich
		2.64 ± .02	8	Creag Stronamus
	G2	2.56 ± .01	7	Mael Ban, Skye
		2.56 ± .01	7	Dunan, Skye
	G2	2.57 ± .01	6	Western Red Hills
	G1	2.63 ± .02	3	" " "
		2.53 ± .02	12	Eastern Red Hills
		2.59 ± .02	7	Beinn an Dubhaich
	Porphyritic			
	Felsite	2.54 ± .03	6	Central Skye
		2.60 ± .01	6	" "
	Gabbro	2.89 ± .01	7	Broadford, Skye
	"	3.00 ± .04	12	Cuillins, Skye
	Basalt	2.85 ± .06	31	North Skye
	Dolerite Sill	2.71 ± .03	5	Broadford, Skye

G1 and G2 refer to Wager and Stewart's divisions of the Red Hills Granite

Table 4

SATURATED DENSITIES OF SEDIMENTARY FORMATIONS

System	Type	Density gms/cc with S.D.	No. of specimens	Locality
OLD RED SANDSTONE	Sandstone	2.60 ± .04	6	Arran
	Conglomerate	2.61 ± .02	6	"
	Quartzite boulders from Conglomerate.	2.64 ± .01	3	"
TRIASSIC	Sandstone	2.30 ± .04	10	E. Arran
	"	2.43 ± .01	10	W. Arran
JURASSIC		2.69 ± .01	8	Skye
Lias	Limestone	2.73 ± .02	9	"
	"	2.72 ± .01	12	"
	"	2.70 ± 0.02	9	"
	"	2.68 ± .01	7	"
	Shales	2.57 ± .05	10	"
Inferior Oolite	Limestone	2.67 ± .01	3	Skye
	Sandstone	2.53 ± .02	4	"
	"	2.56 ± .03	4	"
	Shale	2.46 ± .03	4	"
Estuarine Series	Sandstone	2.52 ± .02	9	Skye
	Shale	2.55 ± .04	7	"
	"	2.63 ± .05	6	"

Table 5

ROCK DENSITIES: IGNEOUS AND METAMORPHIC

Rock Type	Observer	Results Range	Results Mean	Locality
Basalt	Washington and Keyes (1924).		2.96	Hawaii
	King B.C. (1953).	2.84 - 2.98	2.97	Skye
	Published in Cook and Murphy (1952).	2.82 - 2.98	2.88	Antrim
	Washington and Keyes.	2.58 - 3.07		Kukin
	"	2.72 - 3.07		Haleakala
	Jakosky	2.7 - 3.3	3.0	-
	Glennie (1951)	2.88 - 2.91		Bombay
	"	(amygdaloidal)	2.6	Deccan
	Einarsson (1954)	2.9 - 3.0		Iceland
	"	—	2.84	"
Gabbro	King, B.C. (1953)	2.92 - 2.99	2.96	Broadford, Skye
Chilled marginal gabbro	Wager and Deer (1939)	2.95 - 2.98	2.96	Skaergaard
Upper Border Group	"	2.97 - 3.02	2.99	"
Middle Gabbro	"	3.01 - 3.19	3.10	"
Hypersthene olivine gabbro	"	3.00 - 3.04	3.02	"
Olivine gabbro	"	—	2.98	"
Gabbro	Harker (1904)	2.85 - 3.03	2.93	Cuillins, Skye
	"	—	3.00	
Gabbro	Published in Cook and Murphy (1952).	—	3.03	Carlingford and Slieve Gullion
	Jakosky	2.85 - 3.12	2.98	
Tertiary Granites	Published in Cook and Murphy (1952).	—	2.60	Mourne
			2.61	Carlingford
	Harker (1904)	2.49 - 2.66	2.60	Skye
Dalradian	Published in Cook and Murphy (1952).	2.70 - 2.95		Ireland
		2.75		
		2.50 - 2.80		

and the literature of density determinations is much divided as to the legitimacy of using this same value at depth. This is obviously of some importance in the present work, depths of 50000 feet being involved in the interpretation.

Variation of density with depth may be caused by:

Increase of temperature causing expansion.

Increase of pressure causing contraction.

The combined effect of temperature and pressure on interstitial water.

Changes in porosity.

Cementation effects.

Changes in the degree of saturation.

Metamorphic changes.

These effects will be discussed for the major rock types in the areas covered by the survey.

Metamorphic changes can generally be neglected at the depths involved in much of the interpretation. It could be significant in the main Tertiary Centres.

Density variation in sediments

With sedimentary formations the density contrast is intimately bound up with the variation of porosity with depth. Permanent cavities below the water table are occupied by water until they close under hydrostatic pressure at a depth of approximately 10000 metres. Between these limits the value of the porosity is uncertain. ~~indeterminate.~~ Gravity measurements in mine shafts made by Rische (1957) show that for sediments there is a regionally different depth density function. Parasnis (1951) found that the density of the Oxford Clay varied by 0.03 gms/cc in 100 feet.

This problem of clay-shale densities was investigated by Hedberg (1936) who recorded large changes in density with depth. A practical demonstration of this density change is seen in the expansion of shale and mudstone cores from boreholes consequent on the relief of pressure.

The Jurassic succession of North Skye contains 730 feet of shale and, in the light of this evidence, the density used in the reduction is probably low, although the error should not exceed a few per cent.

Van Orstrand (1951) stated that in sandstones the effects of increasing temperature and pressure with depth are self compensating. A similar conclusion was reached by Birch and Dow (1936) who found that at 400 degrees centigrade and pressures equivalent to 50000 feet of rock, the tendency for the density to decrease due to thermal expansion because of the increase of temperature with depth was less than the reverse effect due to the increase of pressure with depth.

There is a considerable divergence of opinion as to the effect of saturation on rock density. Fuller (1906) alleged that saturation increased with depth, whereas Birch (1942) and Evans and Compton (1946) incline to the opposing view. Thiel (1956) assumed complete saturation at depth in the interpretation of the Keeweenawan anomaly. The saturated density is sometimes called the 'natural density' as this is 'assumed to be the condition of rocks in nature.' (Hedberg, 1936). For the purpose of this work, the 'saturated' or 'natural' density has been used. This is probably an over estimate, but an over estimate of the degree of saturation will help to counteract the other factors all of which tend to reduce the density. Probably the best assumption is that the field density lies somewhere between the saturated and the dry density, the extreme density limits being given by the density of a fresh dry specimen as the lower limit, and the grain density - as obtained from the mineral composition - as the upper limit. This assumes that there is no variation in mineral composition with depth which, whilst true of sediments, is not necessarily so in the case of igneous and metamorphic rocks.

Sandstones are the only rock type which appears to be appreciably affected by weathering. Specimens from the Carboniferous of Northern England (measured by Masson-Smith) showed variations in density of up to 0.11 gms/cc and a series of Jurassic sandstones from a quarry in Skye showed variations of up to 0.15 gms/cc. The standard deviations and standard errors of sandstone densities are as a consequence uniformly high.

<u>Density variations in igneous and metamorphic rocks</u>

The measured densities of the igneous and metamorphic rocks were remarkably constant. This was not unexpected. Determinations in mine shafts by Rische (1957)and others had shown that the density is independent of the depth and this is generally assumed in the interpretation. Iddings (1920) showed that for an igneous rock which had crystallised under a heavy cover, the density calculated from the norm is greater than the measured value by an amount determined by the porosity reasonably assignable to the rock. The porosity is expected because of differential decreases in volume with the crystallisation of the rock, and because of the development of, and enlargement of, cleavage spaces when the originally deep-seated rock is exposed at a much lower pressure at the surface.

Porosity and saturation were usually found to be unimportant, the Lewisian, Torridonian and the Tertiary granites all having porosities of less than 1%. Some 'drusy' granites from the Red Hills were found to have porosities of 5% and a correspondingly low density. Granites of this type are, however, atypical of the main mass.

<u>The density of basalt</u>

Basalt densities show wide variations, every value from 2.3 - 3.0 gms/cc having been used in the reduction and interpretation of gravity anomalies. The generally accepted value for the density of basalt used in crustal models is 2.9 gms/cc, rising to 2.95 gms/cc at the base of the 'intermediate' layer.

In the interpretation of the anomalies over the oceanic volcanoes, the density values adopted are those which give the minimum correlation with the topography. By this method a value of 2.8 gms/cc was obtained for the amygdaloidal lavas of Bermuda.

Einarsson (1954), in a study of the Icelandic basalts, obtained 2.84 gms/cc as the mean saturated density of 48 specimens from lava flows. In Iceland - as in Skye - the majority of the vesicular basalts are now filled with chalcedony or zeolites and the density values are uniformly high. A section at Esja in Iceland, composed of a series of tuffs, palagonite, breccia and basalt, gave a mean weighted average of 2.70 gms/cc.

Washington (1924) quotes 2.96 gms/cc as the average density of Hawaii, though this is probably an upper limit, the density being reduced by ash flow, vesiculation, etc.

The North Skye basalts were found to have a mean saturated density of 2.85 gms/cc and as this value is in reasonable accord with those found elsewhere (Table 5) it has been adopted in the reduction and interpretation.

<u>The expected density of the postulated cylinders</u>

In the subsequent interpretation of the main anomalies, the anomalous masses are assumed to have the form of a vertical cylinder, this being a consistent form geologically.

The mean density of these cylinders will presumably lie between the density of the 'intermediate layer' (2.9 gms/cc) and that of the gabbroic masses exposed at the surface (3.00 gms/cc). An extreme upper limit to the density is fixed by the fact that the heaviest rocks in complexes of this type - the ultra basic peridotites of Skye - have densities of 3.3 gms/cc. These rocks have a relatively small surface area, and it seems unlikely that they occur in sufficient volume at depth to appreciably affect the bulk density.

Recent evidence suggest that the Tertiary complexes of Skye and Rhum may have been built up by a process of crystal differentiation and settling, from an originally homogeneous basalt magma, similar to that which operated in the Skaergaard intrusion. Wager and Deer (1939) wrote of the original Skaergaard magma:

> The Skaergaard magma may be regarded as being close to the Porphyritic Central type of magma described in the Mull and Ardnamurchan memoirs .....

If the Skye mass is of this type, then the Skaergaard densities have some relevance to the density problem. The values are summarised in Table 5 and show the majority of gabbros with densities around 3.0 gms/cc, the exception being the Middle Gabbro with a maximum density of 3.19 gms/cc.

The chilled marginal gabbro - representing the probable composition of the original magma - has a density of 2.97 gms/cc.

By analogy then, the postulated cylinders under the Tertiary Centres are more probably basic than ultra-basic, and a density of 3.0 gms/cc has been used for the interpretation.

Chapter IV.

THE REGIONAL GRAVITY FIELD

Introduction

Previous work in the Western Isles has been almost exclusively concerned with the testing of various isostatic hypotheses, and was invariably carried out by pendulum. Bullard and Jolly concluded their 1936 paper on 'Gravity measurements in Great Britain' by saying:

> "It is hoped that further measurements will be made in the next few years and that it will be possible to give a more detailed explanation of the anomalies in terms of the tectonics."

A further series of gravity measurements at sea, made by Browne and Cooper as part of a wider regional study, did little to fill in the gaps. Their conclusion, that the high positive Bouguer anomalies in the Hebrides were due to a rising convection current leaving an excess of mass at the surface, was a speculative geophysical, rather than a geological deduction. It is remarkable how the earlier surveys completely missed the areas of high positive anomalies associated with the Tertiary Plutonic Centres, though there are obvious difficulties in using pendulums in areas of high relief.

The broad features of the gravity field

An examination of Fig. 11 shows that the Bouguer anomaly increases to the west, rising to 60 mgals. in the S. Kilda group and to a maximum of 66 mgals. in the Outer Hebrides. This positive trend does not extend much beyond S. Kilda and therefore cannot be dismissed as a general increase in the

Bouguer anomaly as the Continental margin is approached, although such an increase would be expected as a result of the attenuation of the granitic and metasedimentary layers bringing the higher density intermediate layer nearer to the surface.

Moving eastwards, the Bouguer anomalies alternate in a regular manner, a minimum value of 5 milligals being recorded off Canna.

The distribution of these anomalies is approximately sinusoidal and if the wave length of the gravity anomaly to be explained is λ (measured as twice the distance from the maximum to the nearest minimum) then there is a strong presumption that it has arisen from an anomaly of density at a depth of λ/π at the most. The maximum depth of 8 miles so obtained locates the anomalies within the upper crust and permits explanation in terms of the surface geology.

<u>A suggested interpretation</u>

The tectonics have been briefly described by Bailey (1924) and there is some similarity between the gravity anomalies and the main tectonic lines. A major anticline brings the denser Lewisian to the surface in Tiree and Coll, and here the Bouguer anomaly rises to 30 milligals. This positive trend presumably extends through the main Skye depression and reappears in the positive Bouguer anomaly of 21 milligals over the Lewisian of North Raasay and Rona. The low anomalies around Canna are associated with a syncline, and it is tempting to regard this as a continuation of the low anomalies found over the postulated Loch Snizort basin to the north. Significantly, this trend is

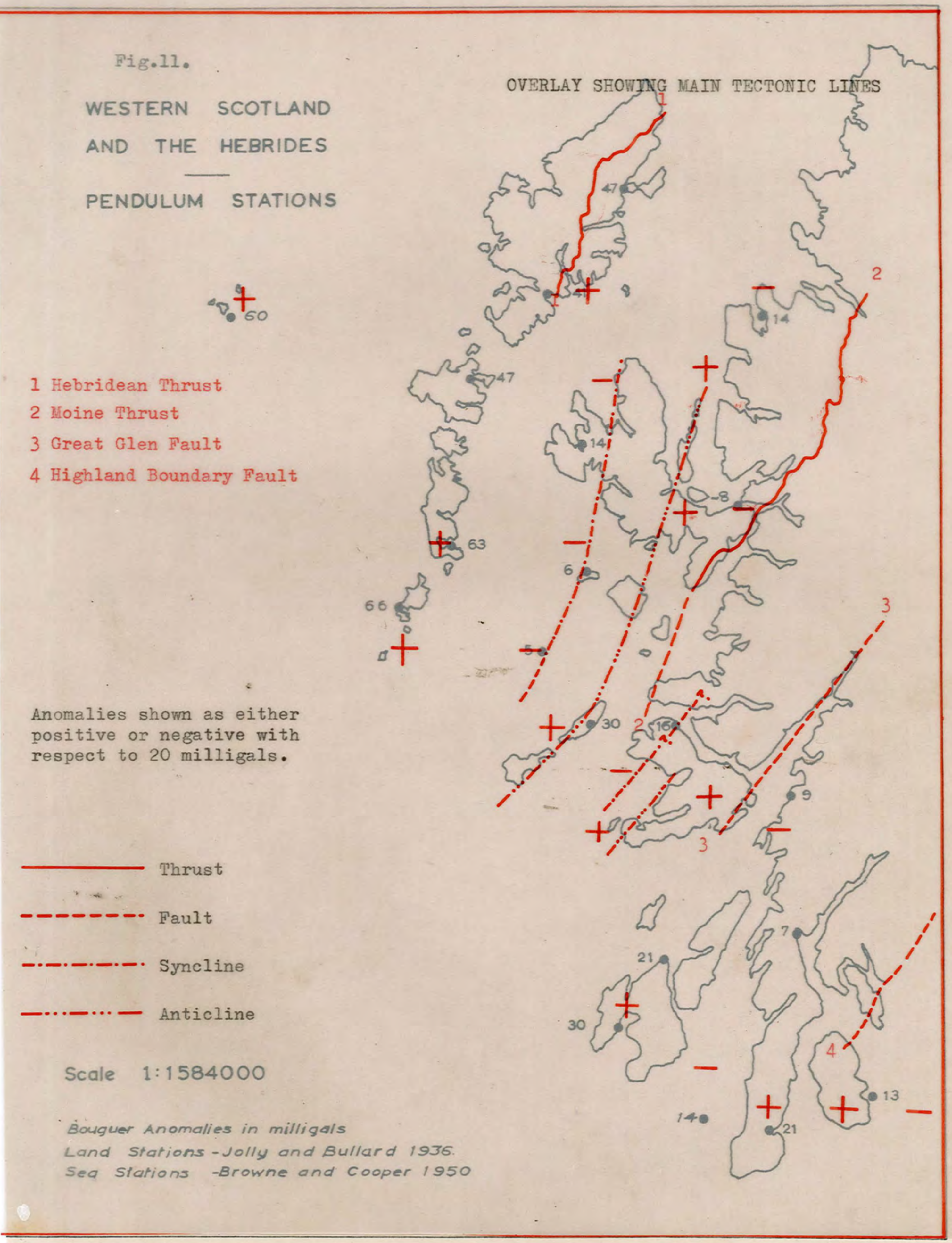


Fig.11.
WESTERN SCOTLAND
AND THE HEBRIDES
PENDULUM STATIONS
OVERLAY SHOWING MAIN TECTONIC LINES
1 Hebridean Thrust
2 Moine Thrust
3 Great Glen Fault
4 Highland Boundary Fault
Anomalies shown as either positive or negative with respect to 20 milligals.
Thrust
Fault
Syncline
Anticline
Scale 1:1584000
Bouguer Anomalies in milligals
Land Stations - Jolly and Bullard 1936.
Sea Stations - Browne and Cooper 1950
60
47
47
14
14
-8
63
6
66
5
30
16
9
7
21
30
13
14
21
1
2
3
4

sub-parallel to the old Jurassic shoreline, which - on the evidence of Ostrea - extended from Duntulm in the north to the Small Isles in the South. These gravity lows are presumably produced by the lighter Jurassic and Torridonian sediments which are preserved in synclinal basins in the folded Lewisian basement. The syncline which is responsible for the preservation of the Staffa lavas is associated with an area of low anomalies along the western coast of Mull. This broad belt appears to unite with the anomaly over the Caledonian Ross of Mull granite (q.v.).

The most westerly extensions of the Thulean Province - the Rockall and Porcupine Banks - are not shown on the text figure. Here the anomaly is again positive (Browne and Cooper 1950) indicating an excess of mass. The Rockall Bank appears to be mainly basalt, whereas 80% of the dredgings from the Porcupine Bank are of olivine gabbro. The submarine ridge culminates in Rockall itself, a small stock of aegerine riebeckite granite, which may represent another Tertiary centre (Tyrell 1924).

Islay is crossed by a dyke swarm which is quite unrelated to any known centre and this is believed to indicate yet another submerged centre. The fact that the ophitic olivine dolerite of Dubh Artach - a rock a few miles west of Colonsay, which Walker (1931), on petrological grounds, regards as being of Tertiary age - is in the direct line of the Islay - Colonsay swarm may be regarded as confirmation for this view.

Pendulum measurements made on Islay in 1936 gave a Bouguer anomaly of plus 30 milligals and this may be an indication of a larger positive anomaly farther west.

Auden (1954) has suggested, on the evidence of fracture patterns in the Inner Hebrides, that another centre may be located near Eigg. Unfortunately there are no gravity measurements in that area.

The positive Bouguer anomalies in the Outer Hebrides were - prior to this work - the largest positive anomalies in the British Isles and they do not appear to be connected in any way with the Tertiary vulcanicity. Further work would show whether the anomalies are connected with the major thrust (The Hebridean) (which has strong symmetrological analogies with the Moine Thrust), or with the high densities of the Lewisian gneisses. Some Lewisian hornblende gneisses from Sleat had densities as high as 2.96 gms./cc., and rocks of this type occur extensively in the Outer Hebrides, the Flannan Isles and N. Rona.

The isostatic anomaly

No attempt has been made to apply isostatic corrections. It would appear from earlier work along the western coast of the British Isles that the anomaly would be positive on any scheme of compensation (Bullard and Jolly, 1936; Browne and Cooper, 1950; Cook and Murphy, 1952).

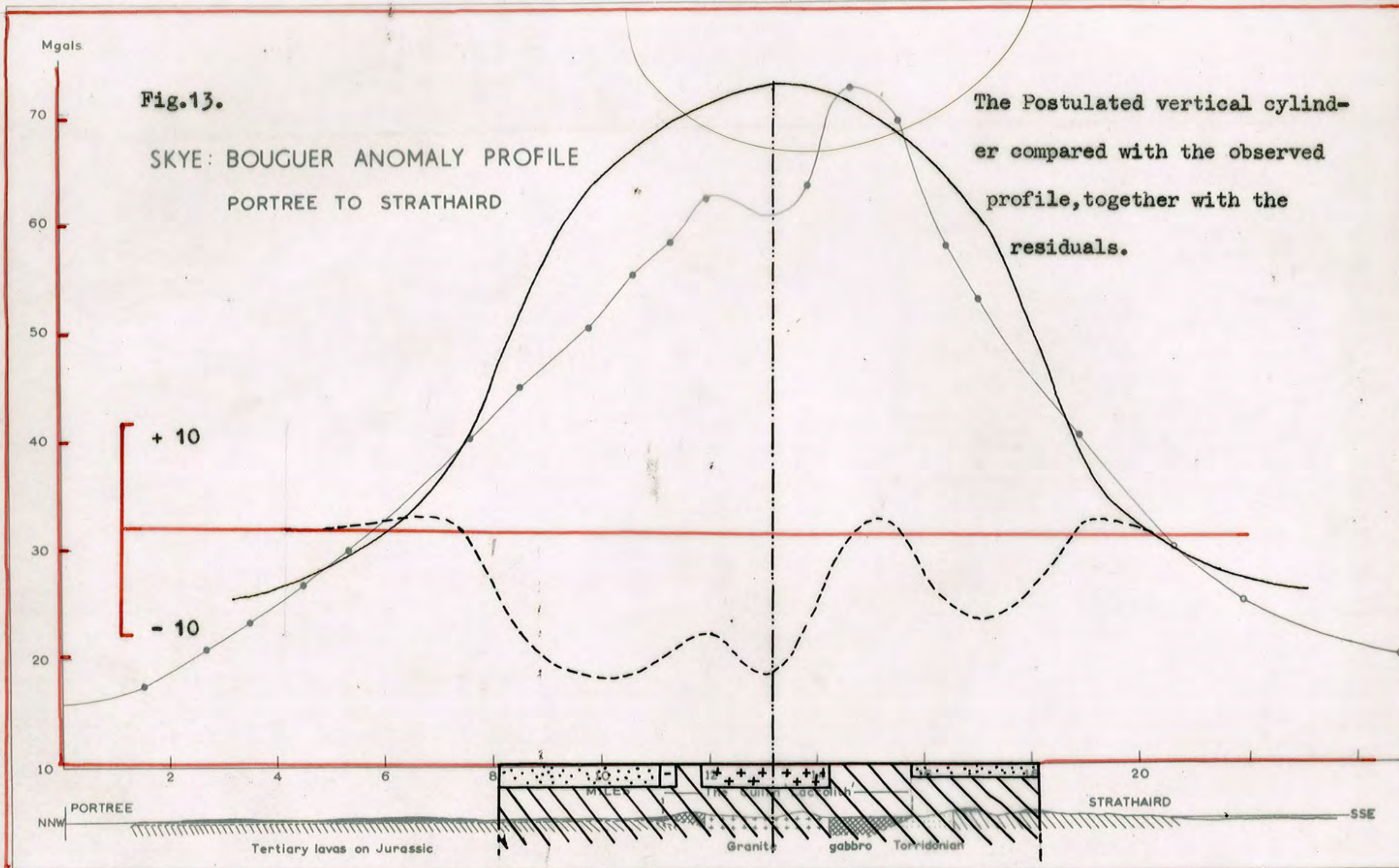


Fig.13.

The Postulated vertical cylinder compared with the observed profile, together with the residuals.

Chapter V.

ARDNAMURCHAN

Introduction

Ardnamurchan is a classic example of a perfectly dissected volcano and in a small area exhibits all the features characteristic of the Tertiary Igneous centres of Western Scotland.

Being a predominantly basic centre - the acid rocks are less than one square mile in extent - it was expected that the space form at depth would best correspond with some simple geometric form. Various theoretical models were tested and the smallest residual anomalies were obtained by using a vertical cylinder. Geologically this form has much to commend it, and the interpretation of the other centres will proceed on the assumption that departures from the normal gravity field associated with a vertical cylinder are due to the complicating effects of the lighter granitic masses seen at the surface.

Geology

Plateau basalts do not cover a wide area in Ardnamurchan, but are usually encountered, either as outliers of the main plateau; in volcanic vents; or as integral parts of screens enclosed by ring dykes of later date. There is no evidence that a central volcano ever existed in Ardnamurchan during the plateau basalt phase. Igneous activity of the central type began with the formation of explosive vents of Centre 1. This centre was subsequently pierced by two successive plugs - the ring dykes of centres 2 and 3.* We are, then, observing in Ardnamurchan the roots of a volcano cut through at different crustal levels.

* The positions of the 3 igneous centres are shown on Plate 2.

The main structural features of the complex are:

- The elliptical shape of the complex as a whole which is reflected in the shape of the individual intrusions.
- The major axis of the ellipse corresponds with the direction of movement of the foci of intrusion.
- The failure of the ring dykes to extend round the northern half of the complex.
- The time relations of the ring dykes - the younger ring dykes are always intruded inside the older ones.
- Where the three dimensional form of the ring dykes can be seen they are all highly inclined, and sometimes it can be shown that the inclination is definitely outwards from the centre.

The magmas would appear to be of the normal Hebridean type with the exception of the tonalite and quartz-monzonite of Centre 3. These are almost unique among the Tertiary rocks and suggest the existence of an independent collateral magma series with distinct end products. A similar magma series is responsible for the bulk of the plutonic intrusions of Old Red Sandstone age in Scotland (Harker 1909).

<u>The Bouguer anomalies</u>

The Bouguer anomaly, over the peninsula of Ardnamurchan (Plate 2) rises to a maximum value of 42 mgals. falling to a minimum value of 14 mgals. in the east. This minimum is not typical of the background value in the area owing to the effect of the negative Bouguer anomaly associated with the Morvern-Strontian granite. Measurements made at Salen and Strontian whilst establishing base connections to Carnach, gave anomalies of 3.6 mgals. and -15.6 mgals. respectively. The association of negative gravity anomalies with post tectonic granites would appear to be an almost universal phenomenon (Bott 1953 and 1956). Further comment on this anomaly lies outside the scope of this work.

The main anomaly is probably elliptical in form with the major axis trending N.E. - S.W. This has a rough correspondence with the direction of movement of the focus of intrusion and presumably reflects the elongation of the underlying magma chamber. A maximum value of the anomaly occurs over Centre 2. This is the centre associated with maximum doming, a total uplift of 3000 feet being deduced from the outward dips of the Mesozoic sediments.

No distortion of the isogals is apparent over the quartz dolerite intrusion of Ben Hiant. The intrusion is over a half mile wide and is believed to represent a vent infilling. The absence of anomaly over a vent of this size will be referred to later when the possibility of vents under the lava plateau of North Skye is discussed.

<u>The interpretation</u>

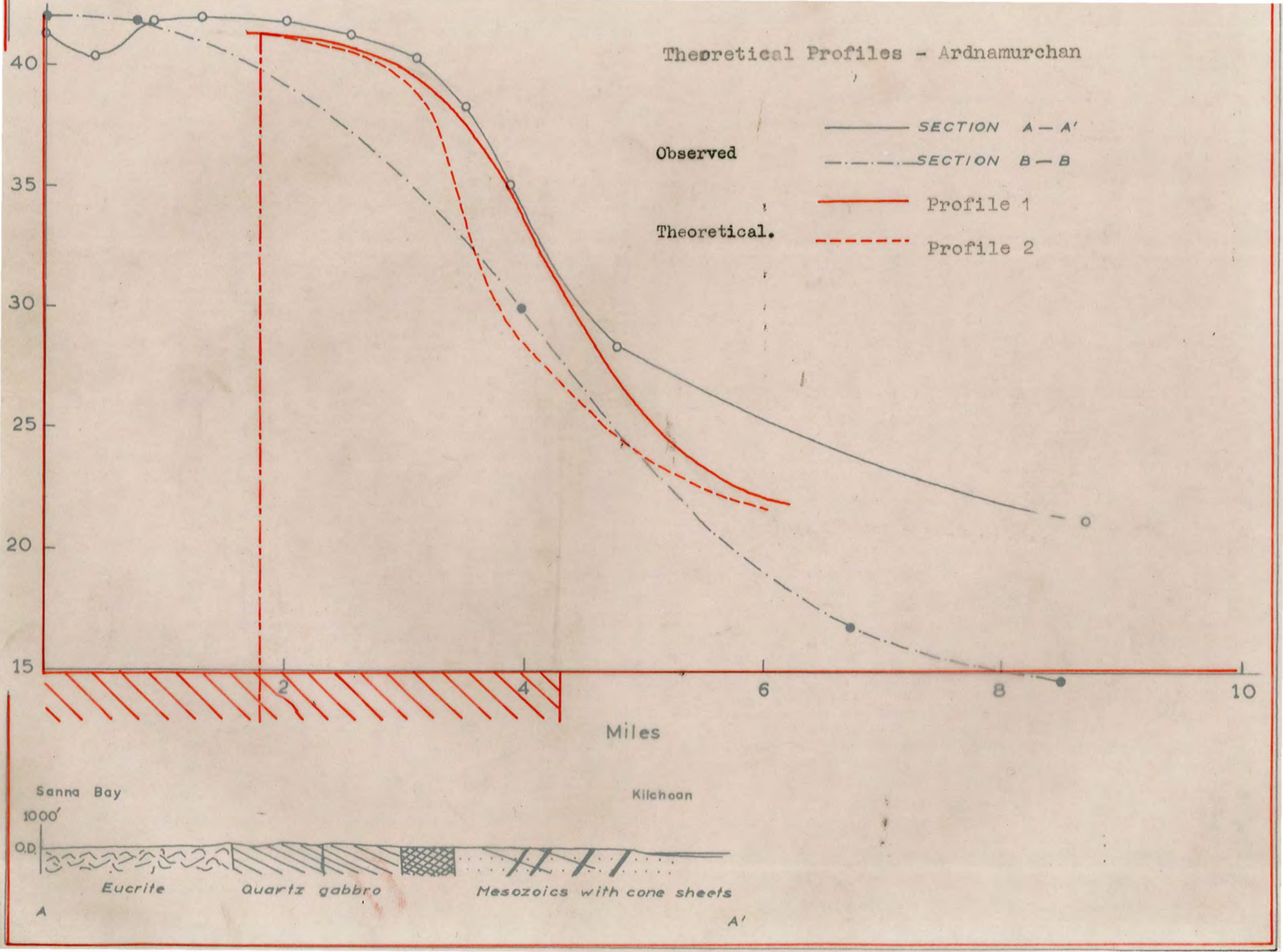
A background value of 20 milligals has been assumed for the Ardnamurchan anomaly. This is the value over the adjacent lava plateau of northern Mull and would appear to be general over the Tertiary lavas; similar anomalies being recorded by Cook and Murphy in Antrim, and by us in Skye.

An estimate of the depth to the top of the mass producing the anomaly can be derived from the relation:

$$d \leq \frac{48\sqrt{5}\,A_{max}}{125\,dA/dx_{max}}.$$

This inequality - due to Bott and Smith - gives a maximum limit to the depth to the upper surface, and has the advantage that it is least sensitive to errors in the background anomaly, and gives a better estimate where the maximum gradients are near the region of maximum anomaly. Both these conditions are present in Ardnamurchan. The value of two miles, so obtained, is of little value in itself except to indicate that the cause of the anomaly must not be sought in deep seated crustal movements and downwarps. An immediate deduction is that the anomaly is produced by the direct density contrast between the dense gabbroic rocks of the major intrusions and the adjacent country rocks (presumably Moine). The magnitude of this contrast has already been discussed in Chapter 3.

If the anomaly is considered to arise from a vertical cylinder of density contrast 0.25 gms./cc. and radius 2.5 miles with its upper surface at sea level, then the lower surface is at - 10000 feet. A theoretical model with these parameters gives a profile remarkably close to those observed (vide Fig. 12). The disparity between the two profiles with increasing horizontal distance from the centre is more apparent than real. There is little or no station control over the observed profile in this region, and the 'fit' is probably much better than that shown. A reduction in the density contrast at depth could give a similar effect; a point which will be referred to again in connection with the Skye profiles.



Theoretical Profiles - Ardnamurchan
Observed
SECTION A — A'
SECTION B — B
Theoretical.
Profile 1
Profile 2
40
35
30
25
20
15
2
4
6
8
10
Miles
Sanna Bay
Kilchoan
1000'
O.D.
Eucrite
Quartz gabbro
Mesozoics with cone sheets
A
A'

The estimate of 10000 feet must be regarded as a minimum depth to the base as quite small changes in the density contrast would considerably lengthen the cylinder. For example, if the density contrast were reduced to 0.2 gms./cc. and the radius to 2 miles, then the cylinder would have to be 30000 feet in length in order to produce the observed anomaly. This model does not give such close correspondence with the observed profile as does model 1 (vide Fig. 12).

The gravity data gives unambiguous criteria for determining the angle of inclination of the contacts. For the circular outcrop of a cylinder whose depth/radius ratio is 0.77, the anomaly at the edge cannot be less than 0.50 of the anomaly at the centre if the contact is vertical. If the anomaly over the edge is greater than 0.50, then the contact slopes outwards, providing always that the density contrast remains constant. These relationships are more fully set out in the Appendix.

Along the eastern and southern margins of the complex - the only places where the junction with the country rock can be seen - the gravity field indicates that the contacts slope uniformly outwards. This would be expected, as the proposed mechanism of ring dyke formation assumes that the boundaries are either vertical or inclined outwards, the suggested theoretical angle being 65-70 degrees. The quartz dolerite ring dykes of Centre 1 are seen to dip outwards and Richey believes this to be the rule, though difficulties of geological observation in an area of low relief make generalisations impossible.

Doris Reynolds has recently cast doubts on the concept of outwardly dipping ring dykes and suggests that the inadequacy of the field evidence is glossed over in order to fit Anderson's dynamic hypothesis. However, the gravity evidence can be regarded as providing independent support, but not confirmation for Richey's and Anderson's view.

The steep gravity gradients along the southern margin of the complex near Kilchoan are probably caused by the high density contrast between the Mesozoic sediments and the gabbro, even though the bulk density of the former must have been considerably increased by cone sheet injection.

Conclusions.

The gravity field over the Ardnamurchan centre is consistent with the complex being underlain by a basic vertical cylinder. The exact depth to the base of the cylinder is difficult to determine owing to uncertainties in the true value of the background field.

Chapter VI.

BOUGUER ANOMALIES AND THEIR RELATION TO TERTIARY PLUTONISM IN SKYE

Introduction

Skye has for long been a favourite area for the study of Tertiary plutonism. A century of accurate but infrequent investigation by Maccullough, Forbes, Geikie, Judd and many others, terminated in Harker's memoir of 1904 - a classic contribution to the subject of igneous petrology. Since 1904 no major work rivalling Harker's has appeared, but a considerable amount of new work has appeared in smaller papers. This, together with a considerable amount of unpublished work, does suggest that the structure of the main Cuillin gabbro and of the associated Red Hills granites is much more complex than was at first envisaged.

Harker's views on the time sequence and structure of the Cuillins are given in the memoir and also summarised in the Regional Guide of 1948. Richey (1932) modified the sequence of events among the main assemblies. He suggested that the three main centres of activity - the Cuillins, the Western Red Hills and the Beinn na Caillich mass - were in action successively and in that order. This progressive shift of magmatic focus is a common feature of the Tertiary Centres and has already been remarked upon in Ardnamurchan.

At the main Cuillin centre, basic and ultrabasic plutonic intrusions were followed by radial dykes, cone sheets and minor intrusions. The Western Red Hills complex of acid plutonic intrusions is not cut by the cone sheets of the Cuillin centre and is for this, and other reasons, regarded as later than the main Cuillin mass. The Beinn na Caillich centre probably represents the last phase of plutonic intrusion.

The Cuillin Gabbro

Geology

At the surface the gabbro appears as an elliptically shaped mass some 8 miles by 6 miles with the major axis trending east - west. The original form of the intrusion has been disrupted along its eastern margin by a tongue of granite from the main Red Hills mass to the north-east.

The form at depth is more speculative. Harker mapped the gabbro as a single sheet and eliminated any space problem which might arise by describing it as a laccolith. Richey rejected the laccolithic form and suggested that the gabbro represented a cone sheet complex such as had already been described in Mull and Ardnamurchan. In 1947 Wager and Stewart re-examined the banding in the gabbro, which had already been noted by Geikie, Teall and Harker, and recognised in it gravity stratification. By analogy with other gravity stratified basic masses such as Skaergaard and Belhelvie, they argued that this was a clue to the mechanism of solidification and presumably to the form of the intrusion.

The age relations of the gabbros have recently been investigated by an Oxford research group. They recognise three main divisions: an outer gabbro, the ultra-basics of Sgurr Dubh, and an inner gabbro, the age relations following the normal ring dyke pattern of the innermost being the youngest.

Description of the anomalies

The most prominent feature of the Bouguer Anomaly map (Plate 1) is a large positive anomaly corresponding with the Tertiary Plutonic Complex. This anomaly is now described in further detail:-

A large closed and elliptical area of positive Bouguer anomalies extend over the whole of Central Skye. The ellipticity is slight with the major axis trending north - east to south - west.

The remarkable symmetry of the anomaly is destroyed by a local gravity low associated with the outcrop of the Red Hills granites and granophyres. The distortion of the lines of equal gravity is particularly marked where a large tongue of granite crosses Glen Sligachan.

The positive Bouguer anomaly of 73.4 milligals, recorded over the Inner Cuillin Gabbro, is the largest positive anomaly so far observed in the British Isles and exceeds by 13 milligals the largest previously recorded in the St. Kilda group (Browne and Cooper, 1950).

Over the north-western, western and south-eastern boundaries of the complex, the horizontal gravity gradients are fairly uniform and relatively low, the average value being 5.5 - 6.5 milligals/mile. An examination of the Bouguer anomaly profile (Fig. 13) shows that these gradients are linear over a considerable area of the northern plateau basalts. To the south of the complex the gradients are abnormally high rising to

13 mgals/mile over the gabbro/Torridonian junction. Over the Western Red Hills the gradients are much reduced, frequently falling to 2.5 - 3.5 mgals/mile.

The physical interpretation

Estimation of the background field

An average value for the background field is not immediately apparent: the gravity field over the Lewisian to the south being complicated by the overlying Torridonian, and that over the northern basalts by the underlying Jurassic. Where the Lewisian basement is exposed at the surface - as in north Raasay and Rona - the Bouguer anomaly rises to 20 milligals.

Eliminating the effect of the geologically predicted 2000 feet of light Jurassic sediments beneath north Skye increases the background field in that area from 16 to 20 milligals.

Over the peninsula of Sleat, the background field is apparently 15 milligals, but as the surface geology is more complex, corrections are difficult to apply. A correction for the thickness of Torridonian above the Kishorn Thrust is described in Chapter 9.

The assumption of a background field of 20 mgals. leaves a positive anomaly of 53 mgals. over the Cuillin gabbro. A similar background value was observed over the lava plateau of Mull; the palaeozoics of Ireland (Cook and Murphy, 1952); and in Kintyre (Bullard and Jolly, 1936). Generally the areas in which the Bouguer anomaly departs greatly from a value of 20 mgals. are relatively small and fairly well defined, and over most of the Palaeozoic and Pre-Cambrian regions of the western coast of the British Isles, the Bouguer anomaly varies only slightly between +10 and +20 mgals.

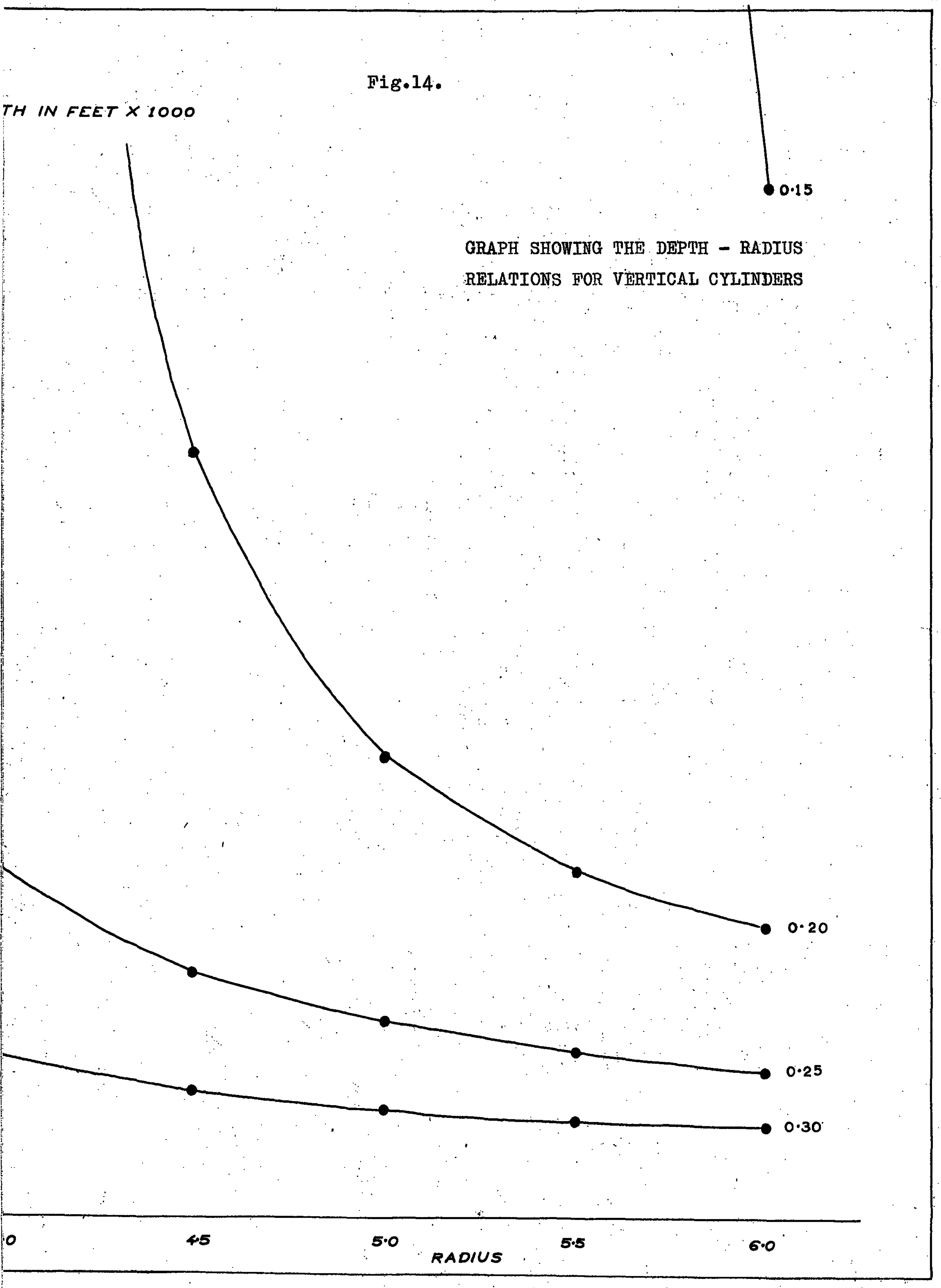
Depth estimates

The maximum depth to the top of the anomalous mass producing the observed Bouguer anomaly can be obtained by considering the maximum anomaly in conjunction with the maximum gradient.

This technique has already been described (Chap. V.), and taking the average gradient - as distinct from the abnormal gradient - as 6 milligals, gives a maximum depth of 7.6 miles. While this places the origin of the anomaly within the upper crust, it is of little value in itself. The observed gravity gradients are inconsistent with such a depth, unless the density contrast at depth is abnormally high. For a variety of reasons already set out, this possibility is considered unlikely. The depth estimation makes no assumptions about either the size of the density contrast, or its origin. The most probable source of the anomaly is a direct density contrast between the gabbro and the surrounding country rock. It is considered likely that the elliptical area of gabbro exposed at the surface represents the upper surface of the mass responsible for the anomaly and that the mass has a considerable extension in depth.

The minimum depth to the base of the anomalous mass can be calculated by assuming the mass to be in the form of a vertical cylinder with its upper surface at ordnance datum. A table has been drawn up showing the depth to the base of cylinders with varying radii and density contrasts.

Fig.14.



TH IN FEET X 1000
0·15
GRAPH SHOWING THE DEPTH - RADIUS
RELATIONS FOR VERTICAL CYLINDERS
0·20
0·25
0·30
0
4·5
5·0
5·5
6·0
RADIUS

Table showing depth - radius relations for vertical cylinders having a maximum anomaly at the centre of 52 milligals

p	6	5.5	5.0	4.5	4.0	Radius in miles
0.3	16.0	19.7	21.0	23.0	26.4	
0.25	25.0	27.1	30.0	35.0	45.7	
0.20	40.0	45.5	57.1	88.6	491.4	
0.15	116.0	279.4	inf.	inf.	inf.	

(depths given in thousands of feet)

It is apparent from both the table and the graph (Fig.14) that a density contrast of 0.15 gms/cc gives a cylinder of either inordinate (35 kms.) or infinite length. This places a minimum value for the density contrast at 0.15 gms/cc.

Since the most probable value for the density contrast is 0.2 gms/cc., the depths to the base are considerable, ranging from 40000 feet for a cylinder of radius 6 miles, to 57000 feet for a radius of 5.0 miles.

Theoretical Models

From the previous work on Ardnamurchan it was thought that the most likely solution to the space form of the mass responsible for the anomaly would be some type of vertical cylinder.

A consideration of the 'half anomaly' suggested that a cylinder of radius 5 miles, depth 10.9 miles and of density contrast 0.2 gms/cc, with its centre close to Harker's centre of cone sheet intrusion, would satisfy some of the characteristics of the observed anomaly. The anomaly produced by a theoretical model with these parameters was computed and compared with the observed profile Portree - Strathaird (Fig. 13).

The 'fit' between the profiles is not good, but this was not unexpected since so perfect a geometrical solid as the upper surface of a gabbro cylinder exposed at sea level is hardly likely in nature. Even a cursory glance at the geological map shows that there are large areas where rocks other than gabbro or granite are exposed within the prescribed five mile radius (these areas are shaded in yellow on the Plate).

One of the major premises in the interpretation is that departures from the vertical cylinder form are due to the complicating effects of the less dense acid rocks at the surface (vide Chap. V.). An examination of the residuals (Fig. 13) shows that these roughly correspond with the surface geology; a residual negative anomaly of 11.5 mgals. being associated with the outcrop of the Red Hills granite.

Subtracting the effect which can reasonably be attributed to the granite still leaves a negative residual. The remainder of this residual negative anomaly to the north, corresponds with an area of plateau basalts underlain at no great depth by some 2000 feet of Jurassic sediments resting on the metamorphic basement. This area of light sediments (2.6 gms/cc) in an area theoretically represented by gabbro would easily account for the negative residual.

Similar reasoning applies to the area to the south. Here the negative residual of 7 mgals. can be correlated with an outcrop of Torridonian sandstone faulted against Jurassic.

The abnormally high gravity gradients - 13 mgals/mile - seen on Fig. 13 confirm that marked density variations are taking place near the surface of the postulated vertical cylinder. In this case it can be shown that the masses responsible lie within a mile of the surface, and that they correlate with a direct surface density contrast between gabbro and Torridonian (0.25 gms/cc), or gabbro and granite (0.4 gms/cc). The form of the profile in these areas suggests that the contacts are vertical or highly inclined.

The comparative steepness of the gravity gradients over 10 miles distant from the centre of the anomaly may be due to either a widening of the cylinder towards the base, or an increase in the density contrast at depth. If the former explanation is correct - and it can but be a speculation - the theoretical model has the 'inverted flower pot' form favoured by Anderson (1936).

Geological Interpretation of the Anomaly

Introduction

Theoretically any complete interpretation of a Bouguer anomaly is an impossible task, since an infinite number of mass distributions can give the gravity field observed at the surface. Fortunately the number of possibilities are limited by the numerical characteristics of the anomaly, and these are limited still further by geological considerations.

The basement

In the physical interpretation a density contrast of 0.2 gms/cc was assumed. The geological evidence supporting this contention can now be set out more fully.

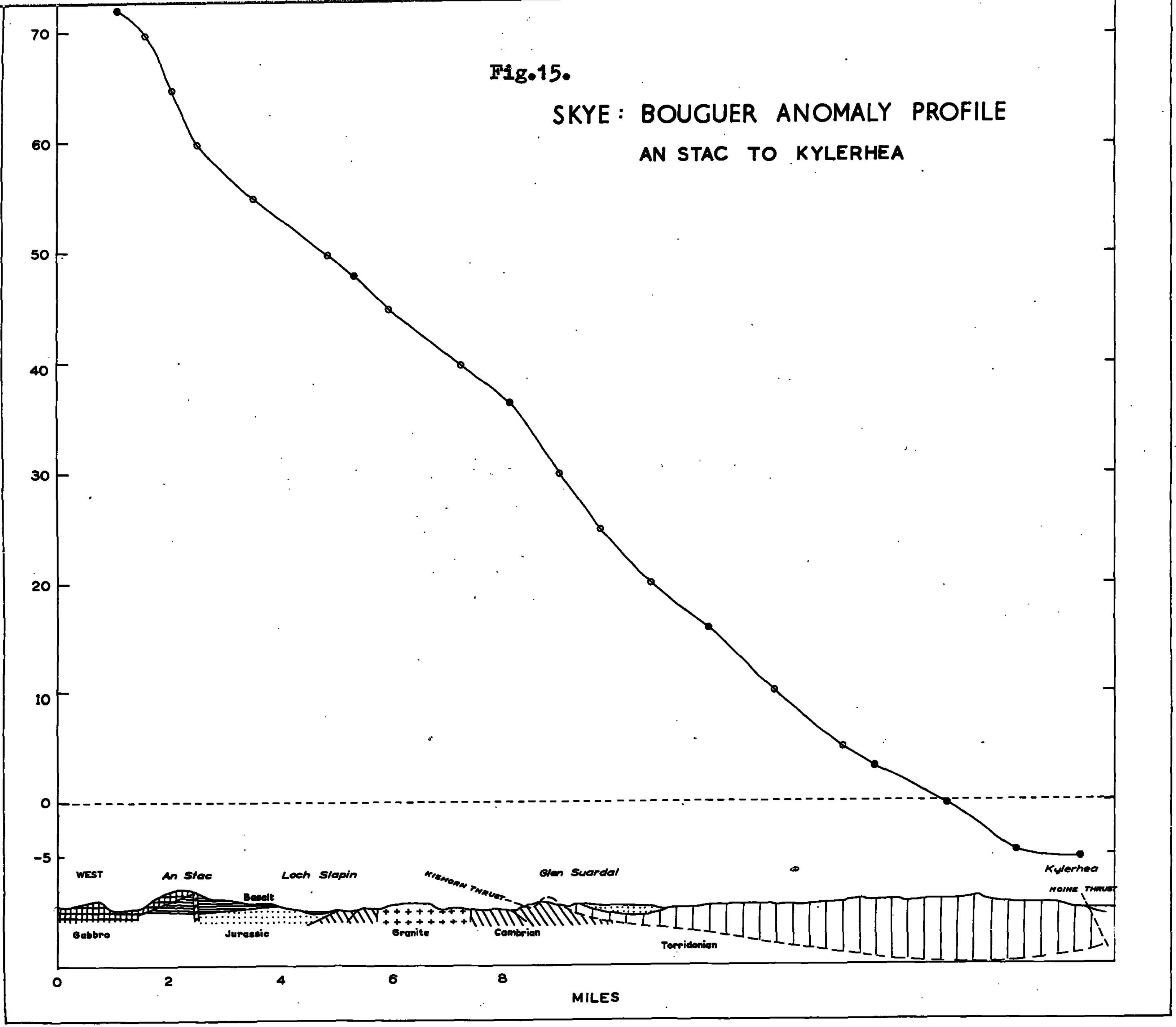


Fig.15.
SKYE: BOUGUER ANOMALY PROFILE
AN STAC TO KYLERHEA
70
60
50
40
30
20
10
0
-5
WEST
An Stac
Loch Slapin
Kishorn Thrust
Glen Suardal
Kylerhea
Moine Thrust
Basalt
Gabbro
Jurassic
Granite
Cambrian
Torridonian
0
2
4
6
8
MILES

Skye forms part of the foreland of the Caledonian geosyncline, and geological sections by Bailey (1955), Kennedy (1954), and others show the Lewisian basement at a depth of five thousand feet beneath the island of Soay 3 miles south of the Cuillin gabbro. Lewisian outcrops to the north of the Cuillins in North Raasay and Rona. Inclusions of gneiss resembling the Lewisian occur in xenolithic granophyres and also in the quartz gabbros of Harker's Gully. In Allt na Teangaidh (Eastern Red Hills) gneisses are exposed beneath the basalts and these may well be of Lewisian age.

We can then safely conclude that the basement beneath the Central Complex is of Lewisian type, rather than of the less dense Torridonian, and that the Bouguer anomaly arises from the juxtaposition of a large, dense and presumably basic mass and a lighter metamorphic basement. The expected density of the basic mass has already been discussed in Chapter 3 and a value of 3.0 gms/cc decided upon. If the average density of the Lewisian is 2.8 gms/cc, then the most probable density contrast is 0.2 gms/cc.

The geometry of the anomalous mass

Irrespective of any detailed conclusions as to the actual geometry of the basic mass, the Bouguer anomalies indicate a roughly circular mass which must extend downwards to a considerable depth. The assumption of a cylindrical form puts the base at a minimum depth of 17 Kms., and this is certainly of the order of thickness of the metasedimentary and granitic layers. An examination of 18 seismic records from Europe shows the average thickness of the granitic layer as 17 Kms., and there is probably little doubt that the mass indicated by the anomaly extends into the intermediate layer.

This has long been suspected for the Tertiary magma chambers. Holmes (1932) shows a cupola shaped mass arising from the base of the intermediate layer and extending upwards into the granitic layer. To the latter, he assigns a thickness of 12 Kms., this being similar to Jeffreys estimate. Anderson (1936) makes a similar assumption, and envisages the Tertiary magma chambers as stock like masses arising from a regional magma chamber.

Cook and Murphy (1952) interpreted the positive anomaly over the Slieve Gullion and Carlingford masses in terms of a horizontal cylinder some 10000 feet beneath the surface. This they equated with Anderson's (1924 and 1936) cupola shaped magma chamber. Their theoretical model left large gravity residuals, and failed to account for the attraction of the masses between 10000 feet and the surface. Despite the obvious attractions of the horizontal cylinder as the source of cone sheets and ring dykes, a paraboidal magma chamber is not required by Anderson's theory. All that is required is that there should be a pressure and a 'push point', and these conditions are equally well satisfied by either the vertical cylinder or the 'inverted flower pot'.

Williams (1954) states that the reservoirs of long lived central type volcanoes appear to be roughly cylindrical, tabular bodies. The actual depth of the magma chamber is variable, ranging from a mile in the case of the Ischian and Tahitan volcanoes to 4 miles at Vesuvius. In most volcanoes, fragments found in the explosion pipes, and breccias indicate a magma chamber between 2000 and 10000 feet.

Since the end of the Tertiary, erosion in the Western Isles has removed several thousand feet of basalt and exposed the roots of the volcanoes. We are in fact examining former magma chambers, and discussions as to their depth are not strictly relevant, only their extension at depth.

The gravity evidence, coupled with much recent field mapping, is completely at variance with Harker's original concept of a 'Cuillin laccolite' fed by a narrow central feeder (Clough and Harker 1904, Fig. 4). The tectonic setting is unnatural, laccoliths being normally associated with compression and orogeny, whereas all the evidence from the Tertiary centres is indicative of a region of tension. The laccolith had much to commend it in that the paucity of the supporting evidence was outweighed by the seeming solution of the space problem. We are now left with the solution of that problem.

Marginal folding to the south of the complex in Strathaird, and lack of folding to the north in Glen Brittle suggests that some asymmetry is associated with the intrusion. Against this, the regular form of both the ring dykes and the cone sheets presupposes a regular and symmetrical magma chamber. It seems fairly certain that both ring dykes and cone sheets are continuous with the underlying magma reservoir, and that the complex accurately marks both the position and lateral extent of such a chamber.

The evidence then of both the geology and the Bouguer anomalies favours a roughly circular and essentially symmetrical mass extending downwards into a regional magma chamber. These conditions are satisfied by the proposed theoretical model.

Subtracting the gravitational effect of the postulated vertical cylinder from the observed gravity field leaves a few areas of positive residuals in addition to the negative areas already remarked upon. These positive residuals obviously cannot be accounted for in terms of lighter masses on top of the cylinder and must therefore be the result of departures from the cylindrical form. Professor Stewart, in a private communication, has suggested that the Central Complex in Skye may be underlain by three magma chambers, centred beneath the Cuillin gabbro, the Western Red Hills, and the Eastern Red Hills. If three circles are drawn with radii corresponding to these masses, it is found that the three interacting cylinders can - with slight errors - be approximated to a single cylinder of radius five miles. With such evidence as we have, it would be difficult to separate the gravitational effect of three cylinders the distance between whose centres is only a little greater than their radii.

A similar problem was encountered by Cook and Murphy (1952 p. 18) in their interpretation of the Slieve Gullion - Carlingford anomaly. There they conclude that the attraction of a horizontal cylinder would not differ radically from that of two adjacent magma chambers or cupolas, and that many more observations would be required in order to separate the two structures.

Possibly one of the differences between the two interpretations lies in that whereas the two Irish magma chambers are 10 miles apart and can be approximated to a horizontal cylinder, the Skye magma chambers are much closer together and approximate more closely to a vertical cylinder. The departures from the vertical cylinder form indicated by the positive residuals, do suggest that the anomalous mass is slightly eccentric with its major axis trending NE - SW.

The Red Hills Granites

Geology

These constitute - after the Mourne Mountain granites - the largest area of granite and granophyre in the Tertiary province. Both geologically and geographically they can be divided into two main divisions: the Western Red Hills and the Eastern Red Hills.

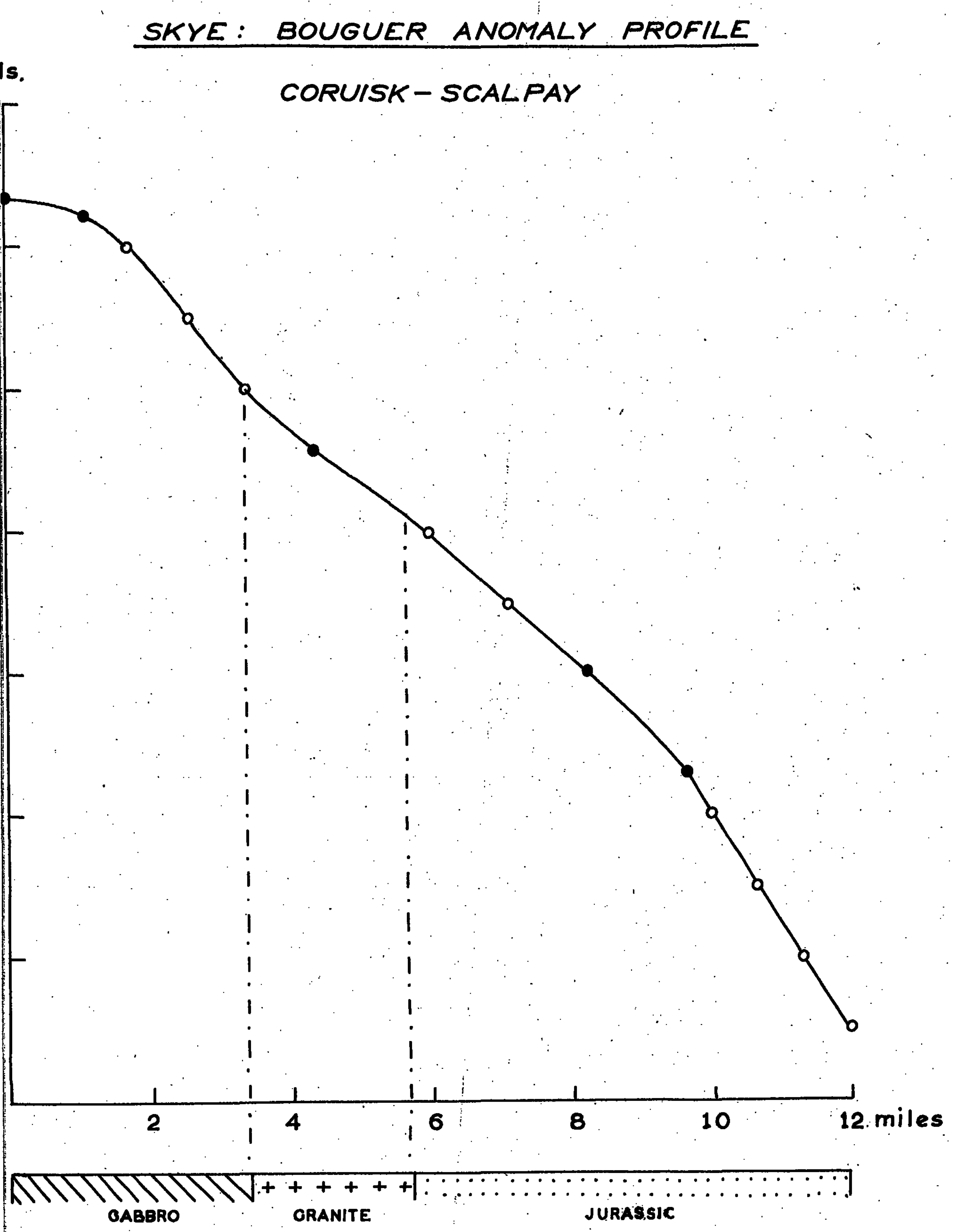
Along its northern and eastern boundaries, the Western Red Hills granite rests successively on basalt and Torridonian, and considering the evidence prior to 1948, the granite appears to have the form of a large irregular laccolith with a southerly dip. The almost straight, vertical boundary along the Sligachan River was believed by Harker to be the source of the magma which then spread laterally eastwards in a series of distinct intrusions - the so called quasi-horizontal sheets. While there is no evidence to indicate the original thickness of the granites, Harker put their present thickness in the central area as exceeding 1500 feet.

Of the Eastern Red Hills, he observes that Beinn na Caillich has definitely 'the boss-like form' and that the structural relations are complex. His structural views are summarised in the comment: "The granite in general has partly the boss like and partly the laccolithic habit and the two types of junction, the vertically transgressive and the obliquely underlying exemplified in Glen Sligachan seem to belong to the different modes of intrusion."

The Bouguer Anomalies and their interpretation

The Bouguer anomalies (Plate 1) show considerable distortion

Fig.16.


SKYE : BOUGUER ANOMALY PROFILE
CORUISK – SCALPAY
ls.
2
4
6
8
10
12 miles
GABBRO
GRANITE
JURASSIC

over the granite area, a ridge of lower gravity extending over the tongue of granite across Glen Sligachan. Curiously enough this ridge corresponds with the Marsco anticline of Harker's Cuillin laccolith which is shown on page 86 of the Memoir. Over the granites the gravity gradients are low, the gradient between Loch Ainort and Glen Sligachan being 2.6 mgals/ml. However, the gabbro-granite junction in Glen Sligachan introduces a high surface density contrast of 0.4 gms/cc. and this raises the gradient to 11 mgals/mile.

The distortion of the anomaly profile over the granite is well seen on Fig. 13. This local minimum appears to have a depth of 10 milligals and if the tongue of granite in the line of section is assumed to be in the form of a vertical cylinder of radius 1 mile, then the thickness of granite below sea level must be less than 3000 feet. This conclusion is quite independent of any assumptions made as to the nature and geometry of the mass responsible for the main anomaly.

Tracing the granite to the east, the profile Loch Coruisk-Scalpay (Fig. 16) shows the anomaly over the main mass of the Western Red hills. The gravity low seen on the Sligachan profile is much reduced in size, being less than 2 milligal. Obviously the granite has become very thin indeed, and is approximating to a thin sheet with its base not far below sea level.

The structural picture indicated by the gravity anomalies is that of a thick area of granite along the line of Glen Sligachan thinning to the east. There is insufficient evidence to form any definite opinions on the form of the Beinn na Caillich mass; though the contours, as interpolated, suggest a sheet-like rather than a stock-like form.

Petrogenetic Implications

The deduction that the acid rocks are comparatively unimportant in bulk compared with the main basic mass raises several interesting points of petrogenesis.

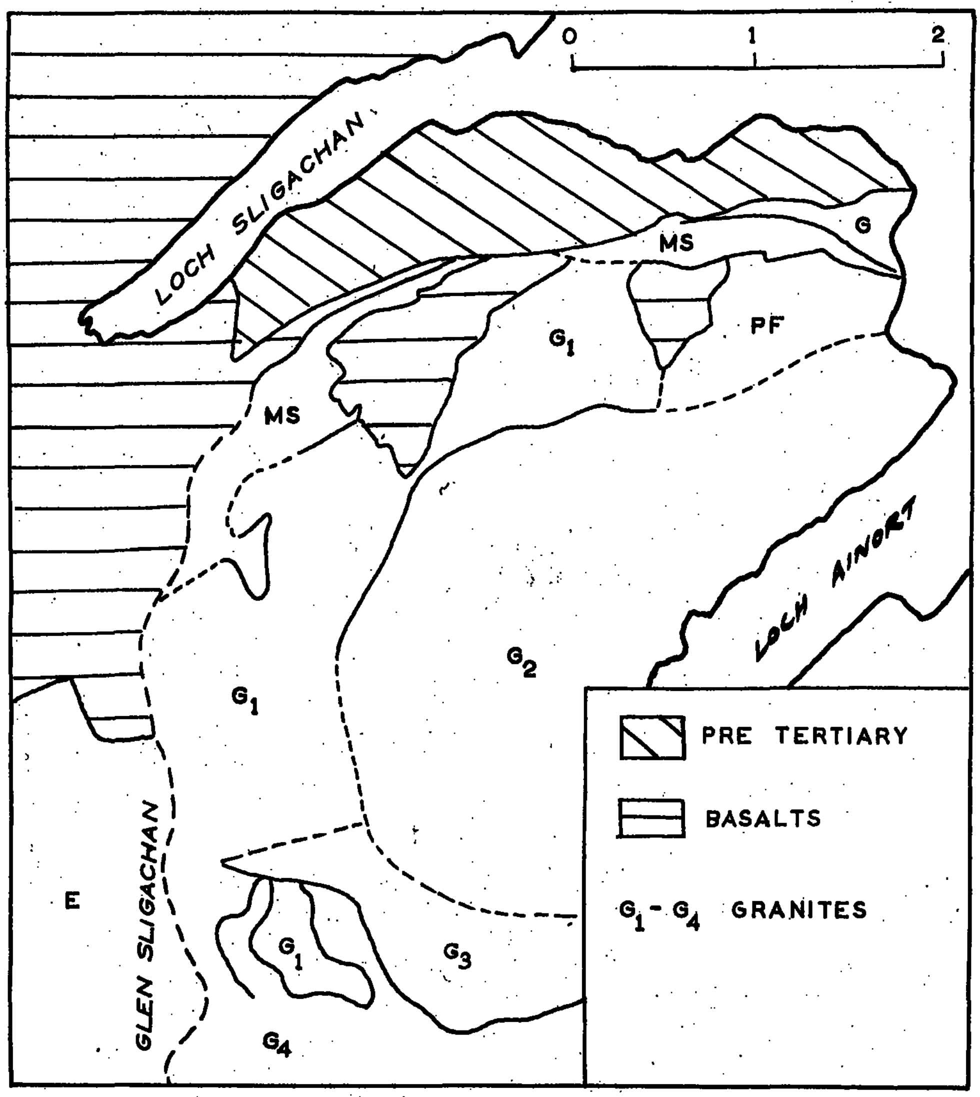
From the gravity evidence the granites and granophyres now appear as a thin scum on an underlying basic magma - almost a text book exposition of the magmatic viewpoint - and if we accept Grout's estimate that a basic magma will yield from 5% - 10% of acid differentiate, the basic mass indicated by the main positive anomaly provides an adequate source.

However, Wager and Deer (1938) record that the mineralogical and textural features of granophyre inclusions at Skaergaard - which have been produced by refusion of acid gneiss - are similar to those of granophyres from the Tertiary Centres of Scotland. King (1953) noted the transformation of Torridonian sandstone to granophyre at Creag Strollamus in Skye, and Black (1954) described the transformation of Torridonian to granophyre in Rhum. M.K. Wells (1951) has recorded that sedimentary inclusions within the hypersthene gabbro of Centre 2 of Ardnamurchan have been transformed to granophyre.

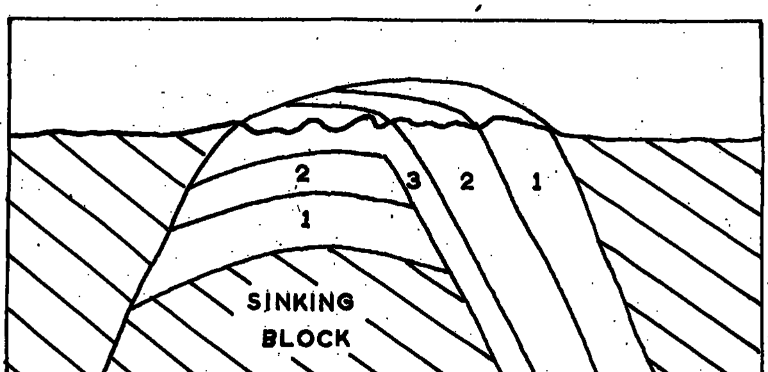
Others, opposed to the idea of transformation, record that both the Torridon sandstone and the Tertiary granites have been melted by Tertiary dykes without change of composition. This effect was noted by Almond (unpublished) in his mapping of the Torridonian-Gabbro contact at Camasunary in Skye.

The solution of the problem of origin of the Tertiary

GEOLOGICAL MAP OF THE WESTERN RED HILLS. Fig.17.



FORMATION OF RING DYKES BY CAULDRON SUBSIDENCE (after Richey)



granites must ultimately come from petrography and chemistry, since the only evidence provided by the Bouguer anomaly is that of a density contrast and this contrast is the same irrespective of the source of the granite.

Yet any theory of Origin must be consistent with the structural picture indicated by the Bouguer anomalies and in this context the parallels with the Mourne Mountain granites are worth consideration.

The gravity field over the Mourne granites is similar to that observed in Skye, the granites having little or no effect on the main positive anomaly. From the absence of anomaly, Cook and Murphy concluded that the granites were thin and that their maximum thickness probably did not exceed 3000-4000 feet. This agreed well with the known structure of the Mournes. There Richey (1928) had recognised four distinct intrusions of granite and from their structural relationships, he suggested that the Eastern Mournes were emplaced by a cauldron subsidence mechanism similar to that which operated in Glencoe (Clough et al. 1909).

It is tempting to consider that the Red Hills granites may have been emplaced by a similar mechanism. This has some geological support: mapping in the Western Red Hills by Richey, Wager and Stewart (1948) has shown the existence of four petrologically distinct granites; and professor Stewart's mapping in the Beinn na Caillich area indicates at least seven distinct granitic intrusions (private communication).

From the gravity evidence the thickest area of granite appears to lie beneath Glen Sligachan. If the Western Red Hills have resulted from a cauldron subsidence, the earliest granite should lie along Glen Sligachan, and from Wager and Stewart's map (Fig.17) this would appear to be so, G1 being exposed along this line. Subsidence of a central block does not involve magma rising along the eastern margin in the Scalpay area. This is consistent with both the observed geology and the gravity field the granite thinning to the east.

Conclusions.

The high positive Bouguer anomalies over Central Skye are interpreted in terms of a basic vertical cylinder of radius 5 miles, possibly extending into the Intermediate layer at a depth of 17 Kms. Departures from the cylindrical form indicated by the gravity residuals, suggest that the anomalous mass is slightly eccentric with its major axis trending NE - SW. This is consistent with the three main plutonic centres being underlain by three interacting vertical cylinders representing original magma chambers. There is also a possibility that the basic mass widens towards the base, in which case the original magma chamber had the inverted 'flower pot' form favoured by Anderson.

Gravity lows along the line of Glen Sligachan indicate a granite approximately 3000 feet thick thinning to the east. These observations, coupled with the field evidence of Wager and Stewart, lead to the tentative conclusion that the Western Red Hills may have been emplaced by a cauldron subsidence mechanism. Further gravity observations in the critical areas would enable a more definite statement to be made.

Chapter VII

BOUGUER ANOMALIES AND THEIR RELATION TO TERTIARY PLUTONISM IN MULL

Introduction.

The Tertiary igneous activity of Mull exceeds that found in all other centres in the extent and complexity of its manifestations. Despite this, the same general structural pattern already described from Skye and Ardnamurchan prevails in Mull. The surface area of the intrusive masses of Skye and Mull are approximately equal (Skye, 59 sq. miles; Mull, 58 sq. miles); there is the same shift of magmatic focus, and a similar development of predominantly basic and acid centres.

These superficial similarities were found to be reflected in the gravity field, the Bouguer anomalies over the two centres of Skye and Mull having the same general form and an almost identical maximum. Not surprisingly, the interpretation proceeds on similar lines and the assumptions made earlier - that the simple gravity field associated with the vertical cylinder was complicated by the presence of near surface acid intrusives - are now carried over and applied in Mull.

Geology

A detailed account of the geology and time sequences would be out of place here, excellent accounts having been given in Bailey (1924) and Richey (1932, 1948). The principal stages relevant to the present work are summarised below:-

There were apparently three main centres of igneous activity: a southern centre around Loch Schridain, a south-east caldera, and a later predominantly acid north-west centre around Loch Ba. The centres have a bilateral symmetry about a NW - SE line, and though the individual sequence of events within the centres is complex, the various igneous assemblages can be simply referred to two successive acid-basic igneous cycles ending with a final recurrence of acid magma.

A significant feature for the work was that whereas in Skye and Ardnamurchan the former existence of a volcano was not immediately apparent, Bailey conclusively demonstrated that during the Tertiary the South East Caldera was a true volcanic sink caldera similar to that of Kilauea.

<u>Description of the anomalies</u>

The Bouguer Anomaly Map (Plate 2) shows many features similar to those already described in Skye. The contours again serve to emphasise the intensely local nature of the anomaly, a large positive anomaly being centred over the Mull plutonic complex. A further description of the anomaly now follows:-

> A large closed area of positive Bouguer anomalies extends over the plutonic complex. The main anomaly is almost perfectly circular - with the exception of the anomalous area over the later acid caldera - though there is a slight NW - SE elongation.
>
> Over the South East Caldera - the wreck of the central volcano - the Bouguer anomaly rises to a maximum value of 71.7 mgals., only 1.7 mgals. lower than the Skye maximum.

To the north of the plutonic complex, the Bouguer anomaly has an average value of 20 - 21 mgals. over the plateau basalts, increasing to 24 mgals. in the extreme north west of the island. This presumably forms part of a positive trend extending towards the 30 mgal. anomaly found over the Lewisian gneiss of Coll. Over the Sound of Mull 8 miles south-east of the maximum value, the anomaly is still falling at the rate of 5 mgals/mile towards the Morvern-Strontian granite mass.

An area of lower (+17 mgals.) Bouguer anomalies along the north east coast of the island would appear to be an extension of a similarly trending low in Ardnamurchan. No obvious geological feature corresponds with this anomaly.

There is considerable distortion of the lines of equal gravity over the acid Loch Ba centre, the horizontal gradient frequently falling to 1 mgal/mile. The maximum horizontal gradient (9.3 mgals/mile) occurs at the eastern end of Loch Scridain. The average gradient appears to be 6 mgals/mile.

<u>The nature of the basement</u>

Mull lies to the east of the Moine Thrust and the metamorphic basement - where exposed - is made up of steeply dipping Moine gneiss striking to the north-east. Lewisian gneiss reappears to the west of the island, and presumably west of the Moine Thrust also, in Iona q.v. Petrologically, the Moine rocks of Mull are predominantly sedimentary in origin and show a high degree of regional metamorphism.

The nature of the basement beneath the Tertiary centres can be assessed from the vent agglomerates. Large fragments of Moine gneiss are found in the peripheral vents and in places parts of the old gneissic floor are exposed by erosion. No pre-Tertiary rocks have been found within the main caldera, and it is inferred that in central Mull the old pre-Tertiary floor had sunk so far down the caldera that it was unaffected by later surface volcanic explosions. No Lewisian has been recorded in any of the vents (presumably for the reason already cited) though it must be present at depth.

Mesozoic sediments ranging in age from Triassic to Cretaceous overlie the Moine basement. They are generally thin reaching a maximum thickness of 1000 feet in South East Mull and 600 feet in Ardnamurchan.

The density contrast

If the plutonic complex is underlain by a basic mass - as the geological evidence suggests - then the positive Bouguer anomaly arises from the density contrast between this mass and the lighter metamorphic basement. The surface density of the Moine is 2.75 ± 0.05 gms/cc. Lewisian densities are generally higher 2.8 gms/cc., and an average value for the metamorphic basement as a whole is probably closer to 2.8 gms/cc. If the density of the basic mass is taken as 3.00 gms/cc., then the density contrast is 0.2 gms/cc.

The background anomaly

Since metamorphic formations have a fairly constant bulk density, the Bouguer anomaly over these areas provides the best estimate of the background. Unfortunately, there are few large areas of the metamorphic basement exposed in Mull from which an estimate can be obtained. The Bouguer anomaly rises to 20 mgals. towards the Lewisian of Iona, increasing to 30 mgals. in Coll. Over the Moine gneiss of western Mull the average value of 10 mgals. is not typical owing to the effect of the adjacent Ross of Mull granite q.v. Bouguer anomalies over the northern plateau basalts vary between 16 and 24 mgals. with an average value of 20 mgals. Similar values have been noted elsewhere (vide 6,42) and seem typical of background anomalies over most of the Palaeozoic and Pre-Cambrian regions of the western British Isles.

The anomalies

The assumption of a background field of 20 mgals. leaves a positive anomaly of 52 mgals. over the South East Caldera and a smaller 30 mgal. anomaly over the later Loch Ba centre.

The Physical Interpretation

Introduction

The interpretation begins with a preliminary estimate of the depths to the upper and lower surface of the anomalous mass, followed by a comparison of the theoretical profiles obtained from vertical cylinders with the observed gravity profiles over the Mull plutonic complex. The residuals are then discussed as departures from the ideal cylindrical form.

(i) Depth estimations

The techniques already used in Skye were again applied in Mull. Using a formula given by Bott and Smith (1958) for a point mass it can be shown that the structure responsible for the main anomaly cannot be deeper than 4.8 miles. This confirms a shallow origin for anomaly and suggests that the most probable source of the anomaly is a direct density contrast between an extension of the plutonic complex seen at the surface and the lighter metasedimentary basement. This result is independent of any assumptions as to the magnitude of the density contrast or the geometry of the anomalous mass.

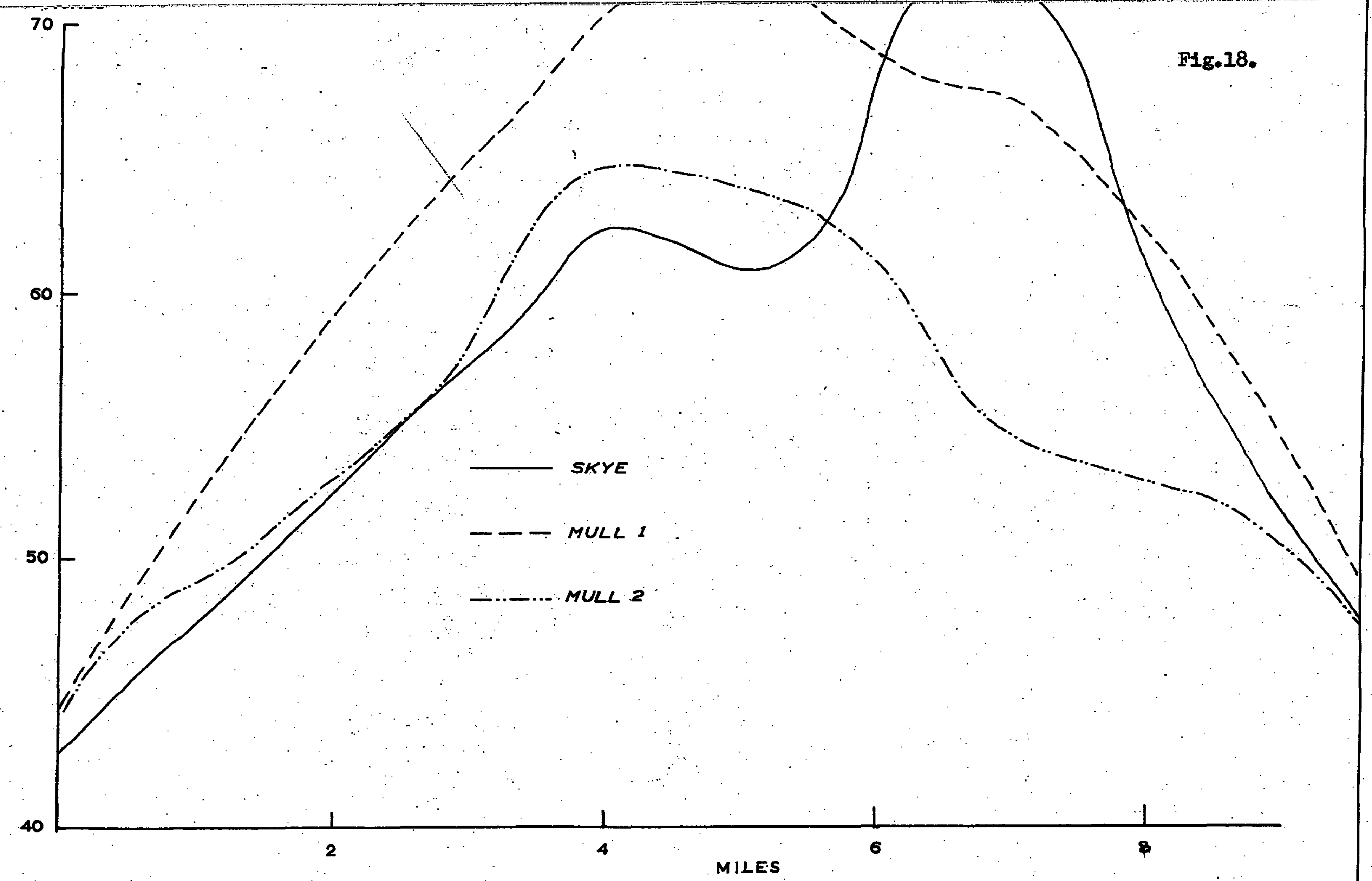
Estimates of the minimum depth to the lower surface can be obtained by assuming 1) a density contrast and 2) that the anomalous mass is in the form of a vertical cylinder. The radius of the vertical cylinder is found from the numerical characteristics of the anomaly and must be greater than the so-called 'half anomaly' radius. (These half anomaly values can be found by referring to the graph given in Appendix 1).

Taking the radius as 5 miles and the total anomaly as 52 mgals., the following minimum estimates were obtained for various density contrasts:-

P	depth in 10^3 feet
0.25	30.0
0.20	57.1
0.15	inf.

It will be seen that a density contrast of 0.15 gives a

Fig.18.



Bouguer Anomaly Profiles of Skye and Mull cylinder of infinite length. This is clearly inadmissible and places an effective lower limit on the density contrast at 0.15 gms/cc. The most probable density contrast is 0.2 gms/cc., in which case, the depth to the base of the basic mass is considerable (17 Kms.) and of the order of thickness of the granitic layer of seismology.

(ii) Theoretical models

Whilst the above results satisfy the numerical characteristics of the anomaly, it remains to find a theoretical model consistent with the observed gravity gradients and the general form of the gravity field itself. This model must also be consistent with the known geological structure.

In Chapter 6 the probable space form of a Tertiary magma chamber was discussed in the light of both the geological and geophysical evidence and a cylindrical form decided upon. It is considered likely that both the Skye and Mull centres have the same general space form and this is borne out by the similarities between the gravity profiles over the two centres (Fig. 18).

In view of these similarities, a theoretical model was constructed for a vertical cylinder having dimensions: radius 26.10^3 ft., depth to base 57.10^3 ft. and density contrast 0.2 gms/cc. This corresponds exactly with the model previously used in Skye. The theoretical profile was superimposed on the Bouguer anomaly profile across the basaltic South East Caldera (C - C') and the result shown on

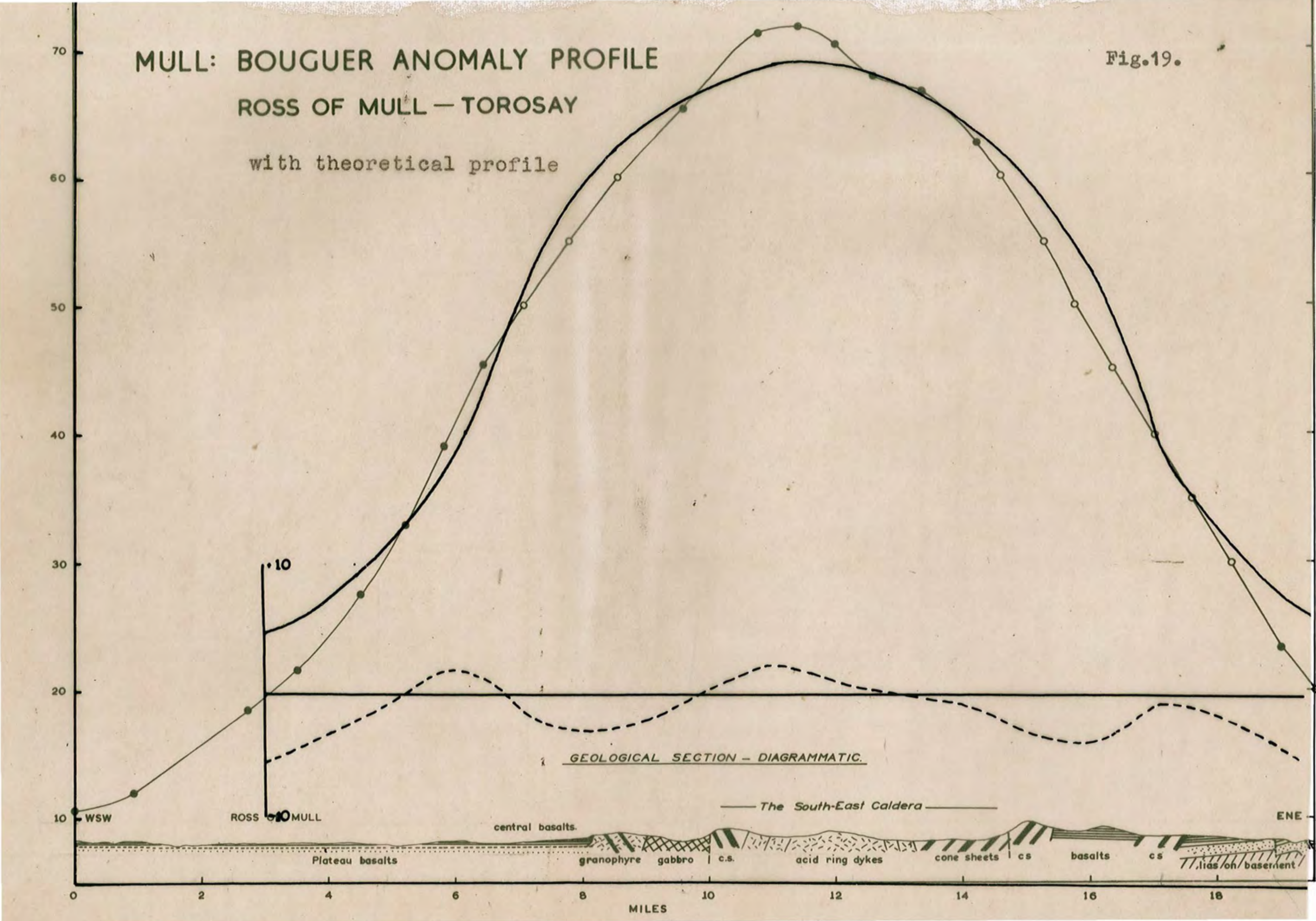

MULL: BOUGUER ANOMALY PROFILE
ROSS OF MULL — TOROSAY
with theoretical profile
Fig.19.
GEOLOGICAL SECTION - DIAGRAMMATIC.
The South-East Caldera
WSW
ROSS OF MULL
ENE
central basalts.
Plateau basalts
granophyre
gabbro
c.s.
acid ring dykes
cone sheets
cs
basalts
lias on basement
MILES
0
2
4
6
8
10
12
14
16
18
10
20
30
40
50
60
70

Figure 19. The 'fit' between the two profiles is reasonable and the smaller departures from the theoretical form can be correlated with the surface geology.

From an interpretative viewpoint, this result was expected since it is a major premise in the interpretation that radical depatures from the ideal cylindrical form are due to the presence of acid intrusives. There are no major acid intrusives within the South East Caldera along the line of section, and so the subjacent basaltic chamber approximates to a single vertical cylinder.

There are, however, some disparities between the two profiles shown in Fig. 19. For example: the observed gravity gradients to the east-north-east are higher, and the total gravity field lower, than would be expected from the theoretical model. This is attributed to the negative gravity anomaly which is known to be associated with the Morvern-Strontian Granite. A similar argument applies to the effect of the Ross of Mull Granite to the west-south-west.

The profile Tobermory - Loch Spelve. - If the vertical cylinder model used in the interpretation of the profile Ross of Mull - Toresay is correct, then the Tobermory - Loch Spelve profile (Fig. 20) should be a chord section of the same cylinder. To test this, the gravity field of the proposed vertical cylinder was plotted as an isogal. map centred over the South East Caldera, and the gravity profile along the line Tobermory - Loch Spelve read off. This theoretical profile (overlay to Fig. 20) was then compared with the observed gravity profile. The results show a general correspondence and confirm the original assumption that the underlying mass is essentially cylindrical. Such departures as there are from the theoretical profile are shown by the gravity residuals and can again be correlated with the surface geology.

(iii) The Residuals

Whilst reasonable agreement between the observed and theoretical profiles can be obtained using a vertical cylinder, it is interesting to note the effect of subtracting the total gravitational effect of the proposed theoretical model from the observed Bouguer gravity field. The principal results of this procedure are summarised below.

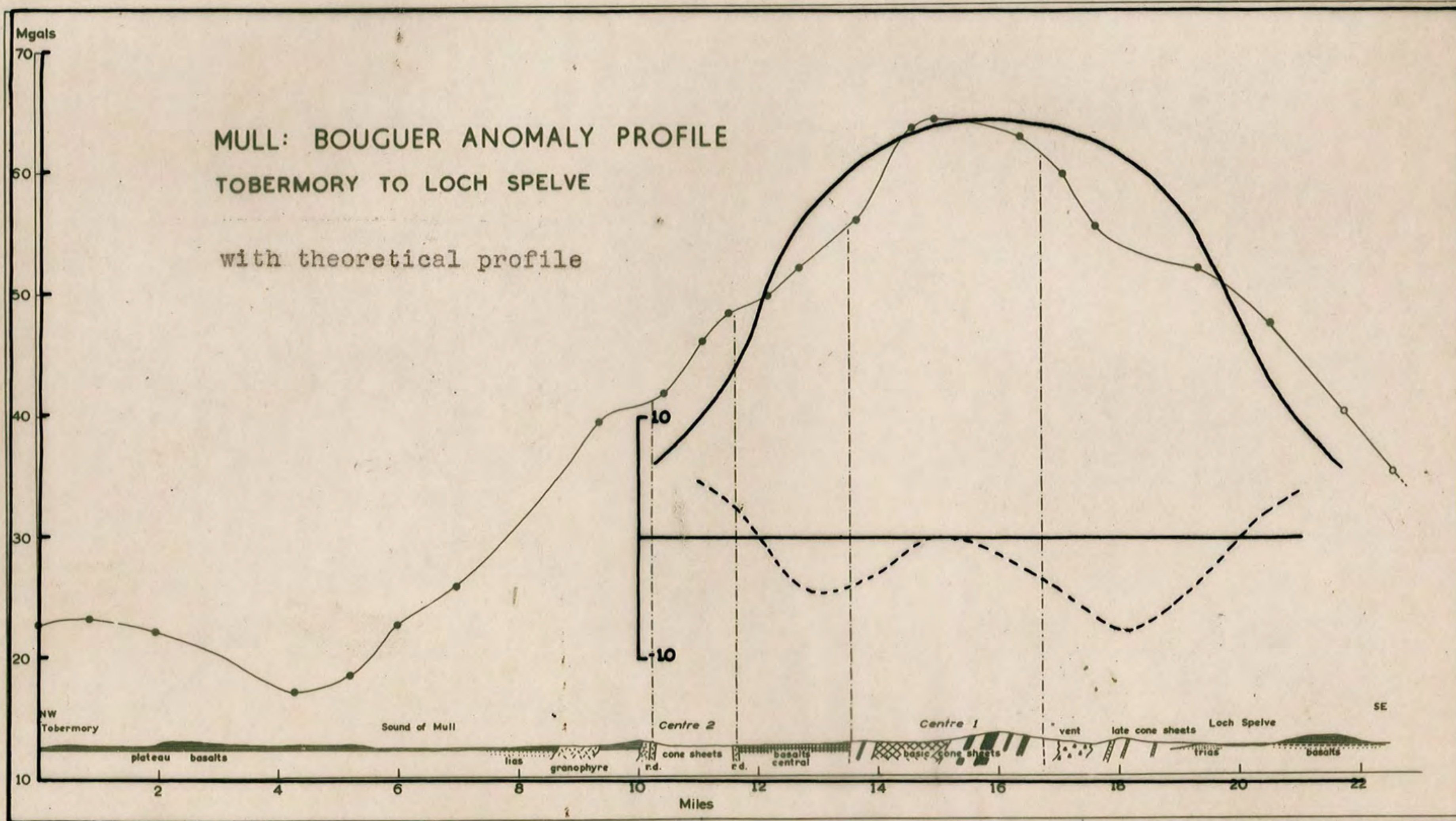
1. Over large areas there are gravity residuals of ± 3 mgals. These residuals could possibly be eliminated by taking a more refined model, but so far this has not been attempted.

2. Negative residuals of up to 10 mgals are found over the outcrop of the acid Loch Ba centre.

3. Areas of positive residuals (5 - 10 mgals.) are found over the north western and south eastern margins of the main plutonic complex. These cannot be explained in terms of lighter near surface masses and must represent genuine departures from the ideal cylindrical form.

(iv) The Space Form

Whilst the proposed vertical cylinder satisfied the majority of the features of the gravity field, further comments can be made.


Mgals
70
60
50
40
30
20
10
MULL: BOUGUER ANOMALY PROFILE
TOBERMORY TO LOCH SPELVE
with theoretical profile
10
-10
NW
Tobermory
plateau basalts
Sound of Mull
lias
granophyre
Centre 2
r.d.
cone sheets
r.d.
basalts
central
Centre 1
basic cone sheets
vent
late cone sheets
Loch Spelve
trias
basalts
SE
2
4
6
8
10
12
14
16
18
20
22
Miles

Section D - D'

The slight ellipticity of the Bouguer gravity field corresponds with the known shift of magmatic focus from the south-east to the north-west Caldera. On the traditional view, this is related to a shift in position of the magma chamber. By analogy with Skye, the ideal space form of the Mull magma chamber would be not one vertical cylinder, but two interacting cylinders, centred beneath the two calderas, with their centres along a NW - SE line. These would behave gravimetrically as one cylinder, though we must expect positive residuals along the NW - SE line. This was found to be so, residuals of 10 mgals. occurring north-west of the Loch Ba Centre.

Geological Interpretation of the Anomalies

The profile Tobermory - Loch Spelve

The proposed theoretical model still leaves residuals over the two plutonic complexes which can best be correlated with the surface geology. The Loch Spelve profile (Fig. 20) reflects strongly the effects of the surface geological formations, the most striking feature being a fall in anomaly of 8 mgals. to the south east of the maximum. This is a definite feature irrespective of the residuals calculated from the theoretical model, and shows, though to a lesser degree, on the Ross of Mull - Torosay profile (Fig. 18, Mull 1).

The area delineated by the gravity 'lows' is geologically complex consisting of Moine gneiss, olivine dolerite, vent agglomerate, felsite and granophyre, and to the extreme south east an outcrop of Trias. With the exception of the olivine dolerite, all these formations have densities considerably less than that of the surface eucrite, or of the proposed theoretical model. A near surface origin for the anomaly is confirmed by the high gravity gradients of 8 mgals/mile.

In view of the large number of cone sheets, and the known position of the margin of the South East Caldera, it is considered unlikely that the anomaly could be caused by a sub-surface extension of the Trias. Thus the most probable cause of the anomaly is a direct density contrast between the lower density acid intrusives and vent agglomerates, and the adjacent eucrite and olivine dolerite. The presence of this low density mass within an area theoretically represented by the basalt or gabbro of the proposed theoretical model is responsible for the 8 mgal. residual.

A fall in anomaly over the north eastern margin of Centre 2 - the Loch Ba centre - is partly the effect of a larger gravity low over the Glencannel granophyre. A contributory factor is the relatively low density of the intermediate to sub-acid augite diorite exposed at the surface along the line of section. The augite diorite becomes increasingly acid upwards in its north eastern extremity (Mull Memoir, p. 218).

The Mull magma chamber

The picture revealed by the Bouguer anomalies is that the Mull plutonic complex is underlain by a 'basic batholith' of radius 5 miles possibly extending into the Intermediate layer at a depth of 17 Kms. Such a magma chamber has long been suspected from the evidence of geology and petrology. Only a large and regular magma chamber could explain the remarkable regularity in the arrangement of the cone sheets and ring dykes. The vast amount of differentiated magma represented by the intrusions related to the Mull centre are only consistent with a capacious local reservoir. Since there is good reason to believe that the reservoir was restricted laterally, its depth must have been considerable (Richey, 1932).

A connection with the Intermediate layer has always been assumed for central volcanoes and this is confirmed from the Tertiary South East Caldera of Mull. Not that this implies that the basalt originated within the Intermediate layer, or that the regional magma chamber was at a depth of 17 Kms. It only implies a loss of density contrast at this depth. From the origin of earthquake shocks below active volcanoes such as Hawaii, it seems more likely that the regional magma chamber and the ultimate source of basalt is at a depth of 60 Kms. or more (Jones, 1938).

The space problem created by the basic batholith and the origin of basalt are discussed more fully in Chapter 10.

The Loch Ba Centre

Introduction

Activity in the South East Caldera closed with a shift of magmatic focus, first north-west to Beinn Chaisgidle and then to Loch Ba around which a marked cauldron subsidence was formed at a later date. The centre as a whole is delineated by the Loch Ba felsite ring dyke, the most perfect example of its type known to science. The main interest of the centre for this work is that the isogals show considerable distortion over the Glencannel granophyre and so enable estimates to be made of the thickness of the granite masses.

The base of the Glencannel granophyre is nowhere seen, but the exposed thickness exceeds 1000 feet. Its space form is uncertain: the authors of the Mull Memoir do not commit themselves, but Richey (1948) describes the mass as either a stock or a thick sheet, the floor of which is not exposed, connected marginally with a ring dyke. In a paper by Van Bemmelen (1938) the thickness of the granophyre is shown as 5 Kms.

The Bouguer Anomalies

The Bouguer anomalies over the Loch Ba centre are shown on Plate 2. From the symmetry of the main positive anomaly, there is an apparent fall in anomaly over the centre of 5 mgals. Over the north-west margin of the Loch Ba ring dyke the horizontal gradient falls from 5 mgals/mile to

-0.5 mgals/mile. This low gradient is maintained over the granophyre, the gradient increasing again towards the south-east margin and the contact with the South East Caldera. There are no gravity stations over the south east margin and the gradient in that area is shown rising uniformly at a rate of 6 mgals/mile.

<u>The interpretation</u>

i) The density contrast

The Glencannel granophyre is intruded into basalts, gabbros, diorites and rhyolites. The density contrast arises from the juxtaposition of the intrusive granophyre (2.55 - 2.60 gms/cc.) and the basic wall rocks of the caldera (2.95 - 3.00 gms/cc.). The most probable density contrast is in the range 0.35 - 0.40 gms/cc.

ii) The anomaly

From the symmetry of the main positive anomaly as a whole, there is an apparent fall in anomaly over the Loch Ba centre of 5 mgals. A second estimate can be obtained by subtracting the effect of the postulated basic vertical cylinder from the observed gravity field. Applying this technique leaves a residual negative anomaly of 10 mgals.

iii) The thickness of the Glencannel granophyre

Estimates of the thickness have been obtained by assuming the granophyre to be in the form of a circular disc of radius equal to that of the Loch Ba centre (1.5 miles). In the table below, the maximum thicknesses are given for the two possible anomalies and two density contrasts.

Estimates of thickness of Glencannel Granophyre

Anomaly	Depth to base in feet	
5 mgls.	1050	1250
10 mgls.	2400	2700
p	0.40	0.35

The estimates for an anomaly of 5 mgals. are independent of any assumptions as to the geometry of the mass responsible for the main positive gravity anomaly. On the other hand, the 10 mgal. value presupposes a cylindrical form for the main basic mass; the anomalies over the granites then being treated as departures from the ideal form.

Irrespective of the numerical values, the main conclusion is that the granites are thin for a large surface outcrop and thus contrast with the typical post tectonic granites, i.e. the space form is laccolithic rather than batholithic.

This compares favourably with the results previously obtained by us in Skye and by Cook and Murphy in Ireland. These are summarised below:-

Thickness of the Tertiary Granites

	No. of intrusions	Max. thickness	Area in sq. miles
Skye	4	3000'	30.5
Mournes	4	3000'-4000'	55
Mull	3	2700'	25

Origin of the Glencannel Granophyre

The essential difference in space form between the Tertiary granites and the typical post-tectonic granites again raises the problem of their origin. This has already been discussed in part in Chapter 6 with regard to the Red Hills granites. There the magmatic origin of the granite was in dispute owing to the assertion that it was derived by transformation of the Torridonian. This argument cannot be advanced in Mull owing to the absence of Torridonian within the Central Complex. Yet the essentially micropegmatitic granophyres of Mull do not appear to be the end member of a differentiation series and in this respect differ from the Red Hills granites which could be so regarded.

A clue to the origin of the Tertiary granites comes from the Tertiary igneous complex of Slieve Gullion. There X Reynolds (1941, 1950) recognised that the Caledonian granodiorite has been converted by the later Tertiary basic intrusions into a rock termed by her - micropegmatite: and the granites of Mourne, Arran and Mull are all micropegmatites.

In the Tertiary plutonic centres as a whole there is a considerable amount of evidence for the selective melting of metasediments or sial. For example, it seems likely that the abnormal quartz gabbros of Ardnamurchan resulted from an admixture of eucrite and mobilised feldspathic Moine granulite. Richey has suggested that two hybrid masses near the Loch Ba centre may represent partially liquefied basement Moine gneiss or sial mixed with some basic magma. If these effects can be produced at high levels in the crust, what may be the effect of molten basic magma upon the granitic sial at depth.

An ingenious idea of Richey's suggests that the Tertiary magma reservoir was in the form of a labyrinth of basic magma within the sialic crust. Stoping and fusion of the granitic crust within the labyrinth would not only give rise to the granite sheets observed at the surface, but would also explain the intermittent character and compositional changes noted in a cauldron subsidence. Selective melting of the sialic crust has the additional merit that it helps to resolve the space problem created by the presence of 850 cubic miles of basic material within the crust, some of the replaced sial having presumably fused to give granophyre.

Conclusions

The gravity evidence suggests that the Glencannel granophyre is in the form of a sheet of considerable areal extent, but likely to be less than 2700 feet thick. This space form is similar to that deduced for the other Tertiary granites and is consistent with the accepted geological opinion that the granites are the result of a cauldron subsidence. The gravity evidence cannot, however, give a definite answer to the problem of the origin of the granite. Their association with a large basic pluton provides either an adequate source of acid differentiates, or sufficient heat to fuse the pre-existing metasedimentary and granitic layers. In Mull the geological evidence favours the refusion of the Moine basement. Large scale fusion of the sial helps to resolve the basaltic space problem created by the basic pluton.

Conclusions

The similarities between the Skye and Mull centres are such that the geological implications of the Mull anomalies only reinforce what has already been written concerning Skye. Certainly the conclusions regarding the form of the Tertiary magma chamber apply equally well to either centre.

It is concluded that the Mull plutonic complex is underlain by a dense and presumably basic mass of radius five miles and minimum depth 11 miles. The most probable shape for the mass is that of two interacting cylinders with their centres along a north west - south east line. Departures from the proposed cylindrical form are shown by gravity lows over the acid Loch Ba centre. This effect is relatively small, and confirms the view that the Tertiary granites are thin for a large surface area. The Loch Ba low has been interpreted in terms of a sheet less than 2700 feet thick corresponding with the outcrop of the Glencannel granophyres.

Chapter VIII

ARRAN

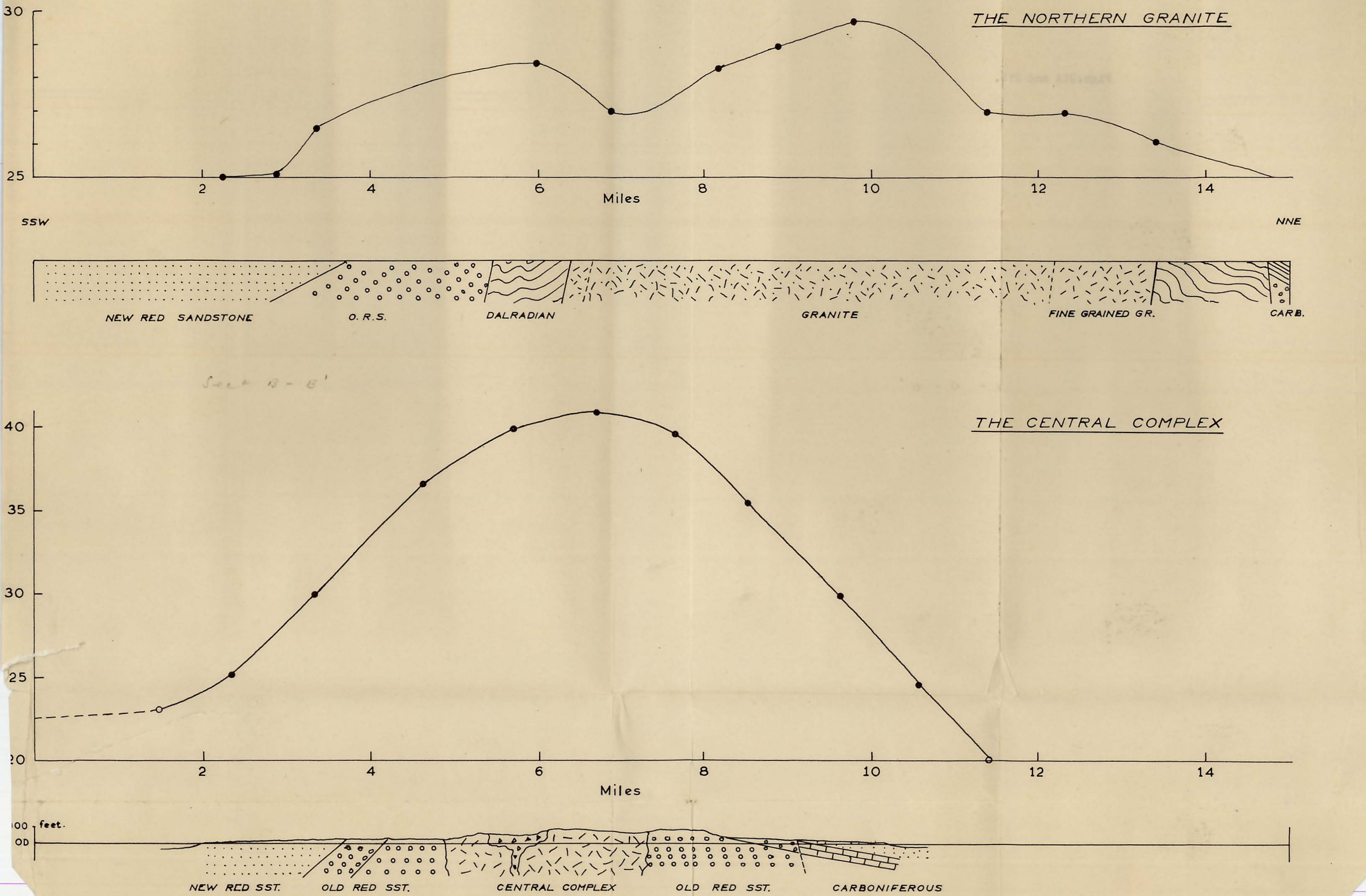
Introduction

Arran is unusual amongst the Tertiary Centres in that it not only contains both the largest and the smallest individual plutonic complex, but that these two centres are eroded to different structural levels. The Northern Granite is a cross section of a deep seated cauldron subsidence whereas the Central Ring Complex represents a much higher level of erosion and the remains of individual volcanoes can be recognised within the main caldera. (King, 1955).

Except around the Central Complex, ring structures are less obvious than elsewhere, and there is no evidence of cone-sheets - at least not at the present level of erosion. All evidence for the former existence of a plateau basalt cover has been removed, except for remanié blocks of basalts within the calderas. The few remaining gabbro masses suggest that a large gabbro intrusion originally extended around half the periphery of the Central Complex (Tyrell, 1928). The later granites of the Central Complex would appear to have been emplaced in conformity with the general structure of the volcanic caldera (King, op.cit.).

Despite the preponderance of acid intrusives at the surface, the Bouguer anomalies were again found to be positive and similar in magnitude to those already described in Ardnamurchan. The general shape and smoothness of the gravity profile is, however, more akin to that of the Irish Centres, and suggests that the origin of the anomaly should be

ARRAN – BOUGUER ANOMALY PROFILES



sought in a more deep seated basic mass. Obviously, the vertical cylinder concept will be more difficult to apply, and the geometrical ideas of the earlier chapters are again extended. The Bouguer field is not only dependent upon the separation of the foci of the individual magma chambers (as was suggested in Chapter 6) but also upon the level of erosion.

The Bouguer Anomalies

These are shown on Plate 3 and follow the same general pattern already observed over the other Tertiary Centres. The main features of the gravity field are a positive Bouguer anomaly of 40.8 mgals. centred over the northern edge of the Central Ring Complex, together with a positive ridge trending NNE - SSW across the Northern Granite. The main anomaly appears to be elongated in a north - south direction, though further gravity stations around both the Northern Granite and the Central Complex would enable a more definite statement to be made. (As it is, many of the contours are shown as uncertain).

Over the Central Complex the gravity gradients are high, rising to a maximum of 5 mgals/mile, falling to 0.5 - 2.0 mgals/mile over the Northern Granite.

Interpretation

General

Any interpretation would be difficult without some knowledge of the gravity field over the adjacent areas of Kintyre and Bute, and I am grateful to Dr. Bullerwell for giving me access to his unpublished maps of these areas.

The Bouguer Anomaly profile (Fig. 21A) shows a symmetrical positive anomaly over the Central Ring Complex flattening off to the west, but to the east still falling towards the Firth of Clyde at a rate of 5 mgals/mile. With the aid of Bullerwell's map many of the marginal features of the main Arran anomaly are seen to fit into the regional pattern. The 23 mgal anomaly over the western edge is now seen as the continuation of an area of c. 20 mgal anomalies over the Dalradian mica schists of Kintyre. (The latter value is comparable with that obtained by Bullard (1936) and shown on Fig. 11). Similarly the steady fall in anomaly to the east now appears as the western margin of an area of low (12 mgal) Bouguer anomalies associated with a basin of Old and New Red Sandstone around the Firth of Clyde. The total thickness of the Permo-Trias in this area probably exceeds 3000 feet (Tyrell, 1928).

The positive ridge over the Northern granite could well be an extension of a NNE - SSW striking ridge of positive anomalies along the line of the Highland Boundary Fault.

The average value of the Bouguer Anomaly over the Carboniferous lavas and Coal Measures of the Ayr Coalfield would appear to be 20 mgals and compares with that found over the Dalradian to the west. In the light of this evidence, Arran appears as an area of positive Bouguer anomalies, separated from the metamorphic basement to the west by an area of submerged Dalradian, and from the mainland to the east by an area of low anomalies associated with a deep sedimentary trough along the line of the Firth of Clyde.

Assuming a background anomaly of 20 mgals leaves a positive anomaly of 20.8 mgals over the Central Complex, and 10 mgals over the Northern Granite

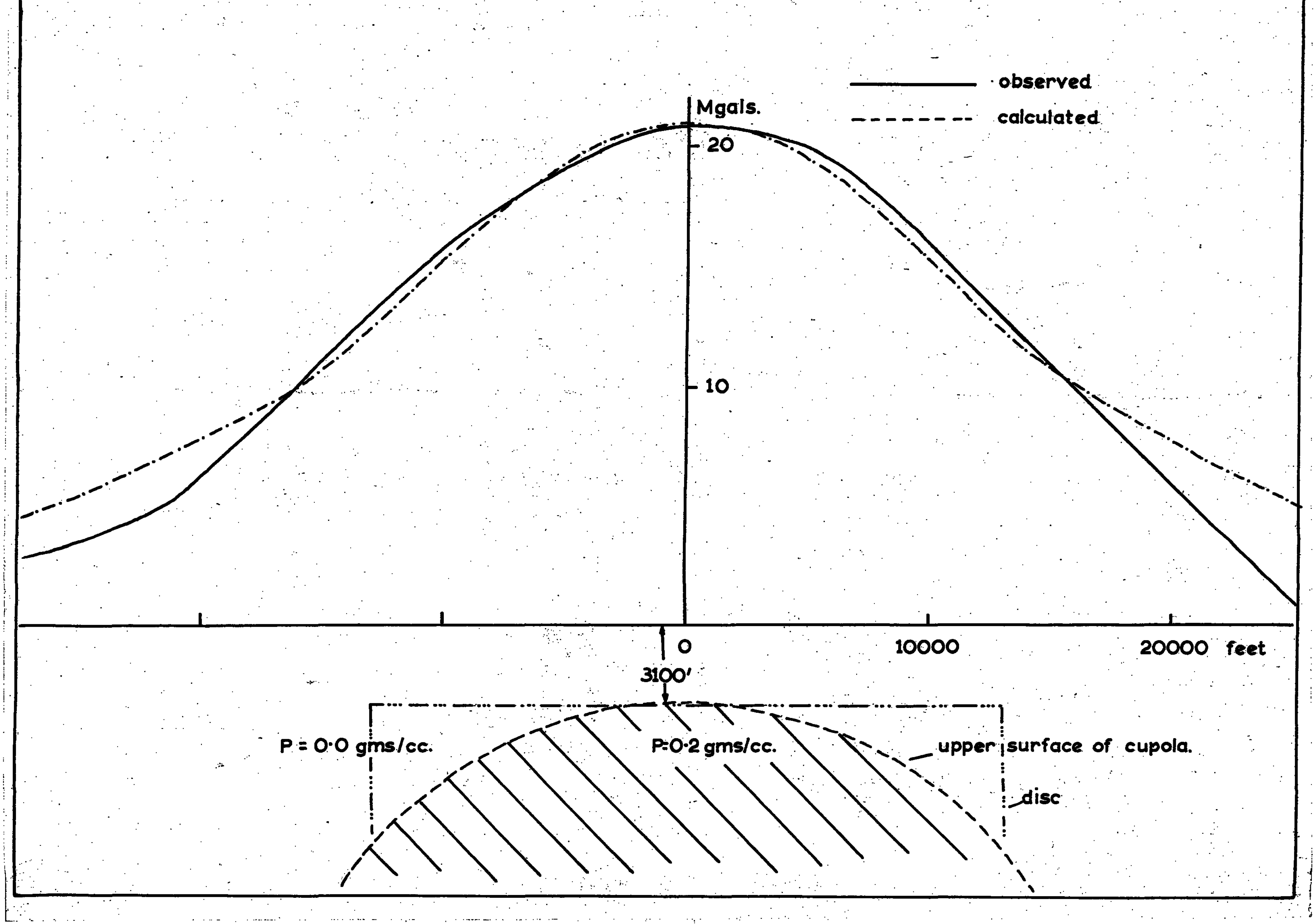
The Central Ring Complex

The comparative absence of basic material exposed at the surface, together with the smoothness of the gravity profile suggests that the source of the anomaly lies at a considerable depth.

The maximum depth to the top of the anomalous mass can be found by considering the maximum anomaly in conjunction with the maximum gradient. This result is independent of the density contrast and places the upper surface at a maximum depth of 3.6 miles.

Qualitatively, the shape of the gravity profile over the Central Complex indicates a spherical origin, and if the anomaly is considered to arise from a sphere of density 0.2 gms/cc., radius 17.1 kilo.ft., with a centre at -20.2 kilo.ft., then the upper surface of the sphere is within 3100 feet of the surface. A theoretical model with these parameters was computed and the resulting profile compared with the observed profile (Fig. 21C). Over most of the profile the fit is reasonable, except on the flanks of the anomaly where the calculated curve is wider than the observed curve. This increasing disparity between the profiles is partly the result of an initial over simplification in the theoretical model, and partly the effect of the low Bouguer anomalies associated with the thickening of the Trias towards the Firth of Clyde.

ARRAN: COMPARISON OF PROFILES



Obviously, the sphere is an unlikely form geologically for a magma chamber, though it could be considered as a first approximation to the more conventional cupola. Closer agreement between the profiles would probably be obtained by further approximating the sphere to two circular discs as is shown on Fig. 21C. Geometrically this form would also approximate to a vertical cylinder widening towards the base, or Anderson's inverted 'flowerpot'.

An estimate of the minimum depth to the base can be obtained by representing the anomalous mass as a vertical cylinder of density 0.2 gms/cc., with a radius greater than the 'half anomaly' radius of the anomaly. If the upper surface of the cylinder is assumed to be at -3000 feet, then the lower surface is at -25000 feet.

The density contrast of 0.2 gms/cc. is assumed to arise from the presence of a large basaltic or gabbroic mass within the metasedimentary layer. Similar assumptions were made in Skye and Mull (q.v.).

The proposed theoretical model of a basic cupola extending from -3000 to -25000 feet below the Central Complex is still an over simplification. Certainly, the cupola form is in reasonable accord with the observed profile over the Complex, but the Arran gravity field is definitely elongated in a N-S direction and the proposed model takes no account of this, or of the 10 mgal positive anomaly over the Northern Granite.

The Northern Granite

The granite has a maximum diameter of 8 miles and is almost perfectly circular with an average radius of 3.5 miles.

From the regularity of form, it is inferred that the granite represents a deep seated subsidence caldera which was subsequently enlarged by the flexuring and upheaval of the surrounding schists and sandstones. Both the thickness and the three-dimensional form of the mass have still to be elucidated (Richey, 1932).

Peach and Horne (1930) regarded the granite as an isolated portion of the Grampian block. The view originally expressed by Geikie (1873) that the granite was of Tertiary age is now universally accepted.

It is difficult to dogmatise on the positive anomaly on account of the complicating effect of the positive anomaly noted by Bullerwell along the line of the Highland Boundary Fault. This rises to a maximum of 23 mgals in Bute, but still leaves an appreciable positive anomaly - whatever its origin - beneath North Arran.

Assuming for the moment that there was no positive anomaly over North Arran, and that the direct density contrast between the Dalradian and the granite was 0.15 gms/cc., (Dalradian 2.75 gms/cc., granite 2.60 gms/cc.), it is obvious from the table below that any appreciable thickness of granite within the cauldron subsidence would introduce a considerable negative anomaly with respect to the 20 mgal background anomaly over the Dalradian.

Table showing variation in Bouguer anomaly with increasing thickness of granite

Thickness (ft.)	Anomaly in mgals		
5000	11.0	8.2	5.5
10000	19.0	14.2	9.5
20000	28.8	21.6	14.4
P	0.2	0.15	0.10

Constant radius of 18200 feet

p = density contrast

Since there is no evidence of a negative anomaly with respect to the background (in fact the strong positive is maintained over the granite as can be seen by referring to Plate 3) it can only be concluded that the granite is either 1) thick and underlain by an enormous basic mass, or 2) that the granite is thin and underlain by a smaller basic mass at no great depth. In either case, the Northern Granite would appear to be underlain by a considerable basic mass, and the space form of the granite is probably sheet-like rather than batholithic. Such a sheet form for the granite would be in agreement with the usual space form of the Tertiary granites found elsewhere, though the North Arran granite is unique in the manner of its intrusion.

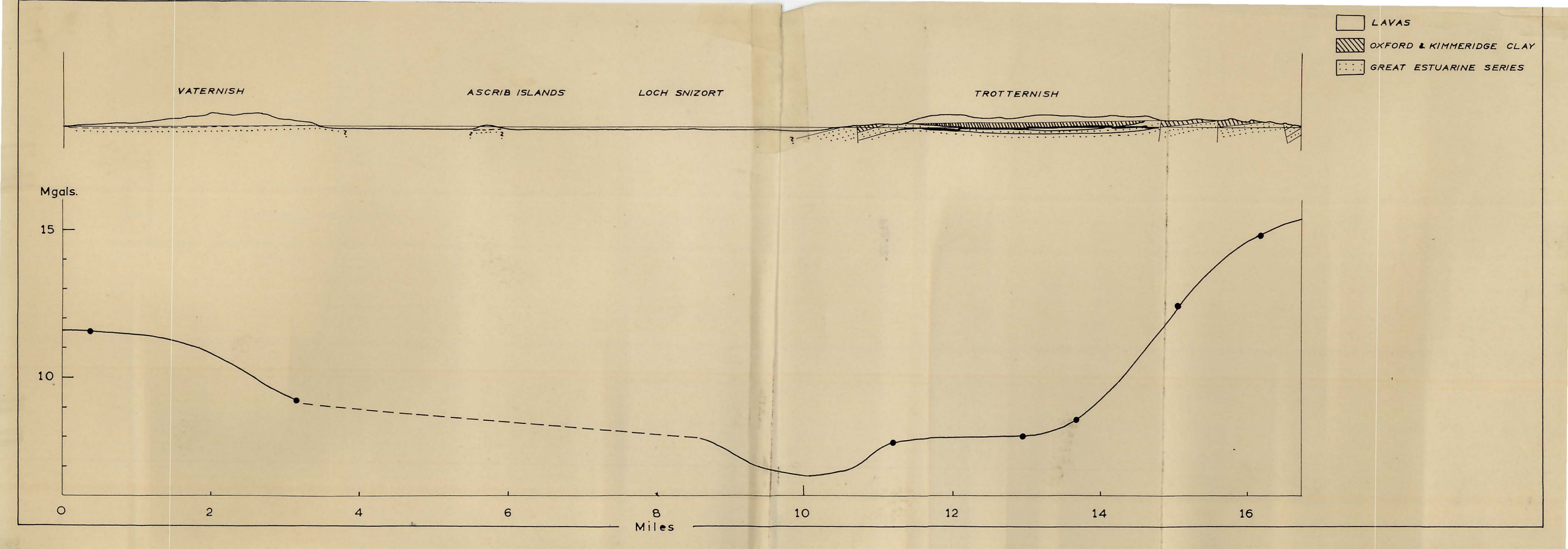
A gravity traverse running north - south, across both the Central Complex and the granite, would probably enable us to make a more definite estimate of the thickness of the granite and of the elongation of the underlying magma chamber.

Conclusions

These can but emphasise the partial and incomplete nature of the interpretation. The profile across the Central Ring Complex is consistent with the complex being underlain by a spherical or cupola shaped magma chamber at a depth of some 3000 feet. To conform with the interpretations advocated for the other Tertiary centres, it is suggested that the cupola can be more accurately represented by two cylindrical discs, but still at depth, since this appears to be required by both the smoothness of the profile and the numerical characteristics of the anomaly.

This leads to the idea that if the upper surface of the cupola were exposed by erosion - as is the case in Ardnamurchan - the gravity field would then conform to that of a vertical cylinder widening towards the base.

The gravity field over the Northern Granite is complex, though undoubtedly positive. A sheet-like space form is tentatively suggested.



LAVAS
OXFORD & KIMMERIDGE CLAY
GREAT ESTUARINE SERIES
VATERNISH
ASCRIB ISLANDS
LOCH SNIZORT
TROTTERNISH
Mgals.
15
10
0
2
4
6
8
10
12
14
16
Miles

Chapter IX

OTHER ANOMALIES IN SKYE AND MULL

Trotternish

Introduction

This region is made up of a series of Tertiary basalt lavas resting unconformably on sediments of Jurassic age. The lavas have a westerly dip of 10 to 16 degrees and are intersected by a series of N.W. - S.E. faults downthrowing to the east. This faulting ensures that the base of the lava series is at no great depth below sea level. Isolated exposures of Jurassic are found along the western coast and a boring at Loch Harport encountered sandstone at -18 feet O.D.

The Bouguer Anomalies and their interpretation

The most striking feature of this area is the area of low Bouguer anomalies in the Loch Snizort area. The average value over Trotternish is 15 milligals rising to 19 milligals in the extreme north, and falling to 6 milligals along the eastern edge of Loch Snizort (see Fig. 22).

Recent workers on North Skye have suggested that the basalt lavas may be underlain by yet another volcanic centre (private communication). The gravity field gives no indication of any such centre, unless the vent is too small, to produce a detectable anomaly. Similarly there is no evidence of any dyke type fissures such as have been confirmed by gravity measurements over the Deccan traps of India (Glennie 1951).

The increase in anomaly to the north may indicate either another centre now submerged, or a return to the average background anomaly of 20 milligals. The latter explanation is the more likely, values of 20 milligals being recorded near the Lewisian basement of Rona.

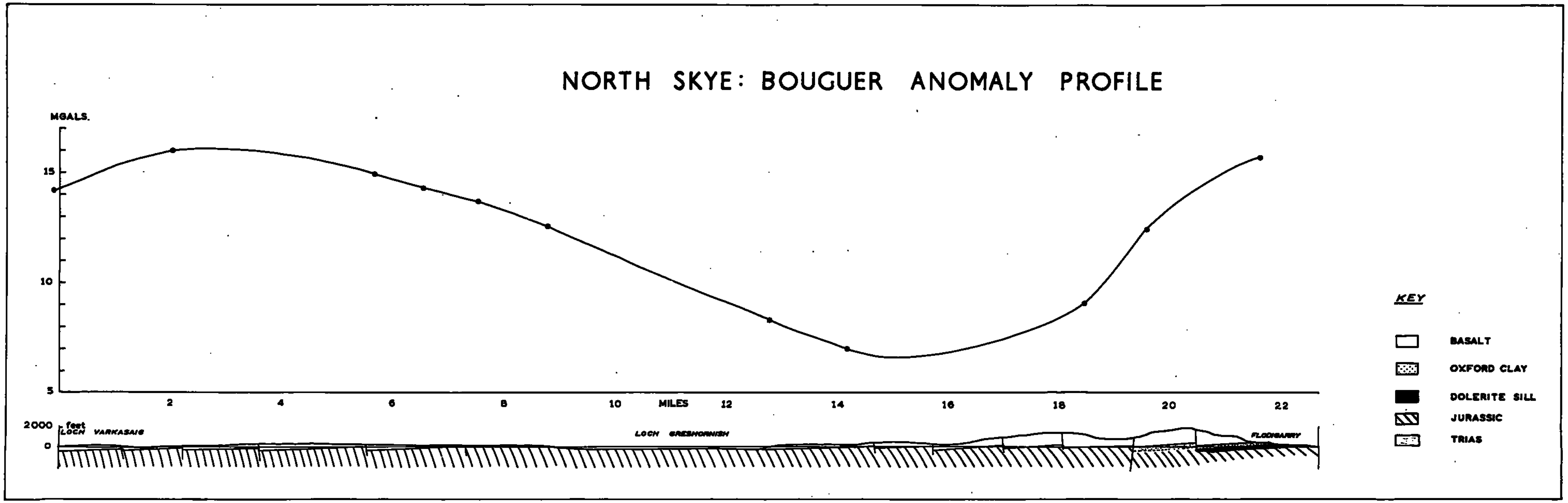
Over the Loch Snizort area, the isogals have an elliptical form with the major axis trending N.W. - S.E. This direction corresponds with the trend of the major faults and also to the regional dyke swarm. A possible explanation of the anomaly is that it is caused by a basin containing relatively light Jurassic and Triassic sediments. Basins of this type are found in areas of Jurassic sedimentation and are commonly formed along lines of crustal weakness. The gradients over the eastern edge are steep (3 mgals/mile) which suggests a faulted margin.

Little is known, geologically, about the Jurassic under Trotternish. It receives mention in Lee and Pringle (1932) and an account of the structure is given by Macgregor (1933).

Macgregor describes the structure as a syncline pitching to the S.S.W. with its axis trending N.N.E. - S.S.W. Unfortunately the Survey maps of the area are still unpublished; there is, however, a possibility that not only the lavas, but also the Jurassic succession may be continually repeated by block faulting.

The two dimensional step formula fixes a maximum limit to the depth of the basin at one mile. Assuming that the anomaly is caused by an infinite slab of density contrast 0.2 gms/cc, the thickness of sediment must be greater than 3600 feet. This is considerably greater than the total thickness of Jurassic; the maximum observed being 2250 feet in Raasay. A similar

Fig.23.



Section E - E'

thickness is seen in North-East Skye and there is no evidence of either thinning or thickening.

Discounting then the idea that the anomaly has been produced by a thickening of the Jurassic, there are two main possibilities:

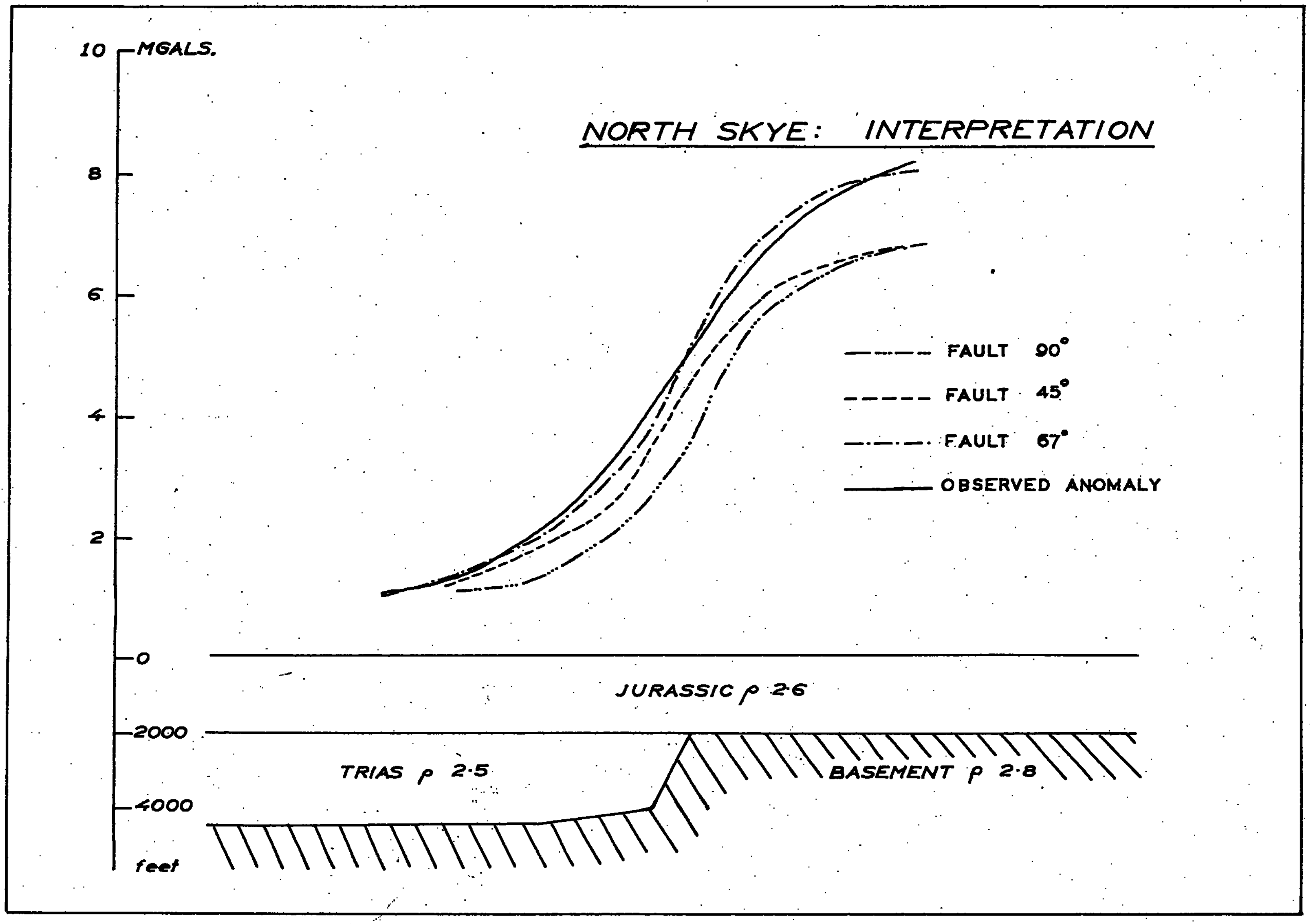
a) That block faulting has preserved some 2000 feet of Cretaceous and Tertiary sediments in a graben-like structure under the Tertiary basalts.

b) That the Jurassic is underlain by a considerable thickness of Trias.

The former alternative is unlikely for although the Cretaceous is believed to have originally covered a wide area, the maximum thickness found in the Hebrides is less than 200 feet. In any case the exposures below the basalts in the Loch Snizort area are almost invariably of the Great Oolite.

Triassic rocks outcrop to the east of Trotternish and vary in thickness from 1000 feet at Gruinard bay on the mainland to 500 feet in Raasay, thinning to a few feet at Lussay in Skye (Judd 1878). If the Jurassic thickness of approximately 2000 feet is maintained under Trotternish, the anomaly could be caused by a wedge of Trias 2400 feet thick, terminated by a near vertical normal fault along the eastern margin. The close agreement between the profile given by this theoretical model and the observed profile is shown on Fig. 24.

A fault of small throw is exposed at the surface along the the line of the postulated fault and it is tempting to regard this as evidence of further movement along a pre-existing line of weakness (see Fig. 22).



NORTH SKYE: INTERPRETATION
10
MGALS.
8
6
4
2
0
2000
4000
feet
FAULT 90°
FAULT 45°
FAULT 67°
OBSERVED ANOMALY
JURASSIC ρ 2·6
TRIAS ρ 2·5
BASEMENT ρ 2·8

Large faults are not unknown in Skye - a fault of considerable throw must traverse the Sound of Raasay if the rapid westerly dip of the Great Estuarine Series and its reappearance in Skye is to be explained. Faults of comparable magnitude are found on the mainland to the east.

Concerning the Triassic rocks of Applecross, Judd (1878, p.689) wrote:

> 'They (the Triassic rocks) owe their position and preservation to the action of grand faults of certainly vast but indeterminable amount of throw.'

There, over 1000 feet of Trias are preserved in a faulted trough and a similar action may well be responsible for the postulated Trias beneath North Skye.

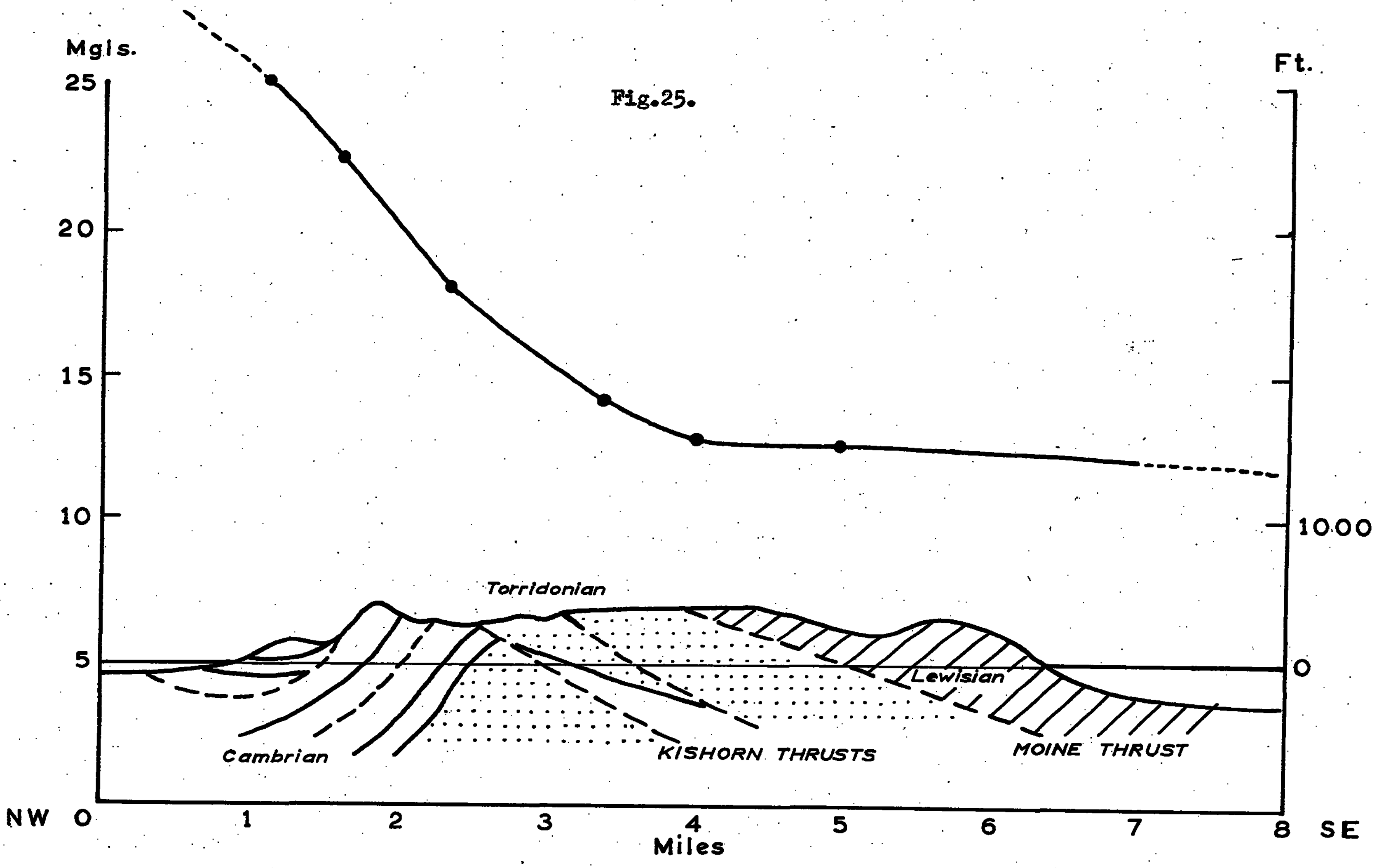
A series of gravity 'lows' over the Antrim lava plateau of Northern Ireland were interpreted by Cook and Murphy (1952) as troughs of light Triassic sediments in a dense palaeozoic basement. An abnormal thickness of both Trias and basalt was subsequently proved beneath Lough Neagh by the Geological Survey borehole at Langford Lodge (Summary of Progress 1957). The Langford Lodge succession was as follows:

Basalt	2590 feet
Cretaceous and Jurassic	120 feet
Trias	2060 feet
Carboniferous - base not seen.	

While providing some support for the concept of Triassic troughs beneath the lava plateaux, it also suggests certain reservations:

1. The base of the basalts beneath North Skye may not be at sea-level, as Harker supposed, and any increase in the thickness of basalt would greatly

Fig.25.



Geological Section and Bouguer Anomaly Profile across Sleat A — A' increase the calculated thickness of the underlying Mesozoics.

2. Similarly, the thickness of Jurassic used in the theoretical model may be in error.
3. And finally, the assumed density contrast Trias/basement may be too high.

Of the three, the latter is thought the least likely and its effect can easily be calculated. Throughout the interpretation a density contrast of 0.3 gms/cc has been assumed between the Trias and the basement. Any increase in the density contrast - consequent upon the assumption of a lower density for the Trias - would reduce the dip of the fault and also reduce the thickness of the Trias.

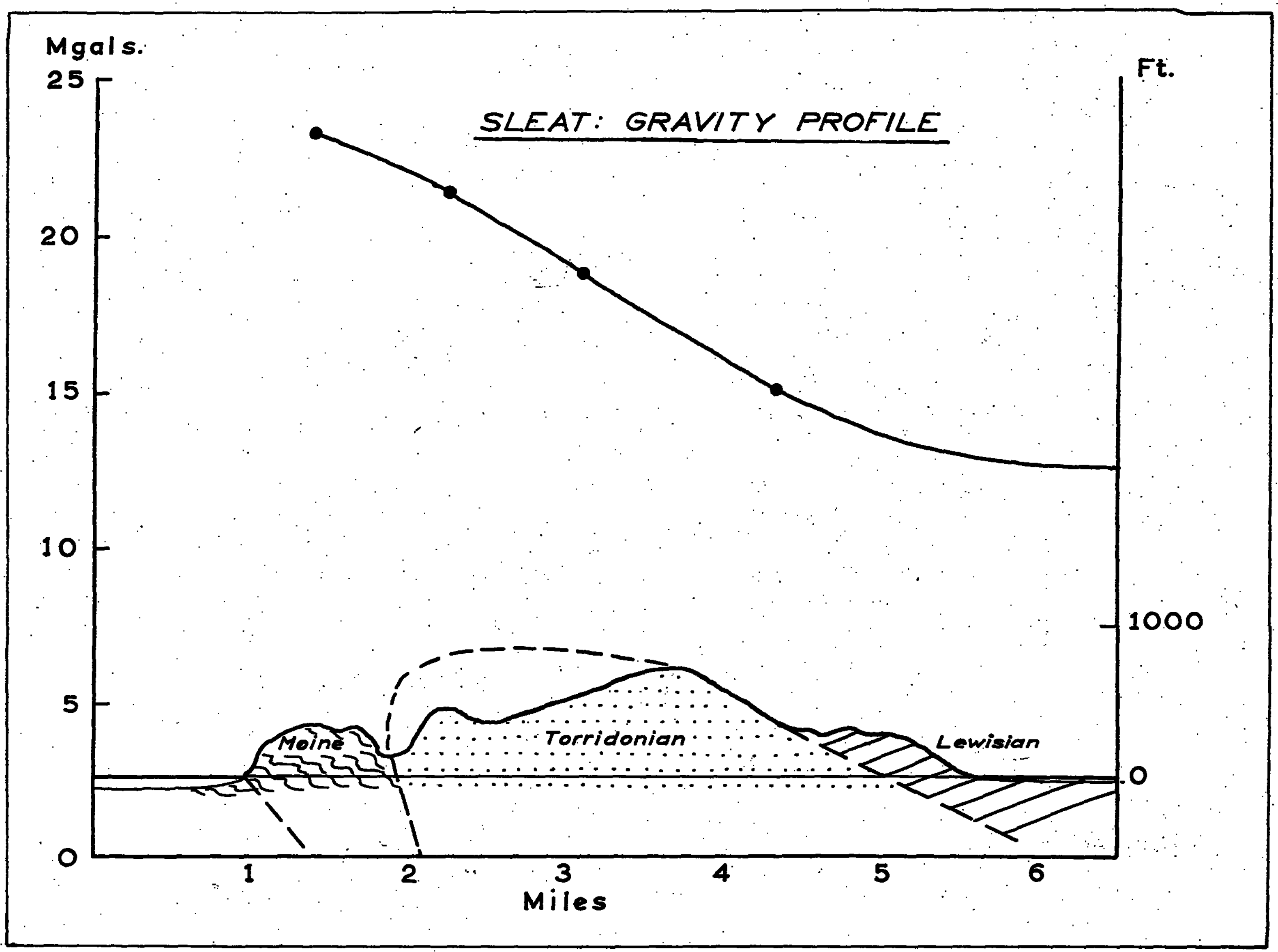
The Peninsula of Sleat

Introduction

The Peninsula of Sleat was geologically surveyed by Clough in 1907 and more recently by Bailey (1939 and 1945) and Kennedy (1954). It consists mainly of non-metamorphosed Torridonian rocks which have been overridden along their eastern boundary by the crystalline Moine Nappe of the Glenelg Morar tectonic zone. Later the Torridonian was itself moved for 9½ miles along the Kishorn thrust against the underlying Cambrian sediments of the Foreland Border complex.

The essential structure then is a great recumbent syncline of Cambrian and Torridonian rocks, closing to the south-east, which was later intersected and disrupted by clean cut thrusting.

Fig.26.



SLEAT: GRAVITY PROFILE
Mgals.
25
20
15
10
5
0
Ft.
1000
0
Moine
Torridonian
Lewisian
1
2
3
4
5
6
Miles

Compared with the considerable attention which has been paid to the geology of the area, previous geophysical interest has been slight; former work being confined to a solitary pendulum observation at Kyleakin (Bullard 1936). Bullard's value (981.69700 cms.sec.$^{-2}$) was found to agree closely with that recorded during the survey of 1955 (981.69819 cms.sec.$^{-2}$).

The Bouguer Anomalies and their interpretation

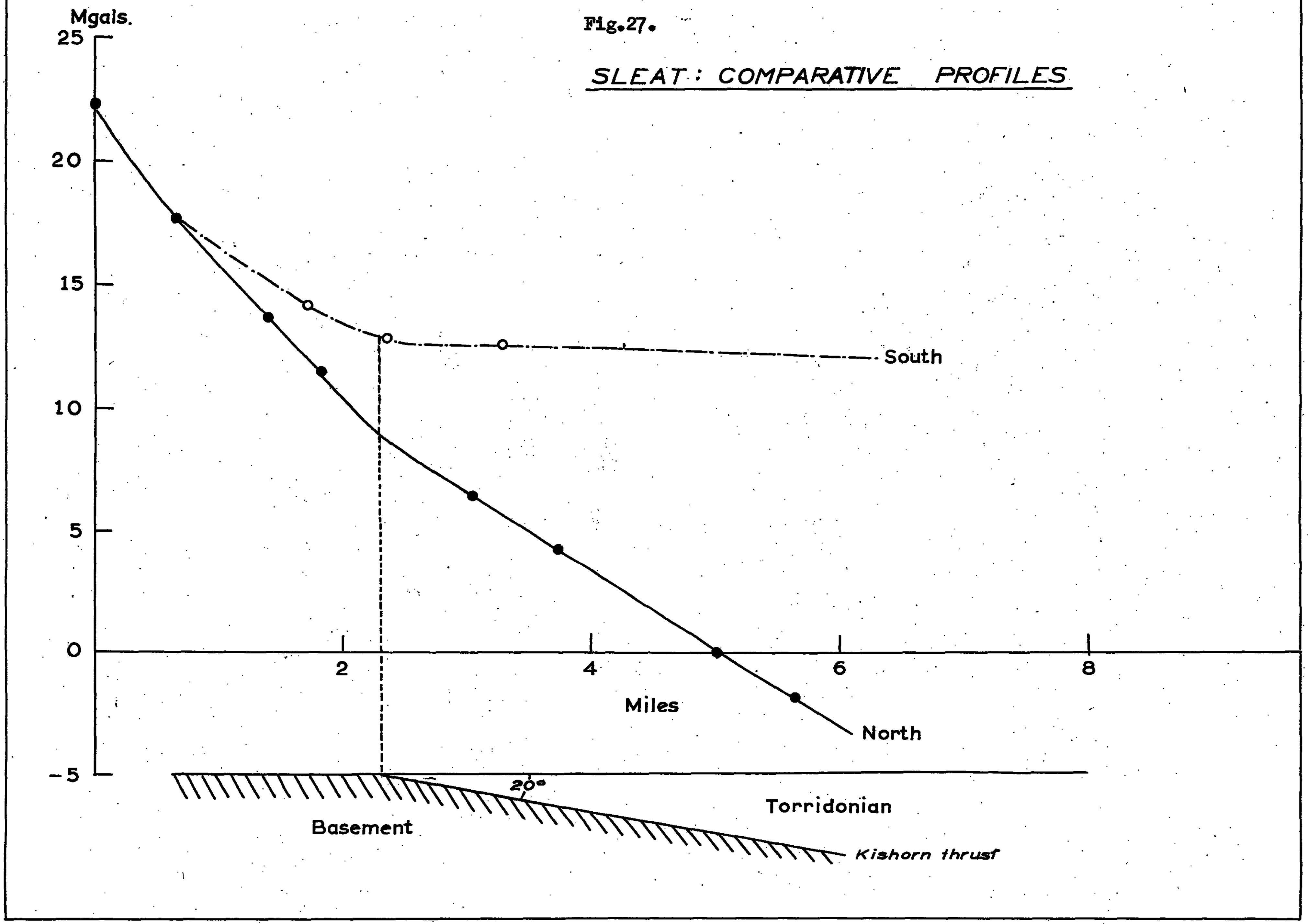
The Bouguer Anomaly Map (Plate 1) shows that the isogals over Sleat are closely parallel to the main tectonic lines and also to the strike of the country rocks. There are, however, marked differences between the northern and southern halves of the area.

In southern Sleat the anomaly changes from 12 milligals in the south-east to 25 mgals at Ord, the average gradient being 4 mgals/mile. A marked change in gradient occurs over the Moine Thrust; the gradients over the Lewisian to the east being much lower, and are generally less than 1 mgal/mile (Figs. 25 and 26). This low gradient persists over a wide area, the anomaly having only fallen to 4.3 mgals on the mainland 9 miles to the south (Bullerwell unpublished). The absence of any marked variation in anomaly over the Lewisian suggests that the interpretation of the anomaly to the North can be made in terms of the overlying Torridonian.

The comparative profiles (Fig. 27) show a large decrease in anomaly to the east in North Sleat, the anomaly falling to -5 mgals. This immediately suggests a qualitative correlation with the great thickness of sediments above the Kishorn thrust, variously estimated at 12000-13000 feet (Bailey, 1955;

Fig.27.

SLEAT : COMPARATIVE PROFILES



Kennedy, 1954).

If we assume the anomaly over the Lewisian to the South to be the normal background value in the area, there is a residual anomaly of 17 milligals in the North which requires explanation. The depth to the base of the mass responsible for the anomaly can be estimated by using the formula:

Depth = max anomaly in mgals. / π x max. gradient in mgals.

A depth of two miles obtained by applying this formula is a maximum limit. This approximates closely to the expected thickness of Torridonian and rules out an alternative explanation that the anomaly could be caused by a peculiarity in the bulk density of the basement. It was suspected earlier that the anomaly might be produced by a reduction in the bulk density of the Lewisian by migmatitic injection of Scourian age (Ramsey 1957).

Considering the Torridonian to be in the form of an infinite sheet of thickness 9000 feet, and density contrast 0.15 gms/cc will again give an anomaly of 17 mgals. This is a minimum estimate of the thickness since the Torridonian is in the form of a wedge rather than an infinite sheet (vide infra).

Since the rate of increase of gravity over a contact is a measure of the dip of the contact - providing the density contrast is known - an estimate of the dip of the Kishorn thrust can be made by using the approximate relation:

$$Ag = \pi G \rho \sin 2i$$

where Ag = difference between the observed gradients

i = angle of dip

p = density contrast

G = gravity constant

This gives an angle of thrust of 20 degrees. If the Kishorn thrust were continued to the east at this constant angle, it would lie at a depth of 13000 feet below Kylerhea, prior to being terminated against the Moine Thrust. Whilst this again confirms the expected disposition of the Torridonian above the thrust, it must be remembered that the angle is dependent upon the density contrast and this may not necessarily be 0.15 gms/cc at depth.

Conclusions

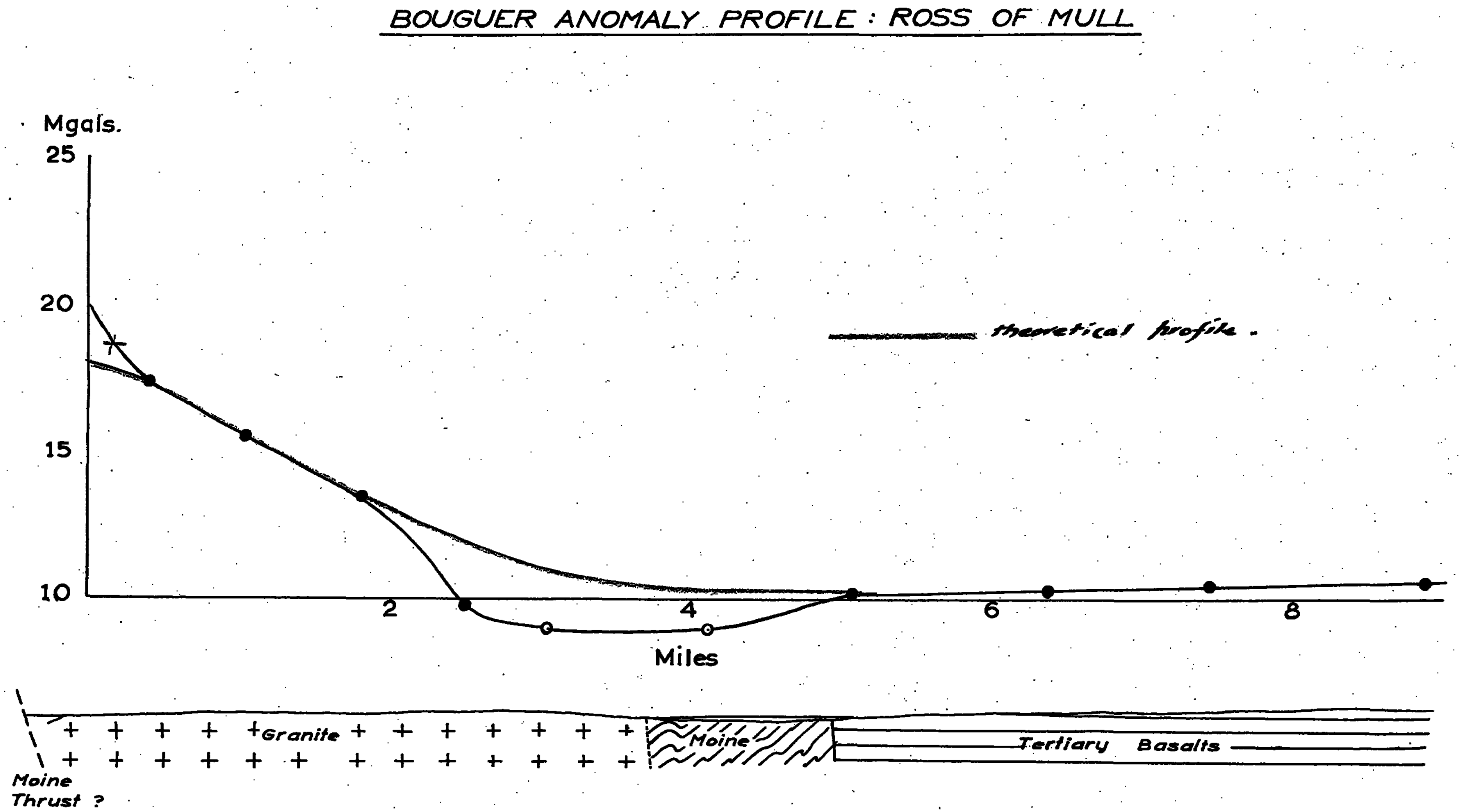
The low and occasionally negative Bouguer anomalies found over Kylerhea are interpreted in terms of a wedge of Torridonian with a maximum thickness of some 13000 feet. Geologically this corresponds with the great thickness of Torridonian which has long been assumed to lie above the Kishorn Thrust.

Ross of Mull Granite

Introduction

As part of the general gravity survey of Mull, a single traverse was made across the Ross of Mull granite. The granite - of presumed Caledonian age - covers an area of some 20 square miles and is bounded to the west by the Sound of Iona and to the east by an injected series of Moine schists. Submerged extensions of the granite to the south and west are shown by the granitic Torran rocks and by small granite islets near Iona. If we include the submerged portions, the total area of the granite is probably nearer 70 square miles.

Fig.28.



BOUGUER ANOMALY PROFILE : ROSS OF MULL
Mgals.
25
20
15
10
theoretical profile.
2
4
6
8
Miles
Granite
Moine
Tertiary Basalts
Moine Thrust ?

The Bouguer Anomalies

A prominent feature of the Bouguer Anomaly Map on Plate 2 is an area of low Bouguer anomalies along the western coast of Mull. The anomaly appears to close over the Ross of Mull, a minimum value of 9.2 mgals being recorded over the Moine schist slightly to the east of the main granite mass. To the west, the Bouguer anomaly increases to 20 milligals towards the Lewisian of Iona and the Moine Thrust. To the east the values are remarkably constant and depart very little from an average value of 10 mgals. A maximum horizontal gradient of 5 mgals/mile was recorded over the granite.

Interpretation

The gravity profile Fig. 28 is unlike those normally associated with British granites - see Bott, 1956 - and implies a different space form.

Geological opinion as to the form of the intrusion differs and there is little evidence on which to form any definite conclusions. Bosworth (1910) favoured a deep seated abyssal mass over which the Moine extended as a roof. On the other hand, Cunningham - Craig (Summary of Progress, 1907), thought that the granite was a thin sheet with a floor of Moine schist. The numerous rafts and inclusions of Moine within the granite are alternatively fragments of the roof, or exposed parts of an irregular floor.

In the interpretation, four possible forms for the granite are considered and their gravity fields compared with that observed. These possibilities are shown on Fig. 29. Models 1 and 2 represent Bosworth's and Cunningham-Craig's viewpoint, whereas 3 and 4 are new.

Model 1.

Bosworth (1910) makes no suggestions as to the westerly extension of the granites towards the Moine Thrust. Certainly the principal density contrast is not at the Moine-granite junction, as is shown by the lack of change in horizontal gradient over the boundary, and by the fact that the lowest value of the Bouguer anomaly is found over the Moine Schist and not the granite.

Model 2.

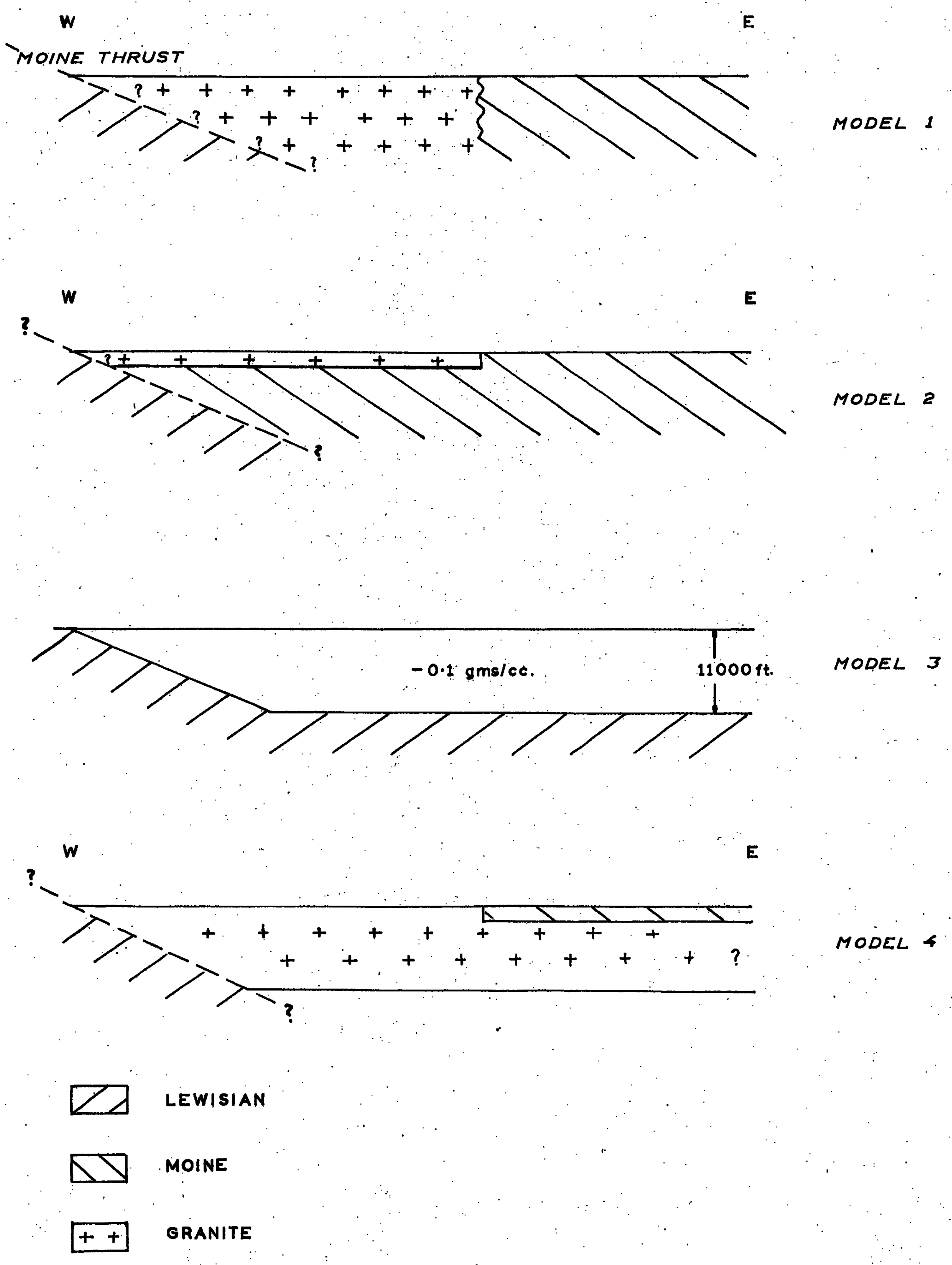
Cunningham-Craig's model again gives no indication of the fate of the granite to the west. Since the inclusions of Moine within the granite are only slightly denser than the granite (Bosworth, op. cit.) the whole mass of the granite and the Moine could behave as a single low density mass against the Lewisian basement. The density contrast would then arise from the juxtaposition of Lewisian and Moine. Even so, the density interface Lewisian/Moine-granite must be inclined at a low angle to the east in order to be consistent with the observed field.

Model 3

The geological ideas of Model 2 lead naturally to the physical Model 3 in which a wedge of lighter rock is assumed to be underlain by a denser basement. After a number of attempts a model with the following characteristics was found to give the best agreement with the observed profile.

Fig.29.

ROSS OF MULL GRANITE



Angle of wedge	30 degrees
Thickness of wedge	11000 feet
Density contrast	0.1 gms/cc

The calculated and the observed profiles are compared on Fig. 28. Obviously any change in the density contrast would alter the parameters, but the general wedge form would remain unchanged.

Model 4.

Model 3 assumes that the Moine and the granite have the same density, which is probably unreasonable. Model 4 surmounts this problem by postulating an easterly extension of the granite beneath a thin cover of Moine. This would satisfy both the observed regularity of the gravity profile to the east, and also Bott's Density Law which states that the granite is always less dense than the surrounding country rock. The model also supports the contention that the Ross of Mull granite is associated with the Morvern-Strontian injection complex (Phemister, 1948).

The foregoing discussion has been a statement of possibilities and no attempt has been made to favour any one model. There would, however, appear to be little doubt that the Granite/Lewisian interface is inclined at a low angle, and that this density interface corresponds with the presumed position of the Moine Thrust (Jehu (1922) was not convinced that the Moine Thrust passed between Mull and Iona and thought that it probably lay farther west). The eastern limit of the granite is more speculative, but Model 4 is not unreasonable.

Whilst the western limit of the granite is defined by the Moine Thrust, the granite itself is post-thrust as is shown by apophyses of granite found on Iona, and by the fact that the Torridonian of Iona is metamorphosed by the granite (Jehu, 1922). If Model 4 is in any way an approach to the truth, it does suggest that the Moine Thrust controlled the movement of the granitic magma and prevented any further extension to the west. Structural control of this type is well known in mineralised areas.

Conclusions

From the evidence available, the Ross of Mull granite appears as a wedge shaped mass terminating to the west against the Moine Thrust. The eastern limit of the granite is more difficult to define, but the gravity field suggests that it underlies the Moine Schist for a considerable distance. This space form is quite unlike that normally associated with either post and syn-tectonic granites (Bott, 1956), or the typical Tertiary granite (Cook and Murphy, 1952). A more detailed interpretation would require more gravity measurements, and an accurate determination of the bulk densities of the formations involved.

Chapter X.

CONCLUSIONS: SOME IMPLICATIONS OF THE ANOMALIES

The Geophysical Evidence

Introduction

An attempt is now made to summarize the conclusions of the earlier chapters, and to suggest a solution to the space problem and the concomitant problem of the origin of the magmas and the centres themselves. Much of the latter must of necessity be speculative since the argument rapidly passes from the field in which the gravity evidence is of any direct help.

The geological and structural similarities between the centres have already been set out in some detail elsewhere (Richey, 1932, 1948) and it would be tedious to repeat them here. The regional tectonic setting is fairly simple. A north-south monocline or geanticline was initiated in late Mesozoic times and continued into the Tertiary. Associated with this was a large N-S sunken trough containing Mesozoic sediments and presumably indicating a zone of crustal weakness. This is the so called Minch Graben (Holtedahl, 1952) and is a tectonic feature accompanying the Continental slope. Whether the deep water trenches shown on the bathymetric map of the area (cf. Steers, 1952) represent old sub-aerially eroded rift fault lines is uncertain. The great centres of igneous activity lie in the region of the Minch and are localised at or near the intersection of major faults and thrusts and the main N - S zone of weakness. Thus the Skye, Rhum and Ardnamurchan centres are close to the Moine Thrust (Skye is also on the line of the Strathcarron fault); Mull is astride the Great Glen Fault; and Arran, the Highland Boundary Fault. Evidence from the dyke swarms of Mull and Arran indicate a crustal stretching of between 4% and 7%, and suggests that during the Tertiary the area formed part of a 'region of tension' (Evans, 1924). The focussing of the dyke swarms on the individual centres has been likened by Bailey to the tearing of a sheet of paper through the perforations, the centres representing holes occupied by magma under excess hydrostatic pressure.

The Bouguer anomalies summarised

The annexed table shows the numerical details of the gravity field s over the Tertiary Plutonic Centres.

The Gravity Anomalies over the Tertiary Centres

	Maximum Bouguer Anomaly	Maximum Anomaly	Maximum gradient	Average gradient	Proposed space form
Skye	73.4	53.4	13mgls/ mile	5.5-6.5	Vertical cylinder.
Mull	71.7	51.7	9 "	6mgls/ mile	"
Ardnamurchan	42.0	22.0	8 "	5 "	"
Mourne	58.8	37.8	8 "	5 "	Horizontal cylinder.
Arran	40.8	20.8	5 "	5 "	Sphere ?
S. Kilda	60.0	-	-	-	-

The structual similarities between the centres, already noted by Richey, were found to be reflected in the gravity field and certain general statements can be made.

1. The Tertiary Centres are characterised by high positive Bouguer anomalies.
2. The maximum anomaly used in conjunction with the maximum gradient suggests a near surface origin for the anomalous masses, and the most likely cause of the anomaly is a direct density contrast between an intra-crustal basaltic chamber and the surrounding metasedimentary and granitic layers.
3. The magnitude of the anomalies indicates that the masses are subjacent rather than laccolithic, and that in Skye and Mull the magma chambers probably extend downwards into the Intermediate layer.
4. In all cases the associated granites are thin, being generally less than a mile in thickness, and this emphasizes the difference in space form between the Tertiary granites and the post tectonic granites of Bott (1956).
5. The essential symmetry of the gravity fields over the centres implies a symmetrical origin and the interpretation was based on the use of basic vertical cylinders and superimposed discs.
6. The volume of the proposed cylinders, coupled with the total mass surplus points to the existence of a new 'basaltic space problem'.

These conclusions are similar to those already reached in Chapter 1 after a study of the gravity field over some active and recently extinct volcanoes. Too much stress cannot be placed on these parallels owing to the suspicion of a subjective factor entering into the selection of the original evidence. We cannot then assert definitely that the Tertiary Centres were originally Central type volcanoes. Yet a positive anomaly is associated with the South East Caldera of Mull, which Bailey (1924) conclusively demonstrated was a basaltic central type volcano during the Tertiary. The almost identical field over the Cuillin gabbro suggests that this too was at one time a basaltic volcano, though now eroded to a much deeper structural level. Similar parallels could be drawn between the anomaly over the Central Ring Complex of Arran and its volcanic caldera, and the deeply dissected Tertiary Centre of Ardnamurchan.

This additional support for the widely held view that the Tertiary centres are the basal wrecks of great central volcanoes does little to resolve the classic dispute between Geikie and Judd as to whether the plateau basalts were erupted from fissures (as in Iceland) or volcanoes (as in Hawaii). Certainly, there is no evidence of any major fissures - or at least not in the area surveyed. In the Deccan, Glennie (1951) found Bouguer anomalies ranging from -18 to +63 mgals. which he explained in terms of a rectangular fissure 5 Kms. wide extending into the Intermediate layer at a depth of 10 Kms. This he thought was probably the main source of the tholeiitic basalts of the Deccan.

The evidence from the Deccan does not exclude fissures from the Tertiary Volcanic Districts. There are for instance no major positive anomalies associated with the Icelandic fissures, yet it was these fissures which inspired Geikie to advocate a fissure origin for all the plateau basalts of the Thulean Province. In Iceland, as in Scotland, the main positive anomalies are associated with cauldron and ring dyke subsidences (Einarsson, 1954).

Glennie (op. cit.) favours a connection between the surface fissure and the Intermediate layer of seismology and such a connection is generally assumed in areas of plateau basalts, since only a uniform earth layer seems capable of generating such an enormous bulk of essentially undifferentiated basaltic magma of uniform chemical composition.

From the Bouguer Anomalies over the Tertiary Centres, it was deduced that the masses of dense - and presumably basic rock - beneath the plutonic complexes extended downwards into the Intermediate layer. At that time no further explanation was attempted, but since some ambiguity attaches to the so called Intermediate layer, a definition is included here.

The Intermediate Layer

The concept of a layered crust above the Mohorovicic discontinuity was originally introduced to facilitate the mathematics of seismology. Jeffries, in his 1926 analysis of Love waves concluded that there were two crustal layers - an upper granitic layer and a lower basaltic layer.

Almost all investigators require an increase in velocity with depth, but as reflections from the top of the Intermediate layer are difficult to obtain, they incline to the view that the transitions are continuous and not discontinuous, though the transitions may only occupy a small fraction of either layer. Such an increase in velocity could be produced by an increase in the proportion of basic to acid material at depth, thus giving rise to the intermediate or basaltic layer of the petrologist. The fact that the velocities found in the layer immediately below the oceans are the same as those assigned to the continental layer, does suggest that the latter may exist as a separate layer.

An account of the continental structures deduced from the study of earthquakes and artificial explosions from 1927 onwards was given by Byerly (1956). While the majority of authors recognise the existence of an intermediate velocity layer, few commit themselves to identifying it with a layer of intermediate chemistry. Certainly there is no proof of petrographically definite granitic and basaltic layers.

The following range of velocities and average thicknesses have been obtained from Byerly's account:-

<u>Generalised Continental Column</u>

	Thickness in Kms.	Vp in Kms./sec.	Density in gms./cc.
Granitic layer	17	5.2 - 6.22	2.7 - 2.9
The Conrad Discontinuity			
Intermediate layer	20	6.0 - 7.4	2.9 - 2.95
The Mohorovicic Discontinuity			
The Mantle		c. 8.0	

The Conrad discontinuity which is taken as the base of the granitic layer shows great variations in depth (from 4 - 18 Kms. in Germany) and cannot always be detected. Despite this, Byerly is of the opinion that the Intermediate layer has a separate entity under the continents - an entity which justifies the title of layer rather than being thought of as a gradual change from the material above it. On the other hand, Stoneley (1948) finds a value of -6.8 ± 9.4 Kms. for the thickness of the Intermediate layer of Eurasia, thus implying that the thickness of this layer is not significantly different from zero! It appears then that the lower crust is essentially heterogeneous, changing in composition not only vertically but also horizontally.

The ubiquitous occurrence of basalt has for long been thought to justify the equation of the Intermediate layer of seismology with a world encircling layer of basalt. Kennedy (1938) on petrological grounds still further subdivided the sub-continental Intermediate layer into a tholeiitic layer overlying one of olivine basalt. Unfortunately, there are few areas where such a sub-division can be sustained on the seismological evidence.

In the interpretation of the main positive anomaly over the Tertiary Centres, the basic vertical cylinder of the theoretical model was assumed to extend downwards into the Intermediate layer. There the only significance attached to the layer was that at this depth the density contrast between the theoretical model and its surroundings vanishes and any further extension of the cylinder impossible to detect. It does not imply that the basalt originated within the Intermediate layer, and it is conceivable that the true base of the centres lies well below the Mohorovicic discontinuity.

The probable space form of the magma chambers

Anderson's mathematical argument of 1936 and such other geological and structural evidence as is available, favours a cupola shaped magma chamber beneath the Tertiary Centres. The actual form is probably more akin to that of an 'inverted flower pot' (sic Anderson). It would be impossible to produce a theoretical model which could exactly reproduce all the characteristics of the observed gravity field, but in three of the Centres reasonable agreement has been obtained by the use of vertical cylinders. In all three forms have been proposed: the vertical cylinder for Ardnamurchan, Mull, and Skye; the horizontal cylinder for the Irish Centres; and the sphere, or two superimposed discs, for Arran.

Ardnamurchan is the simplest case: the three magma chambers revealed by the surface geology being sufficiently close together to behave gravimetrically as a single basic vertical cylinder. Skye and Mull introduce a dual complication, for although the individual magma chambers can again be regarded as acting as a single cylinder, the gravity field is complicated by the effect of the near surface acid intrusives, and there is evidence from the gravity residuals that the proposed cylinders widen towards the base.

The Irish Centres are sufficiently far apart for the individual magma chambers to behave as a single line mass, or a horizontal cylinder, though a more detailed gravity survey might permit further resolution into a number of vertical cylinders. This is, however, only a speculation.

Arran appears to be the exception, but the proposed sphere - which is a close approximation to the classic paraboidal magma chamber - would probably be more accurately represented as two cylindrical discs, or a vertical cylinder widening towards the base.

The Bouguer gravity field over the Centres would appear then to depend on three things:

1. The presence or absence of acid intrusives.
2. The separation of the foci of the individual magma chambers.
3. The level of erosion - since this controls the depth of the magma chamber beneath the present surface.

<u>The mass surplus</u>

The magnitude of the mass producing a gravity anomaly can be estimated by applying the classical Gauss Theorem of mathematical physics. This may be written as:

$$M = \frac{1}{2\pi G}\iint_{p} \Delta g . dS.$$

where g is the gravity anomaly, and M the causative anomalous mass. If the anomalous mass has a density p enclosed in a body of density p′, then the total mass is given by:

$$M = \frac{1}{2\pi G} \cdot \frac{\rho}{\rho - \rho'} \cdot \int_{\rho} \int \Delta g \cdot dS.$$

These methods have previously been applied by Hammer (1945) and more recently by Bott (1958). The following results were obtained in Skye and Mull:-

Area	Assumed background	Mass surplus (10^{17}) gms.
Skye	20 mgals.	3.3
Mull	20 mgals.	2.9

Both these figures are likely to be an underestimate owing to errors in the true background field, and the difficulties in determining the true horizontal extent of the anomaly. The determination of the total mass requires assumptions as to the densities involved and this introduces another possible factor of error. The determination of the anomalous mass by the Gauss Theorem is not dependent on any such assumption and is therefore free from this uncertainty.

Space Problem

The mass surplus, coupled with the volume of basalt involved in the assumption of a vertical cylinder of radius five miles with a thickness equal to that of the granitic layer, points to the existence of a new basaltic space problem. This had already been hinted at in the Skye and Mull chapters. The problem is analogous to the granitic space problem, but more difficult at first sight in that a conventional hydrostatic mechanism seems impossible, the basalt-gabbro column being appreciably denser than the surrounding granitic and metasedimentary layers.

The problem posed by the Bouguer Anomalies must be answered by the geologist and six possible solutions are considered below.

(i) <u>Harker's solution</u>

Of the proposed solutions, the laccolithic form postulated by Harker is now unacceptable geologically and this is confirmed by the Bouguer anomalies, in that the underlying magma chambers are subjacent and possibly extend into the Intermediate layer. In both Skye and Mull, the total mass surplus - 3.0×10^{17} gms. and the assumed theoretical models, require that some 850 cubic miles of normal crust have been replaced by a dense, and presumably, basaltic mass.

(ii) <u>Transformation</u>

Harker's alternative to the laccolith - replacement or transformation - has been applied by Black, Reynolds, King and others to explain the petrographic characters of many of the Tertiary basalts and granophyres. Whilst it is conceivable that the high temperatures associated with the main basic pluton could have a considerable metamorphic effect upon the earlier products of vulcanism, metamorphism can have little relevance to the main problem - the apparent replacement of both metamorphic rocks and granite by basalt.

(iii) Refusion

Holmes (1932) put forward an alternative solution to the space problem: 'If the granitic material (of the crust) was not fused we are at a loss to account for its apparent disappearance'. Fusion of the granitic crust is one solution to the problem though it must result in contamination of the original magma.

(iv) Marginal folding

Most of the movement in the Tertiary Centres would appear to have been vertical rather than horizontal, and there is little evidence in either Skye or Mull of large scale marginal folding. Slight folding is developed in the Jurassic of Strathaird south of the Cuillin centre, but there is none in Glen Brittle to the north. Concentric folds are found around the Mull centres, the minor folds being occasionally overturned as in the Loch Spelve anticline. Bailey (1924), however, regards these folds as a local phenomenon related to the intrusion of the Glas Bheinn and Derrynaculen granophyres; whilst Van Bemmelen (1937) thinks their explanation lies in gravitative sliding. In neither case is there any suggestion that the folds are sufficient to accommodate the main basic mass.

(v) Ejection of the sialic crust

Wager and Deer (1938) resolved the Skaergaard space problem by suggesting that the surplus granitic crust had been removed by way of a central type volcano. "It seems to us that the most reasonable hypothesis to account for the removal of this mass of rock is that the initial explosion which produced the cone fracture shattered the crustal rocks and expelled the greater part so that they were disseminated over a wide area."

The volume of the Skaergaard mass is considerably less than that of either Skye or Mull, this being a direct consequence of the space form - the Skaergaard mass tapering downwards. Even assuming that the Tertiary Centres were originally central type volcanoes, there is still no evidence of 850 cubic miles of granitic crust disseminated around either the Skye or the Mull centres, and it seems unlikely that even the not inconsiderable post Tertiary erosion could remove all traces of so vast an outpouring.

(vi) Stoping

Piece meal stoping - or at a higher crustal level - explosive brecciation, may be factors in the provision of room for ring dyke intrusions. A central block bounded by outwardly dipping ring faults is free to subside into the underlying magma, providing the subsiding block is denser than the surrounding magma. Where the magma is acid - as in the Mournes and Glen Coe - no difficulty arises. On the other hand, subsidence into a gabbroic magma seems impossible. The evidence of the gravity survey is of a positive density contrast between the postulated vertical cylinder and the lighter granitic crust. Initially, this appears fatal to any stoping mechanism, but the space problem is concerned with the basalt at the time of intrusion, and in particular, with its density at that time.

By analogy with present day volcanoes, we can reasonably assume that the basalt was initially liquid and saturated with water and other volatiles. That fluxes were plentiful during the Tertiary is evidenced by the pegmatites in the Great Eucrite of Ardnamurchan. Similarly, that the magmas forming the quartz gabbros with their well marked acid mesostasis had a high water content also seems likely.

The densities of molten basalt have been investigated experimentally and some results for diabase are given below (vide Daly, 1944).

Densities of Diabase

Crystalline density at 20°C	Glass density at 20°C	Melt density at 1250°C	% decrease in density
2,975	2.763	2.59	12.9
2.969	2.780	2.64	11.1

From these results it appears that at atmospheric pressure the density of a basaltic or near basaltic magma when completely molten is some 12% lower than that of the same rock when completely crystallised without voids at 20 degrees Centigrade. The percentage change would be even higher in the case of a more salic lava. A similar table for gabbro-diorite was given by Day, Sosman, and Hostetter (1914) and quoted by Daly (1933).

Densities of Gabbro-Diorite in gms/cc.

Crystalline densities			Equivalent glass		
20°	900°	1100°	20°	1100°	1200°
2.80	2.74	2.73	2.63	2.53	2.52
3.10	3.03	3.01	2.91	2.80	2.79
2.90	2.84	2.82	2.73	2.63	2.63
3.00	2.94	2.92	2.82	2.71	2.70

In the interpretation of the gravity field over the Mihara volcano in Japan, the authors (Iida et al., 1952) assumed a density of 2.0 gms/cc. for the molten basalt with a magma chamber at a depth of 2 Kms. This is the lowest density noted in the literature for basalt, but was apparently consistent with the changes in the gravity field caused by the volcanic eruption.

Conclusions

The experimental evidence favours a low density for liquid basalt, a density which will be reduced still further in nature by the presence of 6% of dissolved water and other volatiles (Daly, 1944). In a magma of this type with a density differential of 0.1 - 0.2 gms/cc. it would be possible to stope large sections of the granitic and metasedimentary layers. This process would be facilitated by the increase in density of the upper crustal layers by cone sheet and ring dyke injection and the development of circumferential flexures. Once stoped the granitic blocks would continue to sink until checked by either an increase in the density or viscosity of the surrounding magma, or by the fusion and assimilation of the block itself. This assimilation may be responsible for the later tholeiites. Daly has pointed out that the contamination of an olivine basalt magma by a low temperature quartz feldspar eutectic in the ratio of 9 : 1 would give rise to a tholeiite, i.e. tholeiites are not derived from a primary crustal layer, but are a syntectic.

Current Theories on the Origin of Basalt

Introduction

Petrology requires the existence of a primary and parental basaltic magma. The distribution of basaltic rocks in space and time, the remarkable uniformity of chemical composition, and the geometry of the lava flows and intrusions are concordant with the source having a world wide distribution and occurring at depths of up to 150 Kms.

It seems reasonable to assume that the major dykes and fissures tapped a uniform earth layer capable of developing basaltic magma quickly and in large quantities, but incapable of differentiating at the source. Whether this layer is the classical Intermediate layer is doubtful, and current theories of origin prefer to derive basalt from within the mantle.

For a large body of magma to originate, one of two conditions must hold good. Either:

1. There must be partial melting of deep seated material of a different composition, or
2. Complete melting of material at a shallower depth under temperature conditions temporarily raised above average.

Under (1) come the hypotheses of Bowen and Kuno which derive primary olivine basalt by the partial fusion of the mantle and under (2) the Intermediate layer theories of Daly, Anderson and Kennedy in which the total melting of a basaltic layer, or layers, is assumed to occur.

Fusion within either the mantle or the Intermediate layer requires either an increase in temperature, a reduction in pressure, or both. Theories of origin then can be divided into those involving temperature, and those involving pressure changes.

Intermediate layer theories

The Intermediate layer of seismology - if it exists - lies within 15-35 Kms. of the surface, and the problem posed by the Intermediate layer theories is increasing the temperature within this layer so as to produce local or regional fusion.

There are considerable difficulties in extrapolating the thermal gradients observed at the surface to depths of 100 Kms. or more (see Verhoogen, 1956) and the temperatures within the crust and upper mantle are variously estimated as being in the range 300° - $700^{\circ}C$ at 20 Kms. rising to

700° - $1200^{\circ}C$ at 100 Kms. These are considerably lower than Gutenberg's previous estimates of $1500^{\circ}C$ at 100 Kms., and vitiate Wolff's (1944) conclusion that the temperature in the mantle below 70 Kms. is everywhere greater than the melting point of olivine. Under the prevailing pressure conditions of 11.10^{3} bars and the calculated effect of pressure on the melting point of basalt, it seems unlikely under normal conditions that these temperatures will produce anything other than a partial melting of the Intermediate layer.

In a tectonically active area such as the West Indies, the Intermediate layer may be depressed in the roots of a tectogene, partially melting and producing an andesitic magma. In a tectonically stable area such as the western coast of Great Britain no such mechanism can be invoked and in any case the prevailing magma type is basaltic and not andesitic. Radioactive heating caused by thermal blanketing by sediments is unlikely with the thicknesses of sediments involved.

Two other possibilities remain: either 1) A regional increase of temperature within the layer could be produced by a convectional overturn. This would temporarily raise the material at the base of the layer above its normal temperature, the surplus heat then being dissipated by conduction. Or 2) The pressure on the layer could be reduced so as to permit fusion at the existing temperature. This is more or less what Daly envisaged in the periodic fusion of his vitreous basaltic substratum.

The generation of basaltic magma as a result of major fissures lowering the pressure on the substratum was developed in some detail by Osmond Fisher in 1885. This presupposes that the crust is in state of tension, which is a reasonable supposition in the Tertiary Volcanic Districts. Fisher, like Daly, envisaged the basaltic substratum as being in a glassy state verging on fusion, a very slight increase in temperature or decrease in pressure being sufficient to start the ascent of magma. The vitreous layer is not consistent with the present seismological evidence and the temperatures within the Intermediate layer seem inadequate. The temperature problems is even more acute in the case of oceanic basalts, the Intermediate layer being much shallower.

The concept of a lower layer 'verging on fusion' has recently appeared in a paper by Press (1959). A low velocity channel at a depth of greater than 100 Kms. revealed by G waves may, it is suggested, be a source of primary basalt magma, and also represent the zone where the mantle is decoupled from the crust for tectonic purposes. This layer is quite distinct from the old Intermediate layer, and fits in better with current theories which derive the primary basalt from the mantle.

Mantle theories

The nature of the mantle itself largely turns on the nature of the Mohorovicic discontinuity. This is variously regarded as representing either a change in composition, a phase change, or the original surface of the earth.

Whilst there is no direct evidence for the chemistry of the mantle, seismic results suggest that it is probably composed of heavy silicates of Fe and Mg with a density of 3.32 gms/cc. Thus, the mantle was formerly thought of as being essentially homogeneous and consisting of either dunite or peridotite, or as Holmes thought - eclogite. More recent seismic results show considerable variations in wave velocities within the mantle which must reflect a variation in mineral constitution. Hill (1957) finds it surprising that the material below the Moho has the same compressional wave velocity whether it is 11 or 35 Kms. deep. The variation in depth, he thinks, must represent some change in the chemistry.

If the upper mantle is heterogeneous, the derivation of basalt by partial fusion probably needs re-examination, since the distinguishing feature of basalt is its remarkable similarity of chemical composition, physical properties and radioactive constituents irrespective of either age or location.

Many materials undergo polymorphic changes to denser forms when moderate pressures are applied, and as far back as 1918, Fermor discussed the significance of eclogite as a high pressure form of gabbro. This ultimately led to the hypothesis of an eclogite shell beneath the Moho. After discussing the petrographic and chemical evidence for the composition of the upper mantle, Ringwood (1958) comes to the conclusion that the upper mantle is dominantly peridotitic with eclogite as a minor by widely distributed constituent.

The dunite-peridodite layer grades downwards into material of garnet-peridotite composition and this is believed to be the present source of basaltic magma. The exact depth at which the phase change eclogite - basalt takes place is unknown.

This suggests that the oceanic lavas are samples of denser sub-crustal material which has reached the surface in a liquid state and then solidified to a normal low temperature mineral assemblage. In an explanation of the positive gravity anomalies over the tensional Red Sea Rift, Girdler (1958) has suggested that the rift is filled with basaltic material derived from below the Moho by a phase change. The phase change was consequent upon a reduction in pressure caused by rifting.

Conclusions

The above discussion is far from comprehensive, but it indicates the main trends of thought. Present day seismic studies are rapidly disproving the existence of a uniform, world encircling intermediate layer. Similarly, studies of the thermal gradient reveal that the layer is too shallow to be the source of the major plateau basalts. The recognition of considerable inhomogeneity within the upper mantle suggests that the ultimate source of basalt must be sought at 150 rather than 50 Kms.

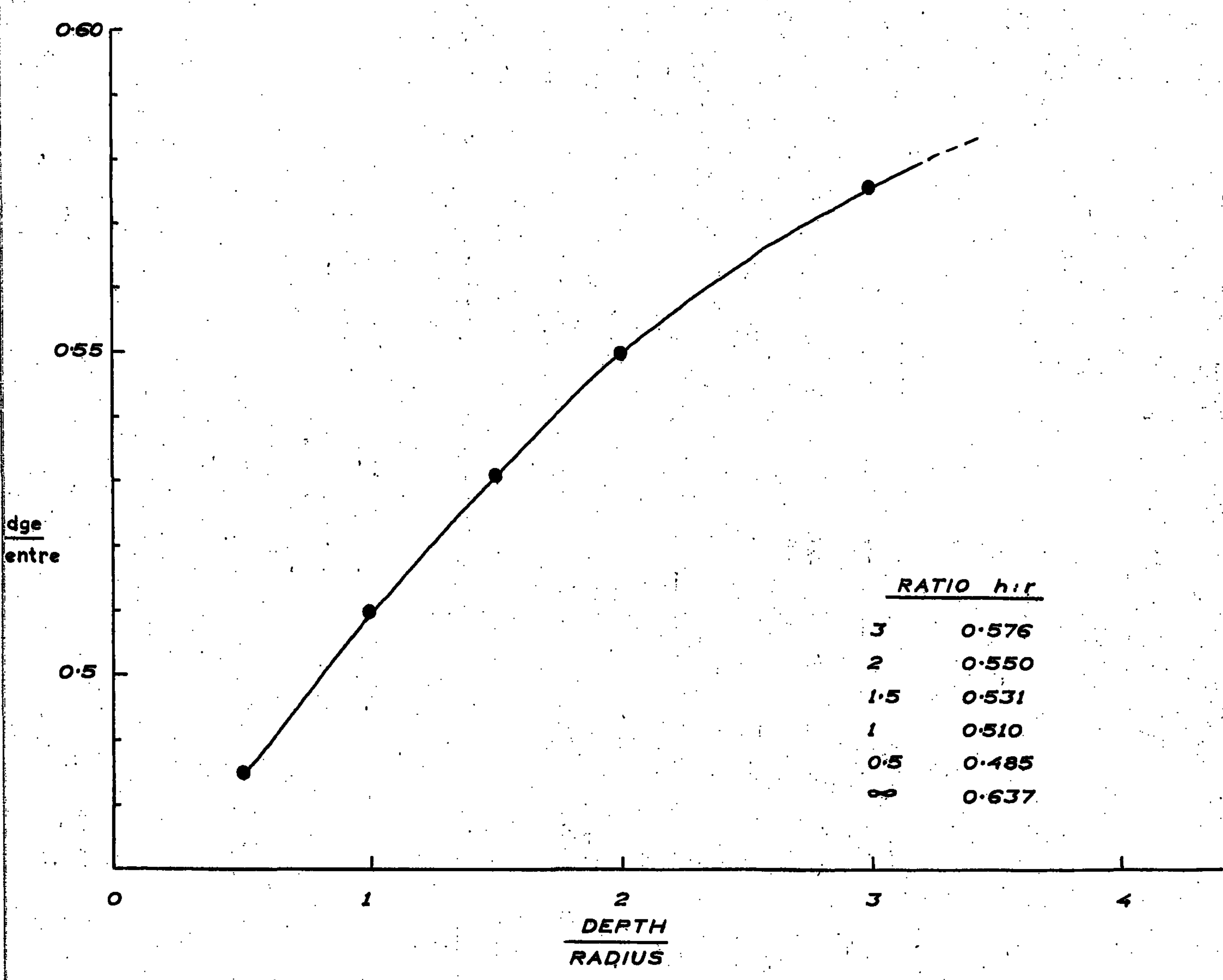
The Origin of the Tertiary Basalts

Two principal lines of evidence assist in determining the origin of the Tertiary basalts and Tertiary centres of western Scotland.

1. The regional gravity field is positive throughout the area and as far west as S. Kilda, and it has already been suggested (Browne and Cooper, 1950) that a rising convection current leaving an excess of mass at the surface could be the cause of the anomaly. This has several attractive features notably - it provides an adequate source of heat for convectional overturn or direct fusion and so resolves one of the problems of the Intermediate layer theories; and secondly, the upward and outward movement of the current and the increase in volume of the mantle would produce tension cracks within the crustal layers.
2. The region is one of tension. This was pointed out by Evans (1924) who related the crustal stretching to a westerly drift towards the Atlantic abyssal plain west of Rockall.

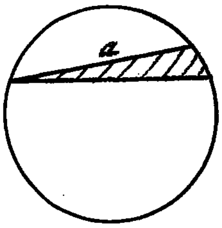
A convection current within the mantle provides both heat and tension, the second theory tension alone. Both could produce basalt by an eclogite-basalt phase change. The rift like character of the Minch Graben and the general north-south lineation of the Tertiary centres as a whole, suggest that a phase change mechanism of the Red Sea type (as was postulated by Girdler) might have some relevance to the Tertiary problem.

RATIO OF ANOMALY AT CENTRE TO ANOMALY OVER EDGE FOR A VERTICAL CYLINDER



RATIO	h:r
3	0·576
2	0·550
1·5	0·531
1	0·510
0·5	0·485
∞	0·637

TO FIND THE RATIO OF THE ANOMALY OVER THE CENTRE TO THE ANOMALY OVER THE EDGE FOR A VERTICAL CYLINDER.



From the figure, the attraction of the shaded portion is:

$$G\rho\,[a + h - (a^2 + h^2)^{1/2}]\,d\theta.$$

Therefore, the total attraction is:

$$2G\rho\int_0^{\pi/2}(2r\cos\theta + h)\,d\theta - 2G\rho\int_0^{\pi/2}(4r^2\cos^2\theta + h^2)^{1/2}\,d\theta.$$

$$= 2G\rho\left(2r + \frac{h\pi}{2}\right) - 2G\rho\int_0^{\pi/2}(4r^2\cos^2\theta + h^2)^{1/2}\,d\theta.$$

The latter is an elliptic integral and has solution:

$$(4r^2 + h^2)^{1/2}\,E_1(k, \pi/2) \quad \text{where } k = \left(\frac{4r^2}{4r^2 + h^2}\right)^{1/2}.$$

Therefore the ratio attraction over edge / attraction over centre is:

$$\frac{2r + \frac{h\pi}{2} - (4r^2 + h^2)\,E_1(k, \frac{\pi}{2})}{\pi\{r + h - (r^2 + h^2)^{1/2}\}}$$

The ratio has been plotted for differing values of r and h as shown on Fig.30

G is the gravitational constant

a is the length of the chord

θ is the angle subtended

h is the height of the cylinder

r is the radius of the cylinder

p is the density.

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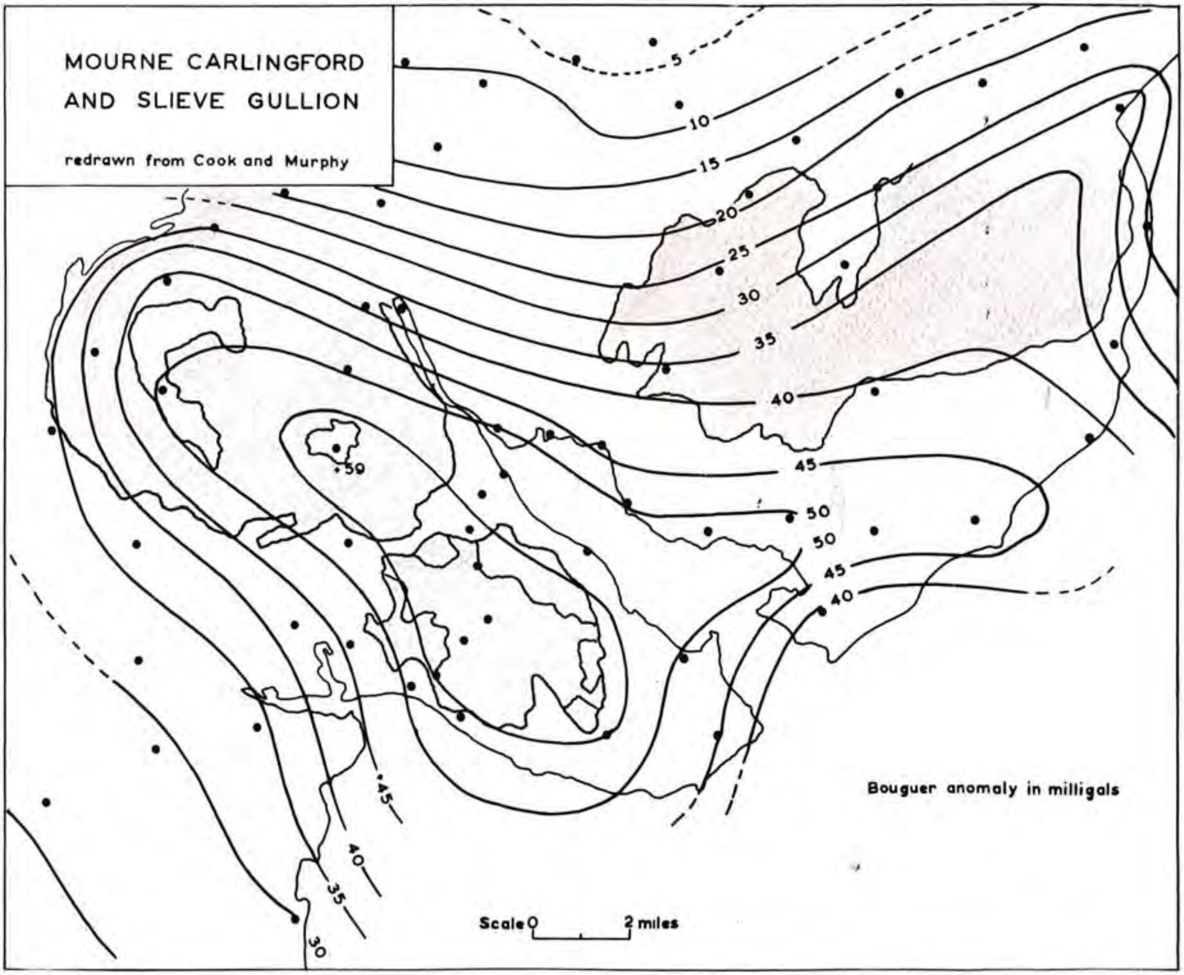
Plate 4.



MOURNE CARLINGFORD AND SLIEVE GULLION
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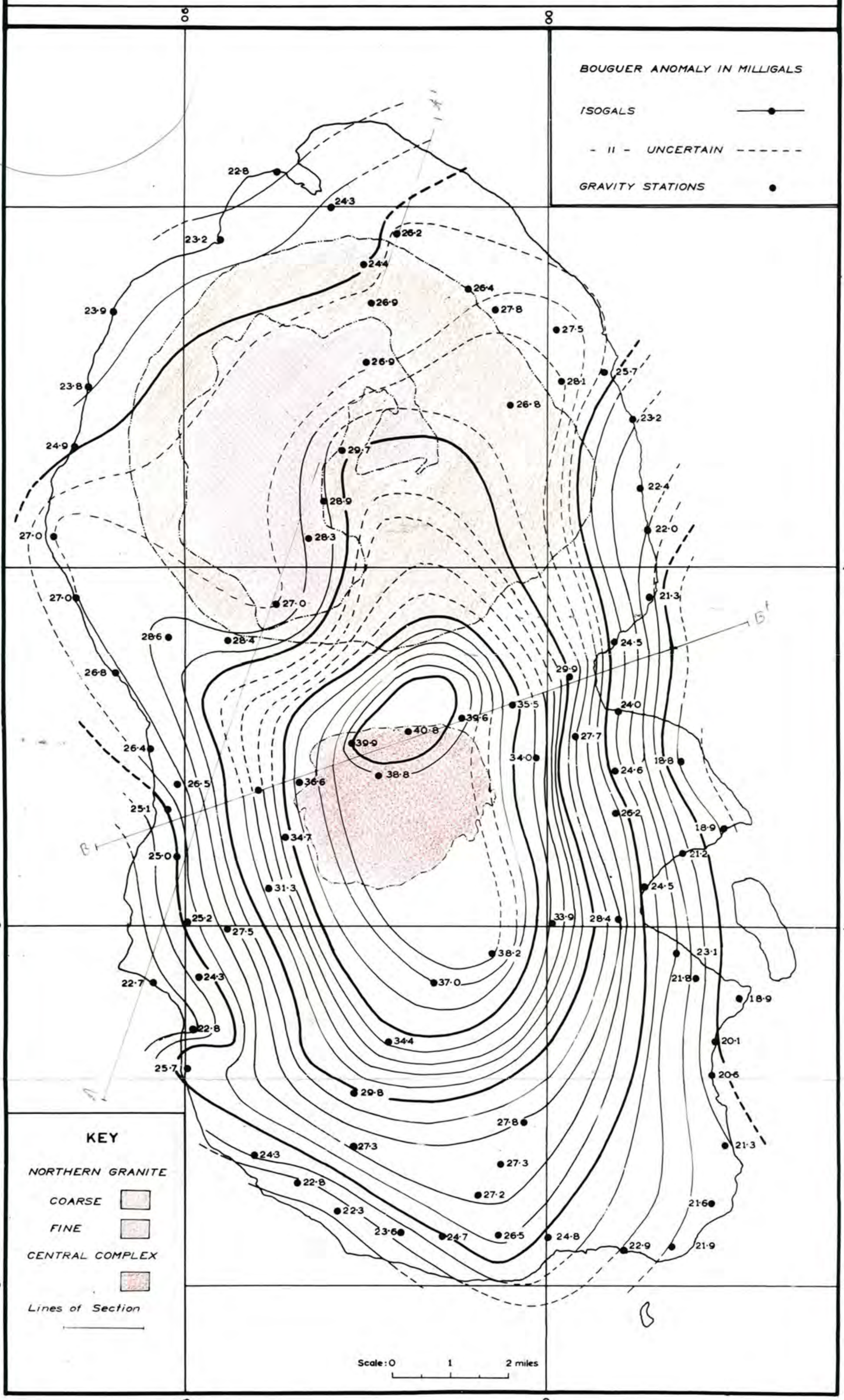
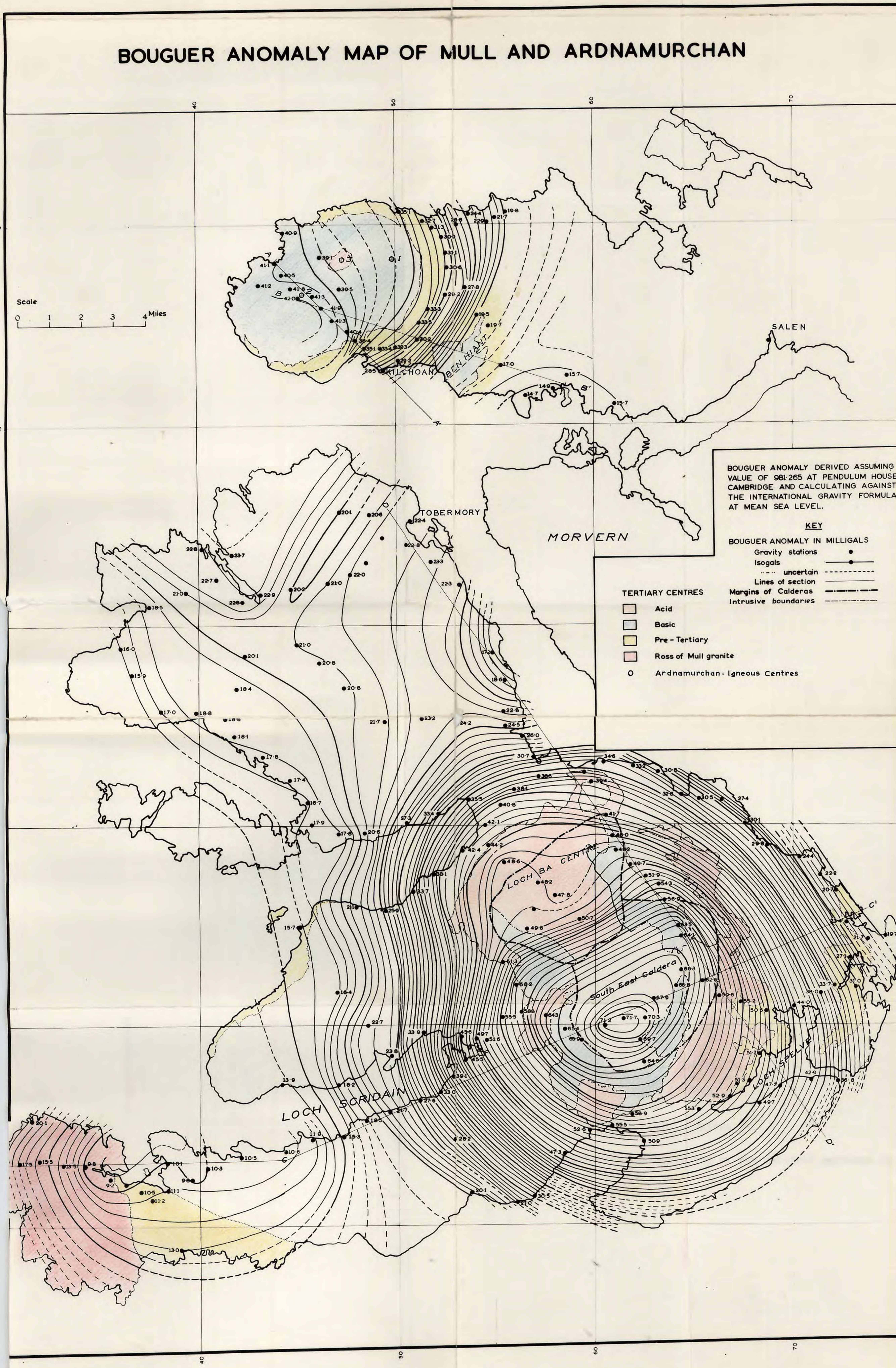
BOUGUER ANOMALY MAP OF ARRAN



BOUGUER ANOMALY MAP OF MULL AND ARDNAMURCHAN



BOUGUER ANOMALY MAP OF THE ISLAND OF SKYE