A GRAVITY SURVEY OF THE CRIFFEL GRANODIORITE

by

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being the subject of a thesis presented for the degree of Master of Science in the University of Durham.

Durham, September 1960

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ABSTRACT.

The results are presented of a gravity survey of the Criffel - Dalbeattie granodiorite complex and the surrounding area, carried out from the Geology Department of the Durham Colleges. Gravity stations are sufficiently closely spaced to allow accurate contouring by means of Bouguer anomaly isogals at one milligal intervals. A large number of density specimens collected during the course of the survey have been statistically analysed and the results used in the interpretation.

The surface geology of the area has already been mapped and described in some detail and this information has been used extensively in the interpretation of the gravity data. The opinion of previous authors is that the complex is of magmatic origin.

The most striking feature of the gravity field is a pronounced negative anomaly over the main granodiorite with very steep gradients over the country rock to the north-west of the granodiorite but smoother gradients on the south-east side. The suggested interpretation, based on three dimensional computer methods, is that the main granodiorite mass extends to a depth of eight miles and exhibits a marked gradational increase in density in its south-eastern portions. It is thought that this is the result of magmatic flow within the intrusion, the magma welling up at a centre slightly offset from the present centre of the outcrop, becoming contaminated by the country rock and flowing down on the south-east side.

The gravity field over the outlying parts of the complex in the Auchencairn region suggests that the granodiorites in this area extend to the same depth as the main intrusion and are an integral part of it.

Regional modifications of the gravity field are also discussed and tentative interpretations put forward.

INTRODUCTION

Within the Southern Uplands of Scotland there occur three major granite masses, of which the most southerly, the Criffel - Dalbeattie granodiorite, has been chosen as the subject of a detailed gravity survey.

The geology of the granodiorite and the surrounding area has recently been re-mapped in considerable detail by Phillips (1956). He has shown that it consists of three different, but closely related granodiorites emplaced into folded shales and greywackes of Llandovery and Wenlock age, this emplacement having occurred before Lower Carboniferous times.

The area has also been the subject of a reconnaissance gravity survey by Bott and Masson-Smith (1960) during the course of their more detailed investigations into the gravity field over the Permian sandstones of the Dumfries basin immediately to the north-east. The results of this survey revealed a large negative Bouguer anomaly over the granodiorite.

The present work was undertaken with the object of enlarging upon the profile obtained by Bott and Masson-Smith across the main granodiorite and also to extend the survey to the south western end of the complex and to the Silurian country rock beyond. The area of ground covered by the present survey is of the order of 300 square miles.

The bulk of the field work was carried out during three weeks in September 1959 by Mr.John Mansfield and the author. A further four days work was carried out by the author alone in April 1960. In all, 359 new stations were occupied.

Chapter 1. GEOLOGY OF THE AREA.

1. GEOLOGY OF THE AREA.

(a) History of research.

The first geological mapping of the Criffel-Dalbeattie granodiorite and the surrounding area was carried out by Horne in 1870, although the accompanying description was not published until 1896, after revisions by Horne, Peach, Teal and Geikie.

Little subsequent mapping was done until MacGregor (1937) re-examined the western end of the complex and showed that it could be subdivided into three different types of granodiorite. He also mapped a narrow band of quartz-diorite surrounding the granodiorite on its western margin and a mass of minor intrusions cutting the quartz-diorite and extending for several miles out into the country rock to the north west.

Phillips' (1956) re-mapping of the whole complex has shown that one of MacGregor's granodiorites is structurally and petrologically a part of the main complex. Phillips' work brings out the close relationship which exists between all the rock types present and suggests a possible mode of origin for the complex as a whole. A magmatic origin is considered to be the most likely.

(b) Stratigraphy and structure of country rocks.

The following formations are present in the area under consideration:-

Quaternary.		Blown sand, raised beach and river deposits.
Permian.		Dumfries Sandstone; red sandstone and breccias.
Lower Carboniferous		Calciferous Sandstone Series.
		Basaltic lavas.
Upper Old Red Sandstone.		Conglomerates, grits and arkoses.
Silurian	Wenlock:	Shales and greywackes.
	Llandovery:	Shales and greywackes.
Ordovician		Shales and greywackes.

Map 2 shows the distribution of the various formations and of the granodiorite. The geology of the sedimentary rocks has been taken from sheets 5 (1927) 6 (1879) 9 (1933) and 10 (1885) of the Scottish section of the Geological Survey of Great Britain. The geology of the granodiorite complex is based on the map given by Phillips in his paper of 1956.

Rocks of Ordovician age are of very limited occurrence in the area, being restricted to a lenticular shaped inlier, four miles in length, to the north of Castle Douglas. The shales and greywackes of which the inlier is composed are very similar to those of Silurian age which surround them and appear to be of comparable density.

The Silurian shales and greywackes themselves are similar to those found over much of the Southern Uplands. They are thought (Horne 1896) to have been isoclinally folded during the Caledonian orogeny, the axis of these folds trending N.E. - S.W. parallel to the general line of the Southern Uplands. Around the margin of the granite, however, the strike swings round to lie parallel to the granite contact, providing good evidence for the post-tectonic nature of its emplacement.

Two very small outcrops of Upper Old Red Sandstone conglomerates and grits occur near Kirkbean. Phillips (1956) has shown that they contain fragments of granodiorite from the Criffel mass, thus demonstrating that the complex was already exposed to denudation in Upper Old Red Sandstone times.

The Carboniferous system is represented by sandstones of the Calciferous Sandstone Series and by basaltic lavas, also placed within the Lower Carboniferous. The Calciferous Sandstone Series forms a long, narrow outcrop along the coast, reaching from White Port, a few miles east of Kirkcudbright Bay, to the mouth of the River Nith. In the western part of the outcrop, the base of the series consists of conglomerates and coarse sandstones, which are composed largely of pebbles of Silurian greywackes. At some localities, fragments of granodiorite are present, again showing that part, at least, of the Criffel mass was exposed at this period.

Basaltic lavas underlie the Calciferous Sandstone Series in the Kirkbean area, but they rapidly thin out to the west and east.

The boundary between the Silurian and Carboniferous rocks is usually marked by a striking unconformity between the highly folded greywackes and the more gently inclined Carboniferous sandstones. In many places, however, the junction is faulted, the downthrow being towards the south.

The Dumfries Sandstone, a series of red sandstones and breccias of New Red Sandstone age, occupies much of the region to the north east of the Criffel complex. These deposits lie unconformably upon the Silurian and Carboniferous rocks.

No other rocks of later age are represented, with the exception of drift deposits. These include river gravels in the Urr and Nith valleys and raised beach deposits along the coast. These cover much of the western half of the Southerness peninsula and may locally be thick enough to have an appreciable effect upon the gravity anomaly.

(c) <u>The Granodiorite Complex.</u>

Phillips' (1956) paper provides the most up-to-date account of the granodiorite complex itself and the following description is largely based upon his work.

(1) <u>The Main Granodiorite.</u>

(a) Field Relations.

The outcrop of the largest element of the complex - the main granodiorite, was originally oval but has since been slightly modified by fault movements along the south western end. The outcrop is fifteen miles long by about seven miles wide at its widest point, the longer axis being aligned in a north-east - south-west direction, parallel to the general regional strike direction of the Silurian rocks of the Southern Uplands.

Along the north western and south eastern margins of the granodiorite, the strike of these country rocks remains undisturbed, but at the ends the strike swings round parallel with the boundary.

The contact of the granodiorite with the country rock is always sharp and dipping steeply outwards. There is no evidence of chilling, although veins of granodiorite often extend into the country rock and xenoliths are often very numerous within a few feet of the contact.

The central part of the complex, which forms most of the high ground in the area, consists of a coarsely crystalline, porphyritic granodiorite, almost oval in plan. Just to the north of Dalbeattie the porphyritic rock is in direct contact with the Silurian country rock for a distance of about two miles, but elsewhere the porphyritic variety is entirely surrounded by the main granodiorite into which it grades uniformly, there being no sharp boundary between the two rock types.

(b) Petrography.

The main granodiorite consists essentially of plagioclase, microperthite, quartz, hornblende and biotite with sphene as a characteristic accessory mineral. The plagioclase, which ranges in composition from An_{15} to An_{35} occurs as small, subhedral crystals commonly showing faint oscillatory zoning and slight alteration to sericite. The quartz forms rather irregular masses, frequently exhibiting signs of strain and often containing inclusions of gas.

Potash felspar is present in the form of microperthite, which often forms large "pools", enclosing altered plagioclase, biotite and hornblende grains. The hornblende occurs as subhedral crystals, in many cases containing relicts of colourless pyroxene. Biotite, however, is the predominant coloured mineral and often replaces hornblende.

As the porphyritic centre of the mass is approached, the microperthite crystals become more prominent, forming large, pinkish phenocrysts, usually enclosing grains of biotite. The rock is generally lighter in colour than the main granodiorite, the dominant coloured mineral being biotite. Hornblende is scarce in the porphyritic part of the pluton.

The usual densities of the commonest minerals found in the complex are given below:-

Hornblende	3 - 3.47 gm/cc.	Plagioclase An_{15-35}	2.64 gm/cc.
Biotite	2.7 - 3.1 gm/cc.	Quartz	2.65 gm/cc.
		Microperthite about	2.56 gm/cc.

These values are taken from Rutley's "Elements of Mineralogy". (Read, 1948).

(c) Xenoliths.

The main granodiorite contains many xenoliths and "basic patches", especially towards the contact with the country rock. Some of the xenoliths consist of recognizable fragments of hornfels, derived from the surrounding shales, frequently containing small masses of hornblende and porphyroblasts of plagioclase.

More commonly, however, these included fragments of country rock have been transformed into "basic patches" containing the same mineral assemblage as the granodiorite, but in greatly different proportions. They usually consist of biotite, hornblende and plagioclase, the mafic minerals predominating and being frequently intergrown with the felspar. Phillips considers that although some of these patches may be "fortuitous segregations" of mafic minerals from the magma, the great majority are derived by assimilation of hornfelses, the constituent minerals having undergone metasomatic alteration to an assemblage which was in mineralogical and chemical equilibrium with the magma.

Xenoliths occur showing all stages of alteration, ranging from those with sharply defined margins to ill-defined lenticular masses, now showing a distinct preferred orientation.

Phillips considers that assimilation has followed two overlapping processes: first, the metasomatic alteration of the hornfelses to a mineral assemblage in equilibrium with the magma and secondly the disintegration of the resulting "basic patches", the constituent minerals being distributed in the magma. As a result, the magma would be expected to be modified most extensively around the margins where assimilation was greatest. It is indeed in the outer regions of the mass where the greatest number of xenoliths occurs and where the rock is distinctly richer in mafic minerals and hence heavier and darker than in the centre of the mass.

Thus, the inward gradation from the typical hornblende - granodiorite to the more truly granitic porphyritic rock, is not only due to the usual processes of late stage concentration of potash rich liquids in the centre but is also the result of the decreasing effect of assimilation from the margin inwards.

(d) Foliation.

Some of the mafic minerals and xenoliths in the outer main granodiorite show a well marked planar orientation, running parallel to the margin and dipping outwards at between 45° and 85°. Phillips (1956) considers that this is a flow foliation, resulting from the circulation of a crystal mush, welling up at the centre of an oval shaped magma chamber and "flowing" down along the walls. The foliation does not extend into the porphyritic granodiorite, from which it is concluded that crystallization of this part of the mass occurred later, under more static conditions.

A secondary foliation affects much of the outer main granodiorite, its secondary nature being implied from the fact that it affects already consolidated minerals and cross cutting aplite and quartz veins. Again, the porphyritic central part is not affected by this foliation showing that it was still largely unconsolidated while the forces which produced the foliation were active.

(e) Structure.

In the Craignair -Dalbeattie area, the porphyritic granodiorite is brought very close to the contact with the country rock. While in part this is probably due to the magma centre being offset to the N.W. of the centre of the mass, it is accentuated by marginal thrusting in this region. The evidence for this comes from numerous talc covered joints and slickensides in the Craignair quarries, indicating near vertical movement, probably the result of magmatic pressure.

The granodorite itself is also dissected by two seemingly complimentary sets of major dislocations which result in sinistral and dextral sets of tear faults within the mass, one trending N.W. - S.E. the other N.N.E - S.S.W.

(f) Emplacement of the Main Granodiorite.

Phillips concludes that all the above petrological and structural evidence seems to point to the main granodiorite being of magmatic rather than of metasomatic origin. The magma is envizualized as being a viscous crystal mush at this level, emplaced in a chamber which it had formed by forcing aside and stoping of the country rock.

Stratigraphical considerations of the distribution of the Wenlock in this part of Scotland show that the rock cover at the time of intrusion was not likely to have been more than 1,500 to 2,000 feet in thickness. This is much thinner than is normally considered to be the case for such a large intrusive mass and Phillips likens it rather to "a gigantic magmatic blister than a chamber entirely scooped out of the crust by the replacement or assimilation of the sedimentary rocks."

Quartz-diorites occurring in places around the margins may be the result of earlier metasomatic transformations while the main magma was still lying at depth. The magma then gradually stoped its way up through its own zone of metasomatic alteration and finally came to rest in contact with the hornfelses where it gradually solidified.

The flow foliation is probably the result of magmatic circulation, rising in the central parts and flowing down the sides, carrying stoped blocks of country rock with it. The absence of flow orientation in the central porphyritic part is thought to be due to the fact that it solidified last, when magmatic circulation had ceased. The concentration of lighter elements and the development of porphyroblasts in this part of the complex also points to its later crystallization.

The assymmetry of the mass is probably largely due to an offset area of uprise, although it is also partly the result of marginal thrusting along the north-western edge.

(2) The Intermediate Granodiorite.

The intermediate granodiorite has a roughly rectangular shaped outcrop, occurring in the area around Auchencairn. It is generally similar to the main granodiorite, but contains more quartz and microperthite and less plagioclase and hornblende. The plagioclase is zoned from An_{30} to An_{15}. Where exposed, the contacts with the hornfelses and the quartz-diorite are seen to be sharp and steeply dipping outwards. Xenoliths are not as common as in the main granodiorite, but where they are present they frequently serve to accentuate the flow foliation, which is parallel to the margin of the granodiorite. Although the exact contact of the main and intermediate granodiorite is not exposed, the foliation of the former would appear to cut across that of the latter, whence it is concluded that the intermediate granodiorite was in place before the main pluton.

(3) The Fine-grained Granodiorite.

The fine-grained granodiorite outcrops on the coast to the south-east of Auchencairn. Its field relationships are somewhat obscure, but it would appear to be associated with a series of north-west - south-east dykes. It may be consolidated from an offshoot magma emplaced into north-west trending tensional fractures within the already crystallized intermediate granodiorite.

(4) Bengairn Quartz-Diorite.

The Bengairn quartz-diorite forms an arcuate outcrop around the western and northern ends of the intermediate granodiorite and also extends out for a further mile towards the north-west. This rock is thought by Phillips (following MacGregor) to have crystallized from a crystal mush which originated by granitization of hornfelses and yet remained more or less in place.

(5) The Metamorphic Aureole.

A contact aureole surrounds the granodiorite complex on all sides. It ranges in width from a half to two miles, being narrowest to the north of Dalbeattie, where the porphyritic granodiorite is in contact with the Silurian country rock and widest around the south-western part of the complex. Within this belt the shales and greywackes have been recrystallized to form fine grained hornblende - diopside - hornfels and biotite-hornfels.

Copper mineralization has occurred in the south of the area and this mineral was formerly worked on Heston Island and on the Balcary promontory. One mine is still being worked here, mainly for the associated barytes.

CHAPTER 2. DESCRIPTION OF THE GRAVITY SURVEY.

2. DESCRIPTION OF THE GRAVITY SURVEY.

1) Introduction.

The major part of the gravity survey was carried out by Mr.John Mansfield and the author during the first three weeks of September 1959, during which 255 new stations were occupied. A further four days field work was completed by the author alone during April 1960 when 104 new stations were added to the total. The Frost Gravity Meter belonging to the Durham Colleges Geology Department was used for the survey. The method of transport was a Bedford Dormobile van, also the property of the Durham Colleges. Field work was normally shared, one person navigating and recording station details while the other attended to the driving and the reading of the instrument at each station. Navigation was done by means of the Ordnance Survey six inches to one mile maps of the area, which were also used for plotting the positions of the stations.

Heights were obtained from bench mark lists published by the Ordnance Survey and from spot heights marked on the six-inch maps where no bench marks were available. A few stations in critical areas had to be levelled using a precision spirit level and Sopwith staff. Height differences of each station from the bench mark were estimated by the use of a hand Abney level used in conjunction with a metre rule.

2. DESCRIPTION OF THE INSTRUMENT.

The Frost Gravity Meter does not measure the absolute value of gravity at a point directly, but provides a measurement of the relative values of gravity between one point and another. In order to pick up geologically significant variations, which may be as little as 10^{-6} times that of the earth's field, a system is used which operates near the point of instability. In the case of the Frost instrument, this system consists of a horizontal bar suspended at one end and loaded with a small mass at the other. The system is supported by means of a spring attached to the centre of gravity of the beam.

The deflection of the beam is not used directly as a measure of gravity, but it is restored to an arbitrary zero position by an auxiliary spring, the lower end of which is attached to the beam and the upper end to a micrometer dial. This means that at all stations the tension of the mainspring is constant and the difference in weight of the suspended system due to a change in gravity is balanced by the weighing spring and read on the micrometer dial.

The range of the dial is 1530 scale divisions, being the total of three scales within the main dial, each of 510 divisions. This represents a total range of 125 milligals. This range may be extended by means of a coarse adjustment screw which operates upon the mainspring of the instrument to raise or lower the beam as need be. There is no way of measuring the amount by which this screw has been turned, so it should not be moved once the instrument is set for the area of operation.

Two thermostats within the instrument keep the working parts at a temperature of 92° F. to within 0.4° F. The power supply for the thermostats and the lights for the levels and beam is a six volt car battery.

Calibration of the instrument.

The calibration factor used throughout the survey for the conversion of scale divisions to milligals was determined by the British Petroleum Company when the instrument was in their possession. The value used was 0.0837 milligals per scale division. The instrument was subsequently recalibrated in November 1959 by members of the Geology Department at Durham by the method of "looping" between Geological Survey base stations near pendulum stations at York and Newcastle giving an accurately known difference in gravity. This resulted in a calibration factor of 0.0832 milligals per scale division.

It is uncertain which calibration factor applied at the time of the survey. Use of the old factor has been retained however, as the instrument is known to have received a serious blow subsequent to the survey but before the calibration run, which may have affected the calibration factor. The maximum error involved in these uncertainties, calculated for the extreme range of readings is 0.2 milligals. The average error is considerable lower.

Operating Procedure.

The following procedure was normally followed at each station:-

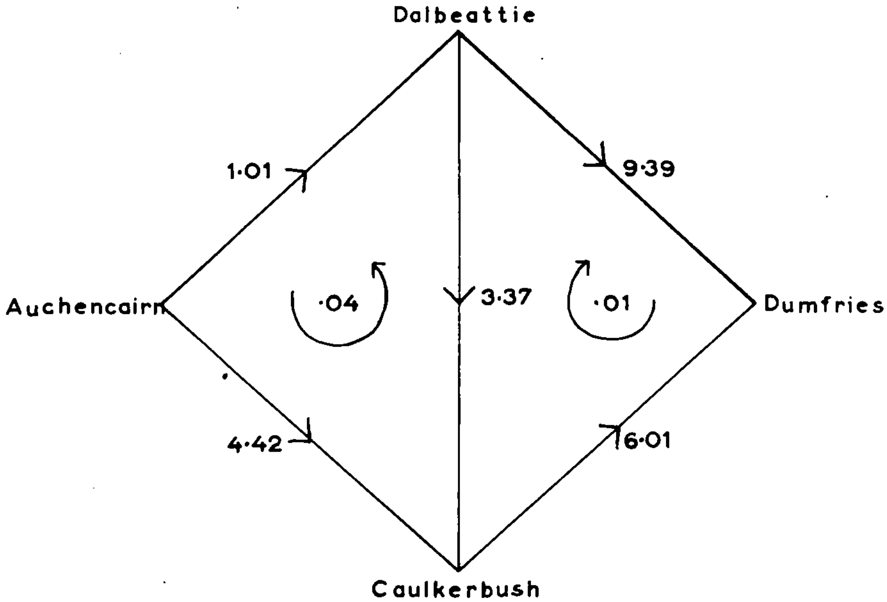
1) Roughly level the gravimeter tripod by means of a bullseye level on the top of the tripod. (It was often necessary to place pieces of slate under the feet of the tripod to stop it sinking into the soft tarmac).
2) Place the gravimeter on the tripod and level it by means of the two levelling screws.
3) Check the previous reading.
4) Unclamp the instrument gently and bring the beam to the zero point on the graduated scale (visible through a telescope mounted in the top plate) by rotating the main dial.
5) Check the levels.
6) Take the reading, correct to the first decimal place.
7) Clamp the instrument.
8) Reload the instrument into its travelling box.

3. VALUES OF GRAVITY.

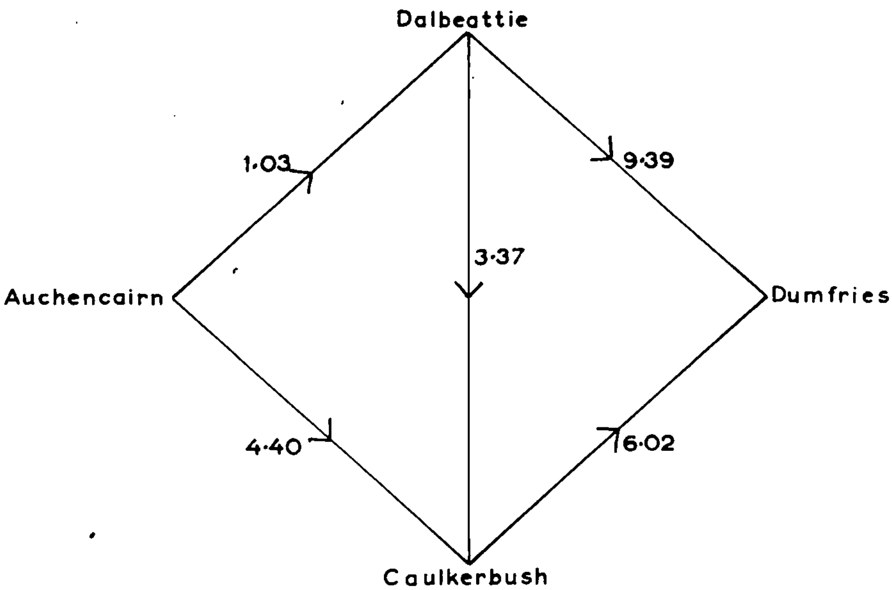
While the Frost gravimeter cannot give directly the value of gravity at a point, it is possible to link the relative values obtained to a primary base where the absolute value has previously been determined by other means. For Great Britain, the primary base normally used is at Pendulum House, Cambridge, the assumed absolute value of gravity being 981.26500 cm./sec^2. Closely linked to Cambridge is a national network of bases which can be used for local surveys. Bott and Masson-Smith (1960) used a local base at Dumfries which is connected to the Geological Survey base at Locherbie. This in turn is linked to base station 2000 at King's College Newcastle. The same reference point has been used in the present survey and so the values of gravity shown in Appendix B are all relative to base station 2000. In the reduction of the data, the latitude correction has been adjusted to give the Bouguer anomaly relative to the International Gravity Formula, assuming the value of gravity at Pendulum House to be 981.26500 cm./sec^2.

Local Bases.

In addition to the base at Dumfries, a number of local bases are also necessary to enable a check to be made on the drift of the instrument. Three such bases were set up within the area of the survey, namely at Auchencairn (station 1), Dalbeattie (station 17) and Caulkerbush (station 18). These three bases have been linked to each other and to Dumfries by



a) Closing errors



b) Corrected values

Fig. 2.1 Base Diagrams

the method of "looping" (Nettleton, 1940). Diagrams showing the closing error and the corrected values are shown in figure 2.1. Diagrams of the positions of the bases are given in Appendix A.

Intermediate Stations.

Owing to the variation with time of the instrument reading, due to slight temperature changes and loss of tension in the spring, and also gravity tidal effects, frequent visits to a base station must be made to determine the amount of drift, so that a correction can be applied to the reading obtained at intermediate stations. On average, a return to base was made once every two hours. Drift between base readings is assumed to be linear, so the amount of correction which must be applied to any intermediate station may be obtained by interpolation from a straight line graph. A typical rate of drift would be between one and two scale divisions per two-hour period.

The number of new stations which can be occupied between base readings depends on the accessibility of the area being surveyed. A normal maximum number would be of the order of twelve to fourteen stations.

A check on the accuracy of the readings, after correction for drift and conversion to milligals, may be made by repeating some stations on a later occasion. Duplicate readings at six stations revealed root mean square difference of 0.03 milligals from the original reading.

4. REDUCTIONS.

After correction of the raw data for drift and conversion to milligals there remain three reductions which must be made to obtain the Bouguer anomaly. These are as follows:

1) Latitude Correction.

The value of gravity increases from the equator to the poles by an amount which can be calculated by the International Gravity Formula. This enables tables to be constructed from which the appropriate correction for any particular latitude may be determined. The correction is usually applied as a difference between a convenient reference latitude and the latitude of the station, to avoid carrying large numbers.

The latitudes of the stations are obtainable from the six inch maps and can be read to the nearest second.

11) Elevation correction.

The corrections to gravity values which account for differences in height are made in two parts; i) the free-air correction, ii) the Bouguer correction.

The free-air correction takes care of the decrease of gravity with increasing height, considering the station to be in free-air and ignoring, for the time being, the material beneath it. Its value is calculated to be +0.09406 mgals.

per foot. (Nettleton, 1940). The correction is made to an arbitrary reference datum, in this case, mean sea level. The correction is added to the gravity value of stations above the datum level and subtracted from that of stations below.

The Bouguer correction allows for the attraction of the slab of material between the station and the reference datum. Its value is - $0.01276\,\rho h$ mgals per foot, (Nettleton, 1940) where ρ is the density of the material between the station and the reference datum (in gm/c.c.) and h is the height in feet of the station above the datum. The Bouguer correction is always opposite in sign to the free air correction. The two factors are often combined into a single constant for each density value. The density values which have been used in the reduction of the data of the survey are given in Appendix B.

111) Terrain Correction.

Terrain corrections have been applied to all the stations using the Pegasus electronic computer belonging to the University of Durham. The programme used was that developed by Bott and described by him in a recent paper. (Bott, 1959). There is no need to elaborate further upon his account.

While the computer deals with the effect of distant topography it rejects certain parts of the immediate neighbourhood of the station, whose contribution must be determined with a conventional Hammer zone chart. The contribution of zones C, D and E was estimated from the six inches to one mile maps, while that of zones F and G, where necessary, was obtained from the one inch to one mile map.

The total terrain correction was usually small and there are few instances of it rising to more than one milligal.

5) BOUGUER ANOMALIES.

The final figures for the Bouguer anomalies are given in Appendix B and shown on Map 1. (These are contained in the folder at the back of the thesis). This map has been contoured from these values and the contours have also been transferred to Map 2 to allow comparison with the geology.

The values shown on Map 1 by the open circles are taken from Bott and Masson-Smith's map (1960). During the course of the present survey, many of those stations were repeated and most of the values were found to agree to within 0.1 mgal.

6) ERRORS IN THE BOUGUER ANOMALY.

The following are the possible sources of error in the determination of the Bouguer anomalies.

1) Observational and drift errors.

These may arise through faulty levelling of the instrument, noting the scale reading wrongly and in assuming linear drift between bases. The error is minimized by checking the levels immediately before noting the reading, checking the previous reading before the dial is moved at the next station and returning to base as frequently as possible. The likely error may be indicated by repeated observations at any station. Six such repetitions were made during the course of the survey (excluding bases) and a root mean square difference of 0.03 mgals from the original reading was calculated.

11) Calibration error.

This has been discussed on page 20 where it was concluded that a maximum error of 0.2 mgal may be present between the highest and lowest gravity readings.

111) Error in latitude of a station.

Latitudes obtained from the six inch to one mile maps are accurate to within one second. An error of one second leads to an error of 0.03 mgal. for the latitude range of the area.

1V) Height errors.

An error of one foot produces an error of 0.09 mgal. (1 x 0.09406) in the free air correction and for a density of 2.65 gm./c.c., an error in the Bouguer reduction of 0.03 mgal. (0.01276 x 2.65 x 1). As these corrections are of opposite sign the effective error will be 0.06 mgal.

V) Density error.

If the density is in error by 0.01 gm./c.c. the reduction will be in error by 0.0001 mgal./foot (0.01276 x 0.01 x 1.0).

Vl) Error in terrain corrections.

Bott (1959) states that the maximum likely error in the computer method is 5%. A comparison of the computer method with the Hammer zone chart method showed an average difference of 2.5%. The maximum terrain correction encountered during the present survey is 1.5 mgal. and hence the maximum likely error is about 0.07 mgal.

The maximum random error estimated from the above figures is 0.5 mgal. Much of this is caused by the uncertainty in the calibration factor and so for the great majority of stations, which lie in the middle of the range of readings the error is considerably less.

Chapter 3. DETERMINATION OF DENSITY VALUES.

3. DETERMINATION OF DENSITY VALUES.

(a) Introduction.

A good knowledge of the densities of the rocks which have been surveyed by gravitational methods is essential for accurate correction of the gravity readings for height and terrain differences and also in the interpretation of the data once they have been reduced. A choice of three different methods is normally available for determining density values, as follows:-

(i) Measuring the value of gravity down a mine shaft at intervals of known height difference and hence calculating the density values required to produce the observed differences in gravity.

(ii) Running a "density profile" with the gravimeter, as described by Nettleton (1939). This consists of taking a closely spaced series of stations over a hill or across a valley and then reducing the gravity readings using different density values. The value which gives the smoothest profile is then taken as the actual density.

(iii) Taking samples of surface material and actually measuring their densities in the laboratory.

Of these methods, only the last, the actual measurement of specimens is feasible in this case. The first method is not possible as the only mines in the area are of the drift type, penetrating into the hillside for a short distance only. There are no vertical shafts suitable for such measurements. The density profile method too could only be carried out with difficulty owing to the lack of roads over suitable topography and also the rapid variation in density which may be expected from the geological map. The accuracy of this method is of the order of $\pm$ 0.1 gram per c.c. which is beyond the limits of tolerance of the present survey.

(b) Measurement of rock specimens.

This method consists of taking eight or nine small samples from each locality, determining the density of each and then finding the mean and standard deviation from the mean of each set of specimens. Care must be taken in the field to select specimens at random from each locality and to obtain a representative selection of each rock type exposed. The specimens must be fresh and are therefore best obtained from new roadside cuttings and quarries which are still being worked. In the Criffel area such exposures are not common, and, particularly on the porphyritic granodiorite, much weathered rock has to be broken away with a sledge hammer before the fresh rock can be reached.

Three different density values may be obtained for each specimen. These are:- (a) the dry density (b) the grain density (c) the saturated density. As the most accurate density values are required in the interpretation of the map, where masses of rock may extend downwards for several miles below the surface, the saturated density is regarded as giving the best estimate, as by far the greater part of the bulk of these masses will lie below the water table, where the rocks will be saturated. Only the saturated density was therefore measured, using the following method.

The specimens were placed in a large vacuum vessel which was then sealed and evacuated by means of a water suction pump to remove the air from the pore spaces in the rock samples. The vessel was then filled with water, without allowing air to enter and the samples left to soak for twenty-four hours. By this means it is insured that the rock will be completely saturated throughout, with no pore spaces still holding air.

After they had been allowed to soak, the specimens were removed one by one and weighed, first in water and then in air. This was carried out by the standard procedure of suspending the rock in a beaker of water resting on a bridge placed over the normal balance pan. Before weighing in air the specimen was dried lightly on a cloth to remove surplus moisture from the outside.

The saturated density of the specimen is then given by the relation:-

$$\text{Density} = \frac{\text{Weight in air}}{\text{Weight in air - weight in water}}$$

A total of 115 specimens collected from 10 different localities in the area were measured in this way and the mean density value for each locality was calculated. The standard deviation from the mean is also given as an indication of the amount of variation away from the mean which is likely to occur. It is a feature of standard deviation values for a normal distribution that 95% of all measurements at any one locality lie no further away from the mean than twice the standard deviation.

Table 1 below shows the result of these measurements.

TABLE 1. ROCK DENSITIES

Age and lithology	Location	Number of Specimens	Saturated density (gm./cc
Porphyritic Granodiorite	(b) Clawbelly Hill	11	2.64 ± 0.004
	(c) Barnbarroch Road	11	2.64 ± 0.004
Main Granodiorite	(a) Kirkgunzeon (margin)	8	2.68 ± 0.024
	(d) Kippford	9	2.70 ± 0.012
	(e) Doonside	15	2.70 ± 0.012
	(f) Sandyhills	7	2.70 ± 0.004
Intermediate Granodiorite	(g) Balcary Fishery	12	2.67 ± 0.02
Silurian shale	(i) Haugh of Urr	5	2.71 ± 0.004
Greywacke	(i) Haugh of Urr	9	2.71 ± 0.002
	(h) Dundrennan	14	2.72 ± 0.006
Porphyrite dyke in Silurian greywacke	(j) Sheillahill	12	2.70 ± 0.024

Similar measurements were made by Bott and Masson-Smith (1960) and some of these results have been used to supplement my measurements. The values used are given in Table 2 below

TABLE 2. ROCK DENSITIES (after Bott & Masson-Smith 1960)

Age and lithology	Location	Number of specimens	Saturated density (gm/cc.)
Porphyritic granodiorite	l") Glensome k") Craignair (margin)	13 12	2.654 ± 0.011 2.662 ± 0.004
Main granodiorite	m") Loch Kindair	15	2.697 ± 0.008
Silurian shale	5 localities in the Southern Uplands	27	2.714 ± 0.049
greywacke	7 localities in the Southern Uplands	63	2.706 ± 0.055
Carboniferous sandstone			2.60
New Red Sandstone	Locharbrigg's Quarry		
	i) At surface	11	2.25 ± 0.05
	ii) At 200 ft.depth	22	2.33 ± 0.04

These values have been plotted on map 2.

It is important to note the rise in density from the porphyritic centre of the Criffel mass outwards across the main granodiorite to the contact. The values obtained from localities b,c and l" probably give the best estimate of the actual density of the porphyritic granodiorite. Specimens from locality k", measured by Bott and Masson-Smith have a slightly higher density, probably owing to the marginal position of the locality.

Specimens from four localities within the main granodiorite have been measured, d, e and f by me and m" by Bott and Masson-Smith. All four localities have an average value of 2.70 gm./cc. This is sufficient to indicate that this outer part of the complex is consistently denser than the inner porphyritic part, although specimens from more localities would be useful to establish more exactly the details of the change.

While the density change between granite and country rocks is likely to be gradational over the south-eastern part of the area, it is noticeably more abrupt over the north-western margin, where the main granodiorite is absent and the porphyritic granodiorite rests directly in contact with the Silurian.

Specimens were difficult to obtain from the intermediate granodiorite, owing to its poor exposure, but measurements from one locality on the coast at Balcary showed a density of 2.67 gram./cc. a value which is comparable to that of part of the main granodiorite.

Specimens were collected from two localities in the Silurian country rock and gave values of 2.71 gm./cc. and 2.72 gm./cc. At one locality (i) the rock consists of interbedded greywackes and shales. Specimens of each rock type were measured and both were found to have the value of 2.71 gm./cc. These figures agree closely with those obtained by Bott and Masson-Smith from determinations of samples collected from a large number of localities throughout the Southern Uplands.

In the area of locality j the Silurian greywackes and the porphyrite dykes appear to be present in roughly equal proportions. At locality j, therefore an equal number of specimens of greywacke and of dyke rock were taken and an overall average was calculated.

The assumed density values for the Lower Carboniferous sandstones and the Permian sandstones are taken from Bott and Masson-Smith's paper (1960).

During the earlier part of the calculations, before the above values were available, provisional figures were used in the reductions from the observed anomaly to the Bouguer anomaly. These are as follows:-

Granodiorite	2.65 gm./cc.	Carboniferous	2.60 gm./cc.
Silurian	2.73 gm./cc.	Permian	2.33 gm./cc.

The differences between these figures and those given in the tables are, however, unlikely to cause errors beyond a fraction of a milligal to the Bouguer anomaly values.

Chapter 4. METHODS OF INTERPRETATION.

4. METHODS OF INTERPRETATION.

(1) Introduction.

Gravity data by itself can never give a completely unambiguous geological interpretation. When combined with other lines of evidence, however, such as that obtained by other geophysical methods, or the evidence of surface and mine geology, it is frequently possible to decide which of several different interpretations is the most feasible. In the case of the Criffel mass, good geological maps are available which show such features as variation of rock type and hence possibly of density within the granite; the nature of the contact; and the extent of the contact aureole in the country rock around the granite. All these lines of evidence may be allied to the purely physical interpretation to produce a likely geological situation.

(2) General Methods.

Before a detailed quantitative interpretation is attempted it is useful to obtain a general picture of the type of feature causing an anomaly by the application of certain general methods.

One of the most important factors to be determined is the maximum depth to the top surface of the source of the anomaly. This will show whether the anomaly is caused by a deep-seated structure somewhere within or at the base of the crust, or whether it is of shallower origin, in which case variation in the surface geology may be responsible.

Several formulae are now available for the calculation, of which the most satisfactory is probably that given by Smith (1959 theorum 3) as follows:-

$$d \leqslant \frac{29.0 \quad x \rho_{max}}{A''} \quad . . . . (4.1)$$

where d is the maximum depth to the top of the source of the anomaly (in miles); ρ_{max} is the maximum likely density contrast; A" is the maximum rate of change of horizontal gravity gradient. This formula has the advantage that it does not need to take into account the background value, as did most of the previously available formulae.

An approximate value for the depth to the base of the feature causing the anomaly may also be obtained by the use of standard formulae. In the case of the main Criffel mass, the nearest approximation to the likely shape of the granite is that of a vertical cylinder, the formula for which is given by Heiland (1940 p.147). From this the formula for the anomaly at a point on the axis of the cylinder and on its top surface is given by

$$A = 2\pi G \rho \left[z + r - (z^2 + r^2)^{\frac{1}{2}} \right] . . . . . . (4.ii)$$

where A is the anomaly in gals, G is the gravitational constant, ρ is the density contrast in gm. per c.c. z is the thickness of the cylinder in centimetres and r is the radius of the cylinder in centimetres.

It must be emphasized that the use of this formula only gives an approximate depth to the base of the anomalous mass. It is, nevertheless, useful as a basis for further calculation.

(3) The use of models.

The methods described above give a few basic features of the source of the anomaly but give no real indication of the shape of the anomalous mass or of other characteristics such as variation of density within it. A further step in interpretation, therefore, would be to try to fit the observed anomaly to a detailed model of the sub-surface structure.

The gravity anomaly itself cannot be used directly to work back to an exact model of the structure which causes it. It is, however, possible to work the other way round i.e. to build up a likely model, calculate the anomaly which it would cause and compare this with the actual, observed anomaly. By a process of trial and error, the model is altered until the calculated anomaly matches the observed anomaly. This in itself will still not give a unique representation of the anomalous mass and there may be several alternative models, all of which fit the observed anomaly. It is, however, frequently possible to combine independent geophysical or, as in this case, geological evidence with the models to decide which is the most feasible.

(4) Computer methods.

The actual calculation of the anomalies produced by the various models is normally a tedious process, involving the calculation of the anomaly at each of a number of arbitrary "stations", usually by some visual method, such as a graticule. Recently, however, programmes have been devised which enable the calculations to be done by electronic computer, thus saving much laborious and time-consuming numerical work.

(a) Two-dimensional models.

The simplest method of interpretation by computer is to draw up a scaled model in two dimensions, regarding the third dimension as infinite. The model will thus represent a cross-sectional profile of the anomalous body.

The programme for the Ferranti Pegasus computer used throughout these calculations has been devised by Dr.Bott, using a similar principle to that described by Talwani and others (1959). The principle upon which the computer programme is based is as follows:-

Consider the general case of a body of polygonal cross

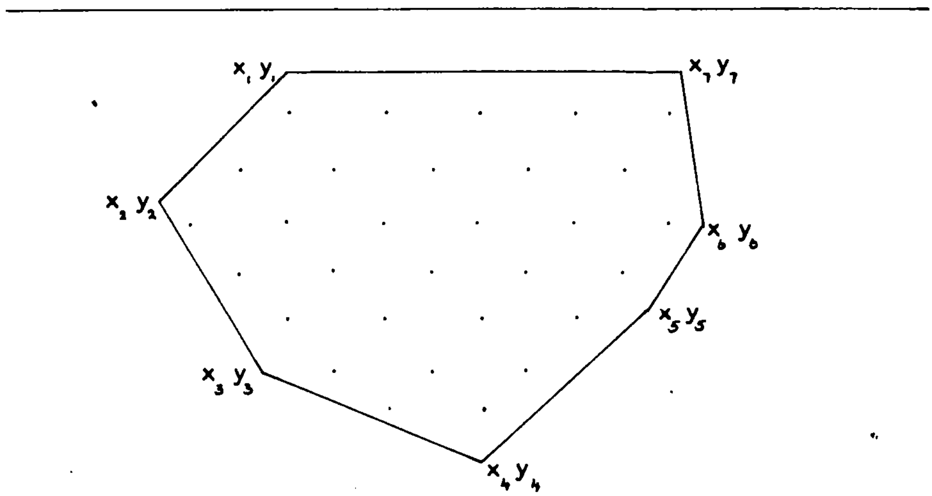


Fig. 4.1 Two dimensional model, general case

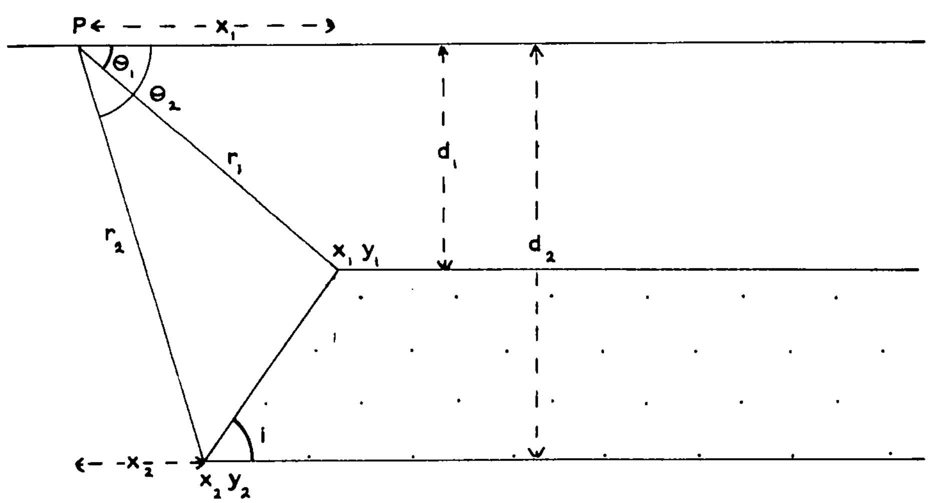


Fig. 4.2 Gravity effect of a slope at a point P

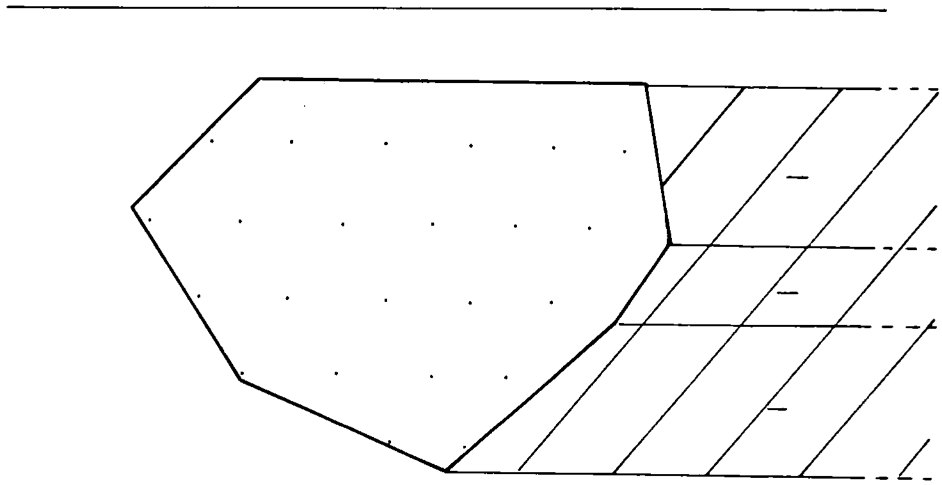


Fig. 4.3a General model showing semi-infinite slabs based upon right-hand sides of the polygon

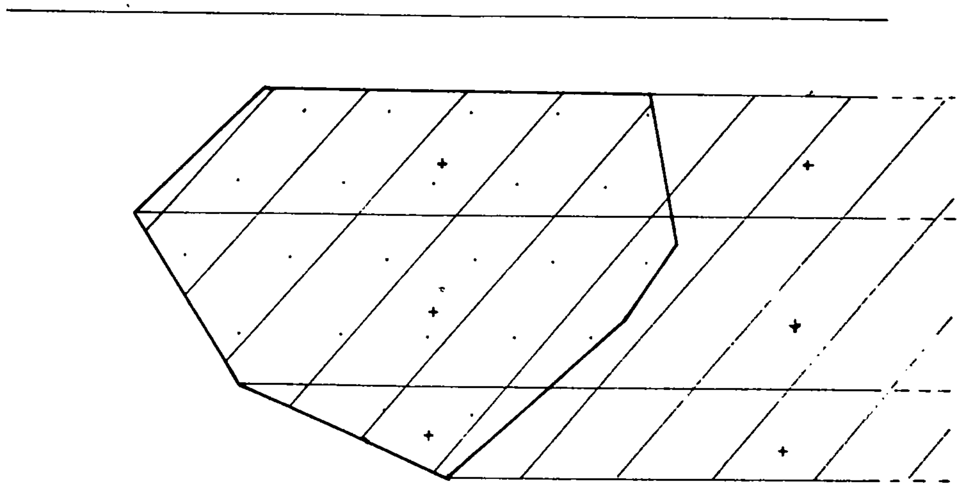


Fig. 4.3b General model showing semi-infinite slabs based upon left-hand sides of the polygon

section lying at a depth below ground level. (Fig.4.1). The extent of the body in the third dimension (i.e. at right angles to the paper) is assumed to be infinite. Now, the gravity effect of such an irregular shaped body cannot be calculated as it stands - the body must first be broken down into a series of standard shapes, for which a formula can be devised. In this case, the body is divided into a number of horizontal semi infinite slabs, the finite sloping ends of which form the sides of the polygon. (Fig.4.3).

Heiland (1940 p.153 equation 7-43b) gives a suitable equation for the calculation of the gravity effect at any external point of such a sloping ended slab. This is as follows:

$$\delta A = 2\,G\rho\left[d_2\Theta_2 - d_1\Theta_1 - (x_1 \sin i + d_1 \cos i)\left\{\sin i \log \frac{r_2}{r_1} + \cos i(\Theta_2 - \Theta_1)\right\}\right] \quad \text{.........(4.iii)}$$

where δA is the anomaly due to the semi-infinite slab, G is the gravitational constant and ρ is the density contrast. (see Fig 4.2 for explanation of the other symbols).

This formula is used upon each of the slabs in turn to determine the contribution of each one to the anomaly.

Now some of the slabs extend to infinity from the right hand side of the body (Fig.4.3a) while the rest are terminated by the edges on the left hand side (see Fig.4.3b). If, therefore, the effects of the slabs on the right are subtracted

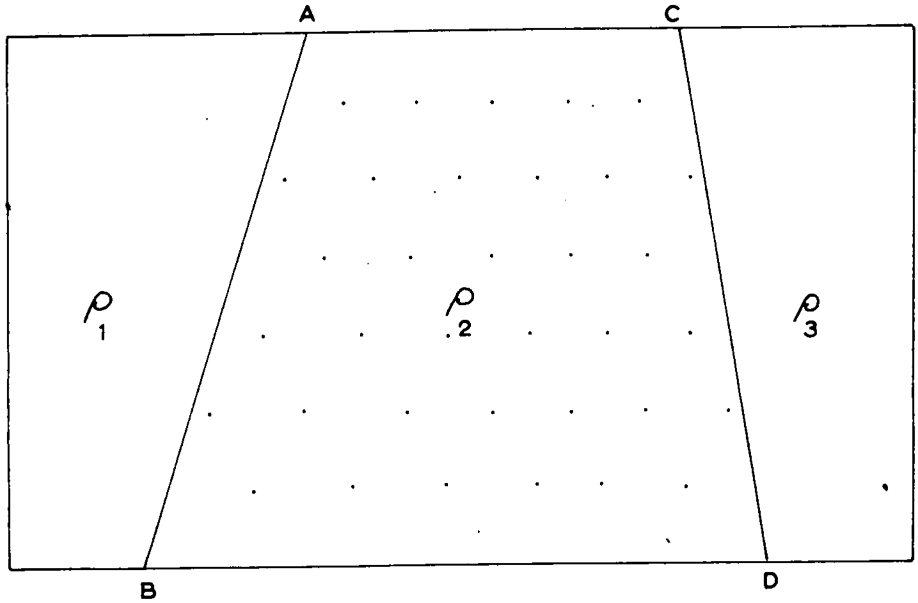


Fig. 4.4 Special case : single density contrast

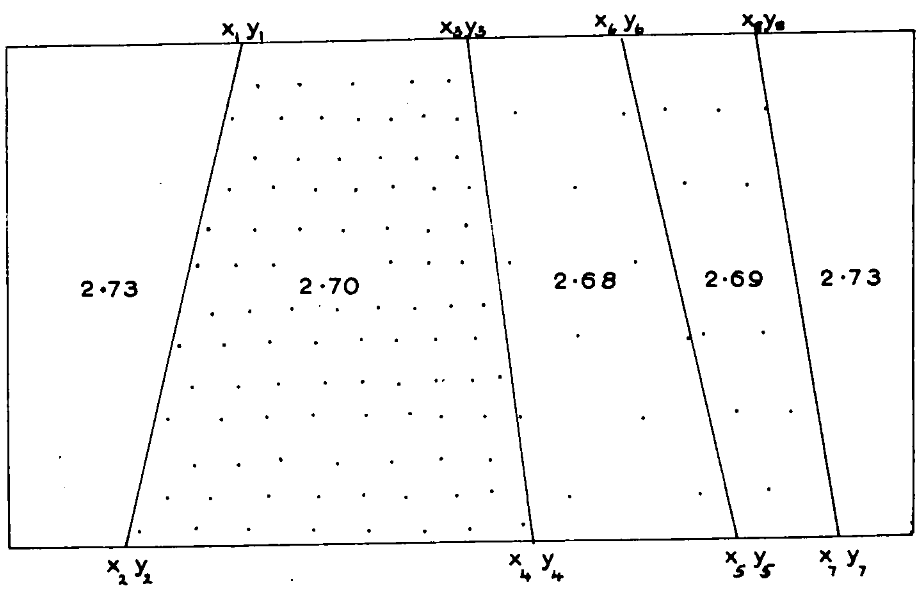


Fig. 4.5 Special case : multiple density contrast

from those on the left, the result will represent the gravity value due to the body itself.

This whole process is repeated to calculate the gravity effect at as many external points as may be necessary to build up a detailed picture of the anomaly across the whole model.

In practice, the sides of the polygon and the positions of the "stations" at which the gravity anomaly is to be calculated are defined on a rectangular co-ordinate system. Two data tapes are prepared, one bearing the "station" details, the other the co-ordinates of the sides of the polygon and the density contrasts. These are fed into the computer after the programme tape and the necessary sub-routines, and the gravity effect of each side of the body upon each station is calculated and stored. When all the sides have been processed, the total effect at each station is computed as described above and the results are printed. They may then be plotted on graph paper and compared with the observed anomaly along the same line of profile. If necessary, adjustments may then be made to the model, the gravity effect of which is recalculated until it fits the observed anomaly.

In much of the intepretation of the Criffel anomalies, it has been found that the polygon of the general case may be modified to a shape similar to that shown in figure 4.4. where the rocks of different density are separated by straight lines for the whole of the depth of the body. In this case the same general programme computes the effect of each slope in turn, starting at the left side of the model and working across. Thus at first it computes the effect of a horizontal slab extending from AB to infinity and of density contrast $\rho_2 - \rho_1$. Similarly, the effect of a slab terminated by CD is calculated using the density contrast between this and the previous slab, i.e. $\rho_3 - \rho_2$. If the density of a slab is greater than that lying to the left of it then its contribution is added to the total anomaly; if the density of the right hand slab is less than that on the left its contribution is subtracted e.g. if in figure 4.4. ρ_2 is less than ρ_1 and ρ_3, the contribution of the slope AB is negative while that of CD is positive. The process is repeated for every "station" until the anomaly across the model has been calculated.

The same programme may be used to calculate the gravity effect of a body with any number of varying densities, as in figure 4.5.

The contribution of each slab is allowed for in the data tape as follows:- if the density to the right of a slope is greater than that to the left, the co-ordinates of the lower end of the slope are given before those of the upper end. If the density to the left of the line is the higher, the upper co-ordinates are given first. In figure 4.5 the suffixes of the co-ordinates indicate the order in which they would be fed

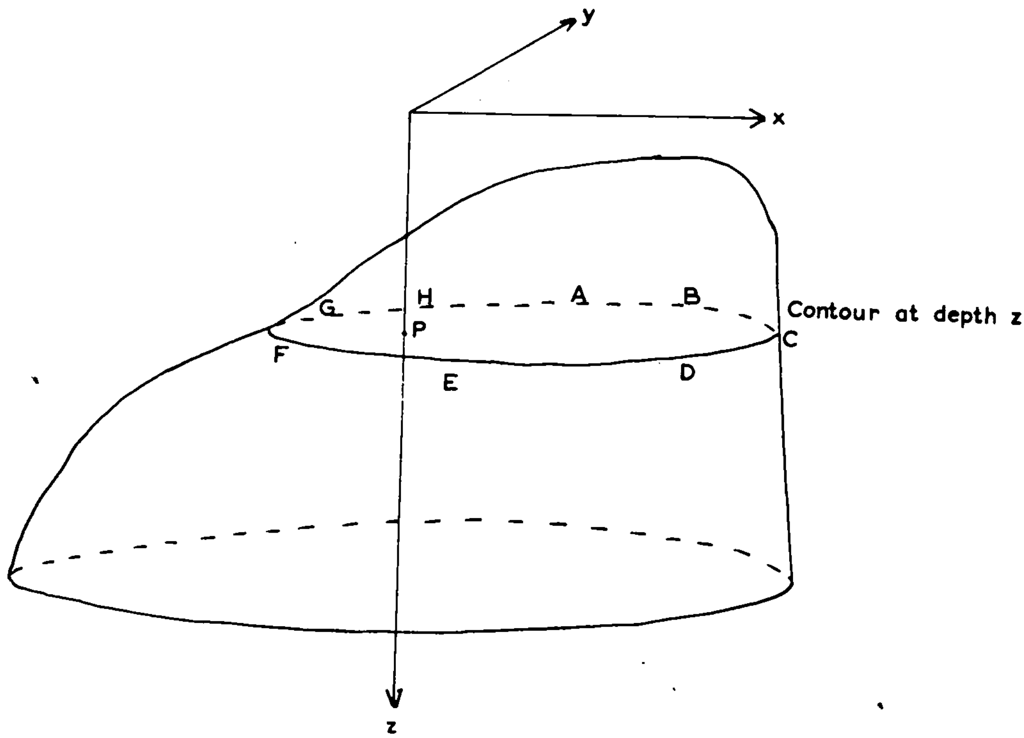


Fig. 4.6 Three dimensional model : general case

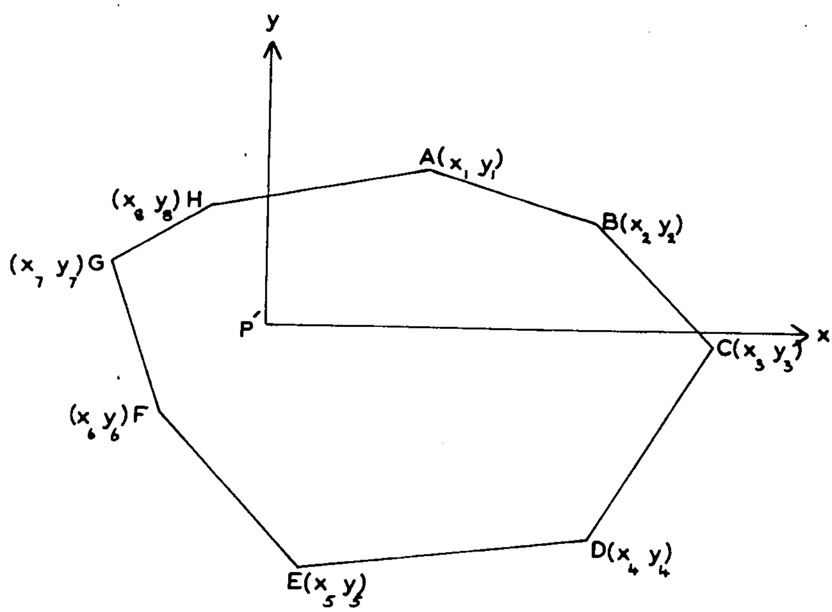


Fig. 4.7 Plan of polygonal replacement of contour in fig.4.6

in, for the kind of variation in density values shown.

Throughout this discussion of the calculation of the gravity effect of a two-dimensional cross-section of a body, it has been assumed that the body is of infinite extent in the third dimension (i.e. at right angles to the paper in the above diagrams). Where the length of the body is many times as great as the width and depth this assumption is justified. In the case of the Criffel mass, however, the length is only twice the width and hence the two-dimensional profile will be in error by a quite significant amount. This error is commonly termed the "end effect".

(b) Three-dimensional models.

In order to compensate for the "end effect", computer methods have now been devised to calculate the gravity effect of a three-dimensional anomalous body. A published account of such a method is given by Ewing and Talwani (1960). A similar procedure has been used by Dr.Bott to develop a programme for use in the Pegasus computer.

The principle upon which the computer programme is based is as follows:- The outline of the three-dimensional body is first represented by contours spaced at a convenient vertical interval (Fig.4.6). Each contour is then replaced by a horizontal n-sided polygon, the number of sides depending upon the accuracy with which it is required to fit the line of the

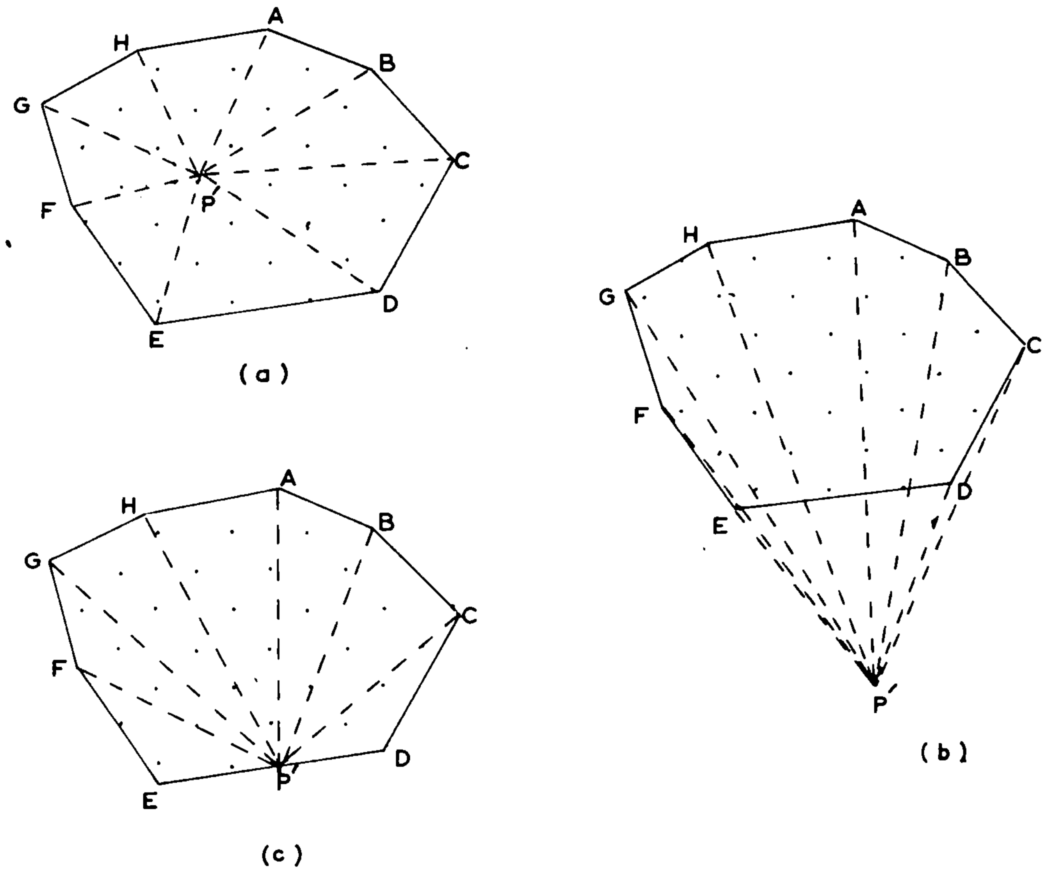


Fig. 4.8 Possible positions of the projection of point P in the plane of the polygon

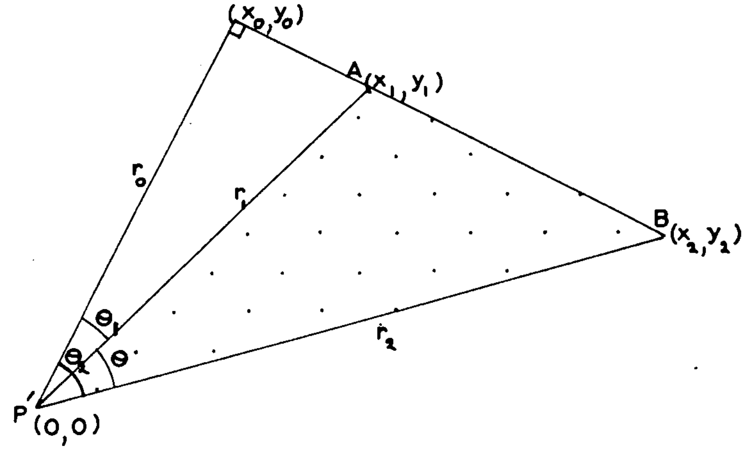


Fig. 4.9 Gravity effect of a triangular lamina

contour. (Fig.4.7). The body is thus now represented by a series of horizontal polygonal laminae spaced at intervals throughout its depth. The gravity effect of the whole body at any external point may then be determined by finding the effect of each lamina and integrating the results from the bottom to the top of the body.

As it stands, however, the gravity effect of each lamina cannot be determined directly: it must first be split into a series of standard forms, the effects of which may be calculated by use of a standard formula and then added together to give the effect of the whole lamina. In this case the lamina is considered to be divided into a number of triangles, each being based on a side of the polygon and having as its apex the projection in the plane of the lamina of the point at which the anomaly is being calculated. The three parts of figure 4.8 show the three possible types of situation where this point P' may fall:- (a) where the projection of the station falls within the polygon; (b) where it lies outside the polygon; (c) where it lies on one of the sides of the polygon.

Now the gravity effect at an external point of a triangular lamina is given by the formula:-

$$\delta A = G\rho t \int_{\theta_1}^{\theta_2} \left\{ 1 - \frac{z}{\sqrt{z^2 + r_o^2}} \right\} d\theta \quad \ldots\ldots\ldots \text{(4.iv)}$$

where δA is the gravity effect; G is the gravitational constant; ρ is the density contrast; t is the thickness of the lamina and z is the depth to the lamina. (See Fig.4.9 for an explanation of the other symbols used).

Integrating formula 4.iv.

$$\delta A = G\rho t \left\{ (\theta_2 - \theta_1) - \left[\sin^{-1} \frac{\sin\theta}{\sqrt{1 + \frac{z^2}{r^2}}} \right]_{\theta_1}^{\theta_2} \right\}$$

Hence

$$\delta A = G\rho t \left\{ \theta - \left[\sin^{-1} \frac{\sin\theta}{\sqrt{1 + \frac{z^2}{r^2}}} \right]_{\theta_1}^{\theta_2} \right\} \ldots\ldots\ldots\ldots\ldots (4.v)$$

In figure 4.9 the only details of the dimensions of the triangle which can be fed into the computer directly are the co-ordinates of the side of the polygon (x_1, y_1) and (x_2, y_2) and the co-ordinates of the projection P' of the "station", taken as (0,0) in the figures. In order to calculate the gravity effect of the triangle, however, the values of $\sin\theta_1$, $\sin\theta_2$, and r_o must first be found from the above data. The principle of the calculation is as follows:

Drop a perpendicular from the point (x_o, y_o) on the side AB to the point P' . Now, from the theory of similar triangles,

$$\frac{y_o - y_1}{x_o - x_1} = \frac{y_2 - y_1}{x_2 - x_1}$$

Therefore $$\frac{y_o - y_1}{y_2 - y_1} = \frac{x_o - x_1}{x_2 - x_1}$$

Therefore $$Y_o = \left\{\frac{y_2 - y_1}{x_2 - x_1}\right\} X_o + \left\{\frac{y_1 x_2 - y_2 x_1}{x_2 - x_1}\right\}$$

The equation is thus now in the form $mx + c$, the general equation for a straight line.

Now, the perpendicular from the origin to such a line has the general equation $y = -\frac{1}{m} x$.

It meets the line AB at (x_o, y_o)

Solving simultaneously the equations $y_o = -\frac{1}{m} x_o$

and $y_o = mx_o + c$

we obtain $c = (1 + m^2) y_o$

Therefore $y_o = \dfrac{c}{1 + m^2}$

and $x_o = \dfrac{-mc}{(1 + m)^2}$

and $r_o^2 = x_o^2 + y_o^2 = \dfrac{c^2}{1 + m^2}$

Substituting for m and c

$$y_o = \frac{(y_1 x_2 - y_2 x_1)(x_2 - x_1)}{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

$$x_o = \frac{-(y_1 x_2 - y_2 x_1)(y_2 - y_1)}{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

$$r_o^2 = \frac{(y_1 x_2 - y_2 x_1)^2}{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

Incorporating this schedule into the programme, then, enables the computer to evaluate x_o, y_o and hence r_o. By simple trigonometry on the right angled triangle the values of sin θ_1 and sin θ_2 may then be obtained. All the necessary data are thus available in a form which may be substituted by the computer into formula 4.v, from which the gravity effect of the triangle ABP$'$ may be calculated.

In order to obtain the gravity effect of the whole polygon the total effect of all the triangles must now be computed.

Whether any one triangle is added to or subtracted from the total depends upon the position of the point P$'$. Thus in figure 4.8a the point lies inside the polygon. Taking each of the sides of the polygon in turn, in order of clockwise rotation, it is evident that the effect of each triangle must be added to the total in order to account for the whole polygon. It is noticeable, too, that the total angle subtended at the centre by the addition of each triangle is always increasing, until it finally reaches 2 π radians on completion of the whole polygon.

In figure 4.8b, however, starting at the top of the polygon and taking each side in order of clockwise rotation as before, we see that although the effects of the triangles based on the top sides must be added, those of the lower sides must be subtracted from the total. Examination of the behaviour of the total angle subtended at P' shows that the addition of each positive side involves a progressive increase in a clockwise direction, while the subtraction of the effects of the negative sides involves a swinging back of the angle so that it increases in an anti-clockwise direction. By the time every side of the polygon has been considered, the total angle subtended at P' will have swung out to a maximum and back again, resulting in a total coverage of zero.

It now becomes possible to formulate a rule for the addition or subtration of the effect of any side, as follows:- If on going from one side of the polygon to the next, in order of clockwise rotation, the angle subtended at P' is increased in a clockwise direction, then the effect of the new side must be added to the total. If the angle increases in an anti-clockwise direction, the effect of the new side must be subtracted.

Consideration of the co-ordinate geometry of Fig.4.9 shows that rotation is clockwise and therefore regarded as positive if $y_1 x_2 - y_2 x_1$ is greater than zero. Rotation is anti-clockwise and therefore negative, if $y_1 x_2 - y_2 x_1$ is less than zero.

This means that the computer may now be supplied with a method for determining whether to add or subtract the effect of each triangle to produce the total effect due to the whole polygonal lamina.

Having calculated the effect of the first lamina, details of the next one are brought into the computing store and the whole process repeated until the effect of each lamina has been obtained. The total effect of the whole body is then found by summing the effects of all the laminae between the bottom and top limits of the body. The complete procedure is then repeated for as many different "stations" as may be required.

In the present case, the amount of calculation which can be performed is restricted by the availability of the electronic computer. It has therefore been found more practicable to concentrate on obtaining a few accurate lines of profile across the area rather than to attempt an even network of "stations" over the whole map. This means that certain simplifications may be made to the data, all of which help to save computer time.

In the case of the main Criffel anomaly, the main consideration is to produce a profile across the three dimensional body along the same line as that used in the

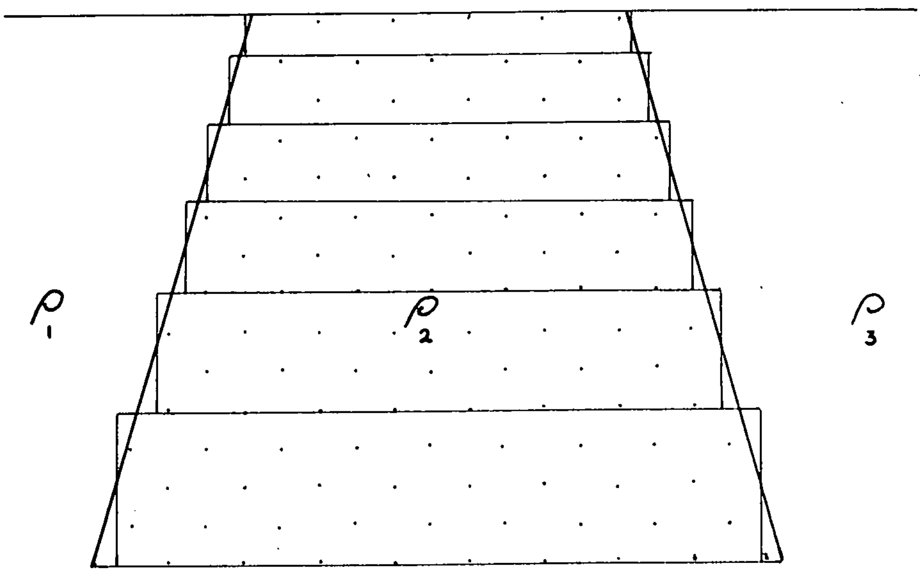


Fig. 4.10 Cross section of three dimensional model

two dimensional work i.e. approximately across the centre of the mass. Accurate contouring of the extreme ends of the body is therefore unimportant as the ends are sufficiently distant from the line of profile for minor variations to be of negligible influence. The broad oval shape of the main granodiorite renders it readily replaceable by laminae of simple rectangular plan, which enables the working out of co-ordinates and the computer calculation itself to be carried out considerably more quickly than if a more complex polygon were being used.

In place of the intricate contouring system of Ewing and Talwani (1960) the body is divided into a number of horizontal slabs, the greater the number of slabs the greater being the accuracy, especially near the surface (Fig.4.10). The anomaly of each slab is calculated by computing (as detailed above) the effect of a central lamina at which the mass of the slab is assumed to be concentrated. The total anomaly is then obtained by adding the effects of all the laminae. The whole process is then repeated for as many other "stations" as may be required.

Again two data tapes are prepared, the first containing details of the shape which is being tested. For each slab are given; the density contrast between it and the adjoining slabs; the depth from the surface to the central lamina of the slab; the thickness, and the x and y co-ordinates of its ends.

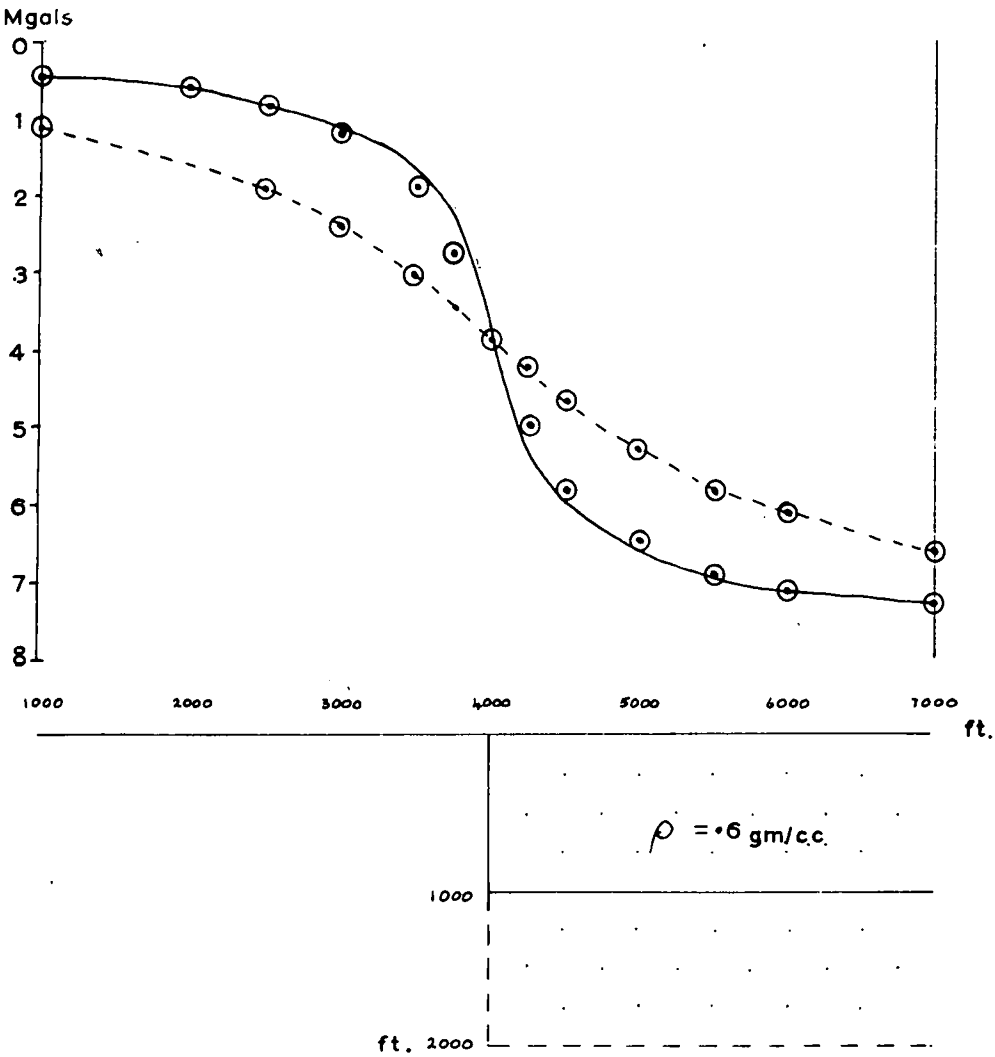


Fig. 4.11 Error of the three dimensional method

The second tape contains the x, y and z (height) co-ordinates of the "station" at which the anomaly is being calculated. The z co-ordinate is taken as zero throughout, i.e. mean sea level, to conform to the reductions of the observed field data.

Error of the three dimensional method.

An estimate of the error involved in approximating the slab to a central lamina has been made with the use of the two dimensional programme. The result is shown in figure 4.11. In this figure, the solid line represents the anomaly for the semi-infinite slab, outlined in solid lines, calculated by the two dimensional computer programme. The dashed curve represents the anomaly for the lower semi-infinite slab, outlined by dashed lines. The dots are the values calculated by hand for the two semi-infinite central laminae.

The correspondence for the lower slab is, at worst, only 1.5% in error. For the upper slab, however, there is a divergence of up to 14% for the station close to the contact between the two different densities. For this reason, the near surface slabs in the three dimensional model must be made as thin as practicable. Throughout the interpretation of the Criffel anomaly, the uppermost slab of the three dimensional models has been taken as 1000 metres thick, involving a maximum error of 0.3 mgal. This is of the same order as the allowable discrepency between the observed and calculated anomalies and is therefore permissible.

Chapter 5. DESCRIPTION OF ANOMALIES.

5. DESCRIPTION OF ANOMALIES.

The gravity contour maps for the Criffel area are shown in Maps 1 and 2. Map 1 shows the distribution and gravity values of the stations, from which it may be seen that the interval between stations is sufficiently close to allow quite accurate contours to be plotted. These are adequate for a general regional interpretation and also for more detailed investigation of certain portions of the map. Map 2 shows the relationship between the geology of the area and the gravity contours.

In the description of the gravity field of any region, it is customary to choose a background value, against which significant variations in the field may be compared. In this case, the steadiest values are found over the Silurian country rocks. These occur over a very wide area and may be considered as the normal, regional rock type, into which local variations have been introduced, as for example, by the Criffel complex itself and by the Permian trough around Dumfries. For these reasons the values of the Bouguer anomaly over the Silurian rocks have been taken as the background. There are gradual, yet distinct, regional changes in this background, but it is quite possible to take these into account for each part of the complex when calculations of depth, etc., are being made.

The undisturbed background value over most of the area is in the region of 15 or 16 milligals, but this rises steadily to a maximum of 27 milligals to the south of Kirkcudbright.

The main anomalies superimposed upon this background are as follows:-

(1) The negative anomaly over the main granodiorite.

There is a very pronounced negative anomaly over much of the Criffel mass, the gravity contours corresponding very well with the oval shape of the outcrop. Like the outcrop they trend north-east - south-west. The lowest measured value is - 0.9 milligal, but the actual minimum, lying over an inaccessible part of the granite may be as low as - 2 milligals. This represents a drop of some 15 milligals below the background value. The lowest part of the anomaly is not centrally located, as is usually the case with granites, but is displaced a matter of 1½ miles to the north-west of the geometrical centre of the pluton where the granite is of the porphyritic variety.

The spacing between contours is also of considerable interest. On the north-western side of the mass, over the granite itself, the gradient is shallow, being about 2 milligals per mile. Once the contact is reached, however, it shows a sudden increase to an average value over the nearby country rock of nearly 5 milligals per mile - a value which is quite consistent along most of this north-western boundary.

On the other hand, the gradient over the south-eastern margin is remarkably steady, the value being about 3.5 milligals per mile for at least two miles on either side of the contact of the granite with the Silurian.

The generally oval shaped anomaly is modified slightly on this south-eastern side by a sudden local decrease in gradient in the region of Caulkerbush, where the value drops from 3.5 milligals per mile to 1 milligal per mile and then gradually resumes its former value.

(2) The negative anomaly over the Permian sandstones of Dumfries.

This large negative anomaly, occupying the north-eastern part of the map, reaches a minimum value of + 2 milligals i.e. 14 milligals below the background. The anomaly is linear and trends N.N.W - S.S.E., cutting almost at right angles across the north-eastern end of the Criffel anomaly and locally modifying the latter. Bott and Masson-Smith (1960) have demonstrated that this negative anomaly is caused by a great thickness of Permian sandstones and breccias, with whose surface outcrop the anomaly corresponds. As the present survey does not cover this area, however, this anomaly will not be examined further.

(3) The north-westerly decrease in anomaly.

Going to the north west, away from the main mass of the

Criffel granodiorite itself, the anomaly rises steadily to the background value of around 15 or 16 milligals. This remains constant for a distance of two or three miles but then starts to fall away uniformly to the north west at a rate of about 2 milligals per mile. A minimum value of + 10.6 milligals was recorded, but it is likely that progressively lower values would be found were the survey to be extended further to the north west.

This decrease does not correspond to any immediate surface feature, the rock being a uniform sequence of Silurian shales and greywackes. A small inlier of Ordovician age is present to the north of Castle Douglas, but the rock type is similar to the Silurian and it has no appreciable effect upon the gravity field.

A wide ridge of positive anomalies runs north eastwards from Kirkcudbright, in effect separating the negative anomaly of Criffel from that of the north-west corner of the map.

(4) Regional increase of background anomaly to the south.

Gravity measurements to the immediate south of the Criffel granite obviously cannot be extended as far over the country rock as on the north side, on account of the sea. There are, however, sufficient stations to show that a steady background is not reached but that the gravity values are still climbing. At Southerness Point (the furthest point away from the granite on its south-eastern side) a value of 18.1 milligals was recorded. It is only here, at the most outlying part of the coast, that the gradient begins to slacken off from about 3 milligals per mile to 0.5 milligals per mile, this latter being measured between the last two stations on the point itself. It is therefore likely that the anomaly reaches a value of + 20 milligals or even higher a short way out into the Solway Firth.

To the south-west of the Criffel mass, in the Kirkcudbright region, the Bouguer anomaly reaches a maximum of 27.1 milligals. Again, a steady background is not reached, although the gradient does decrease from 2 milligals per mile east of Kirkcudbright to 0.5 milligals per mile on the coast. From the general trend of the contours it would seem that they may possibly close within a short distance of the coast.

None of these increases can be explained by comparison with the known geology, as the rocks here consist of shales and greywackes of very uniform density.

(5) The anomalies of the Auchencairn district.

The anomalies over this south-western part of the granite complex are difficult to correlate with the geology.

The main features are, firstly, a small positive anomaly of about one milligal over Orchardton Bay to the north-east of Auchencairn and, secondly, the presence of a steep gradient over the southern part of the intermediate granodiorite.

CHAPTER 6. INTERPRETATION OF THE GRAVITY ANOMALIES.

6. INTERPRETATION OF THE GRAVITY ANOMALIES.

In this chapter an interpretation is given of the features shown on Maps 1 and 2 and described in the previous chapter. The anomalies are treated in practically the same order as described, using the methods discussed in chapter 4. The interpretation is approached in three stages:
1) from a purely physical viewpoint, to determine the type of crustal feature causing the anomaly. 2) interpretation of the gravity field in relation to the surface geology.
3) assuming the cause of the anomaly, a detailed study of the shape is made using models.

1) The negative anomaly over the main granodiorite.

a) Physical interpretation.

The most important feature of the anomaly is that it is negative relative to the background. This means that there is an underlying mass deficiency, caused by a body of less dense rock than the surroundings.

The gravity field over the granodiorite is of broad oval outline over a wide area, showing little local variation away from this generally smooth regional pattern. It may, therefore, be assumed that the feature which causes the anomaly is itself of large dimensions and probably of regular outline.

The existence of rapid changes in the horizontal gravity gradients shows that the source of the anomaly cannot lie very deep in the crust. These changes can, in fact, be utilized to give a maximum figure for the depth to the top of the mass deficiency, using equation 4 i (p.37)

$$d \leqslant \frac{29.0 \times \rho_{max}}{A''}$$

The value of A'', measured from Map 1, is eleven mgal. per mile per mile. ρ_{max} is assumed to be 0.5 gm/c.c., the maximum likely density contrast in the crust. This gives a result of about 1.3 miles, demonstrating that the upper surface of the mass deficiency lies within the topmost part of the crust.

b) Comparison with the geology.

The gravity anomaly shows a close correlation with the outcrop of the Criffel granodiorite. Since the anomaly has been shown to be of shallow origin, it would therefore seem that the granite itself is the cause.

Granites in many other areas (Bott 1956) are known to show similar negative anomalies. Furthermore, measurements on density specimens from the Criffel granodiorite have shown that the granite is less dense than the country rock, on average by about 0.06 gm/c.c.

Other features which might possibly cause such an anomaly, such as a trough of light sediments or a salt dome structure may be ruled out on the basis of an unsuitable tectonic environment and the lack of any geological indication

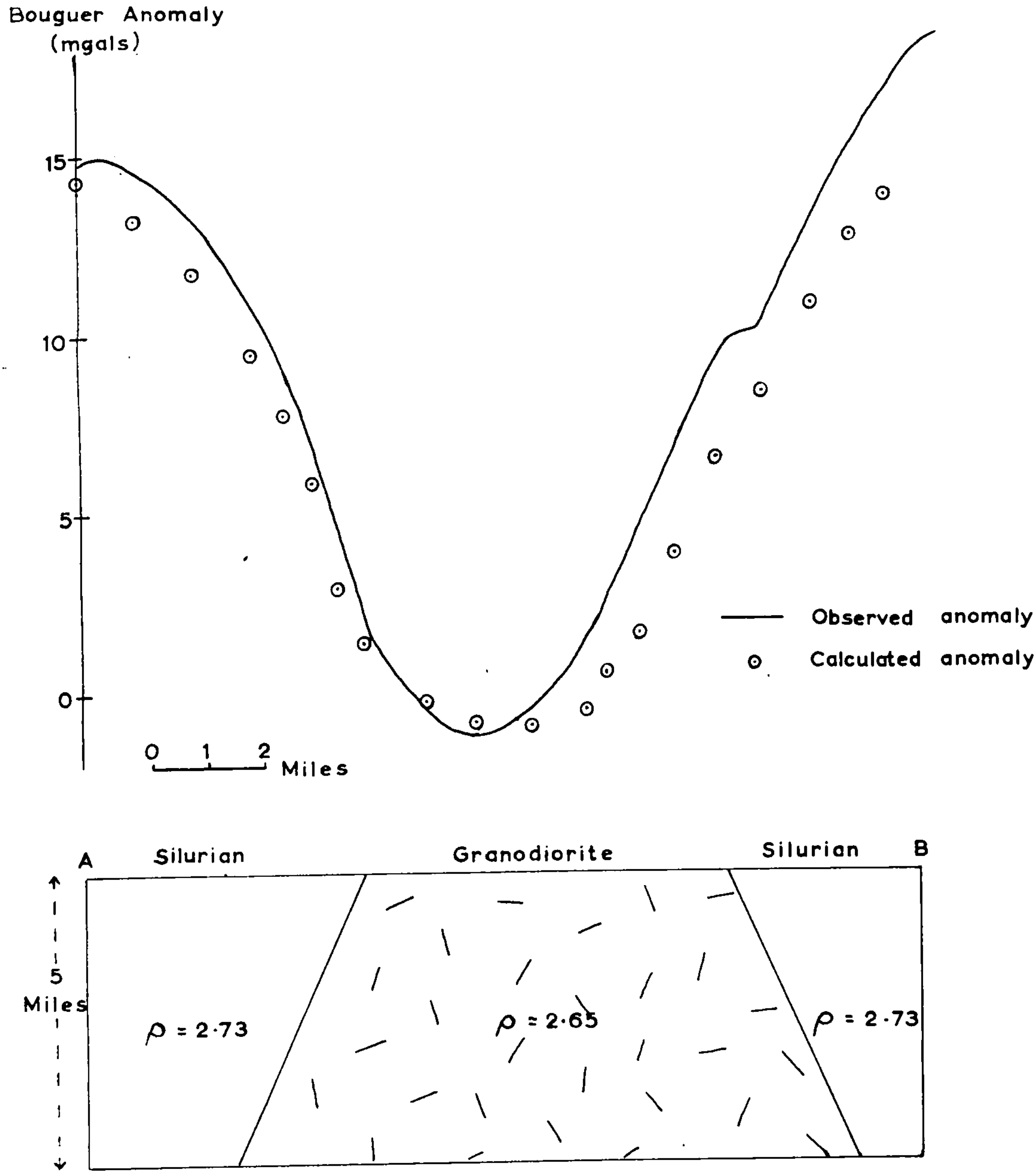


Fig. 6.1 Comparison of anomaly due to the two dimensional model shown above with the observed anomaly over the granite

of their existence.

It therefore seems logical to conclude that the granite itself is the cause of the anomaly.

c) Interpretation by models.

Having assumed the cause of the anomaly, it is now possible to build up models of mass distributions, to calculate the anomalies to which they would give rise and to compare them with the observed anomaly. A satisfactory model must reproduce all the described features of the anomaly, chief among which are the asymmetry of the centre of the anomaly in relation to the granite boundary and the nature of the changes in the gravity gradients.

Two dimensional models are produced in the first instance since these are simple to construct and use comparatively little computer time. Having obtained an approximate shape by this method, three dimensional models are then developed to give a better reproduction of the shape causing the anomaly.

i) Two dimensional models.

The two dimensional models which are described represent cross sections of the granite along the line A B shown on Map 2. For each model, the observed anomaly is shown in addition to the calculated anomaly to enable comparison to be made.

Figures 6.1 and 6.2 show simple models where the granite

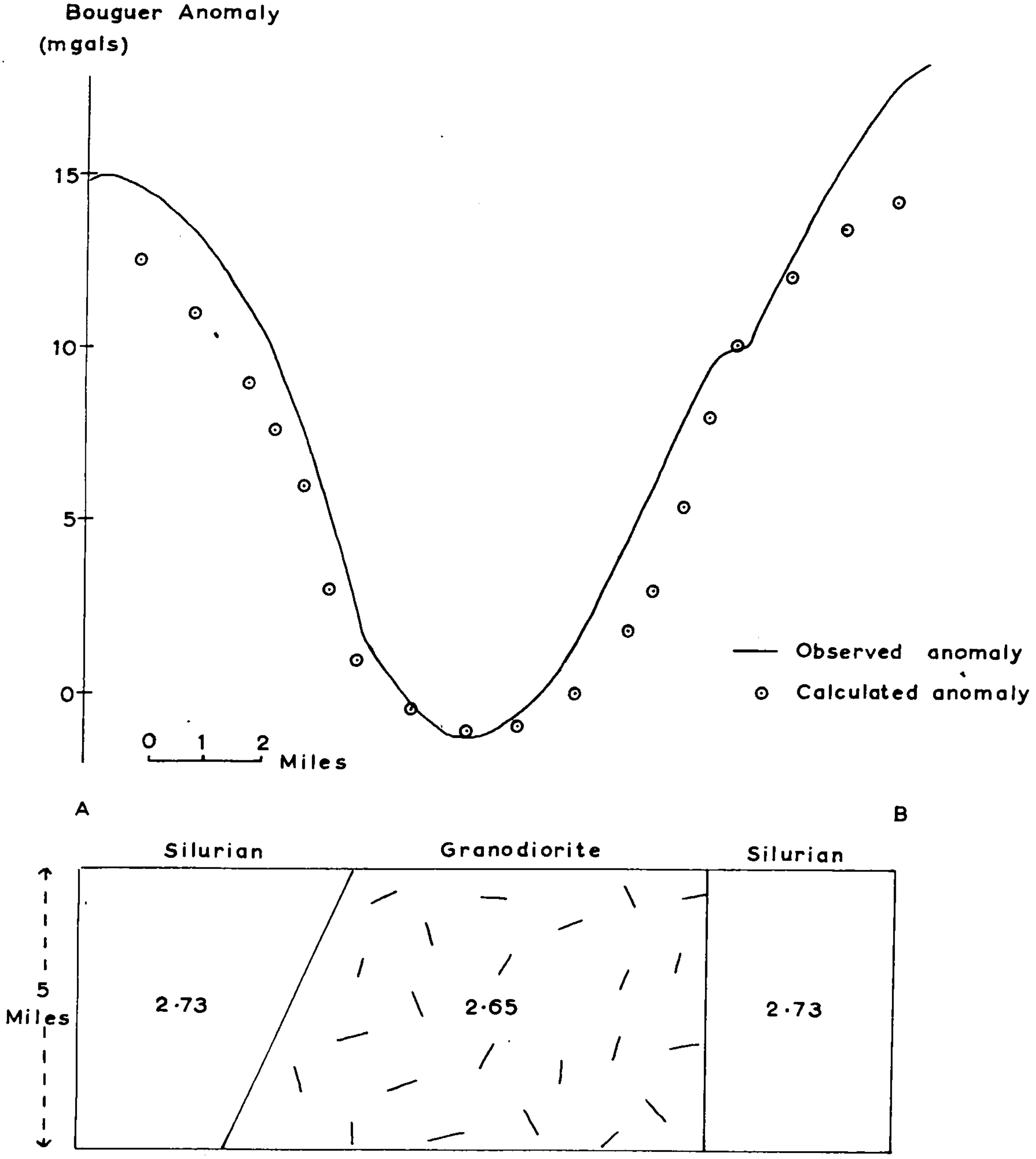


Fig. 6.2 Comparison of the anomaly due to the two dimensional model shown above with the observed anomaly over the granite

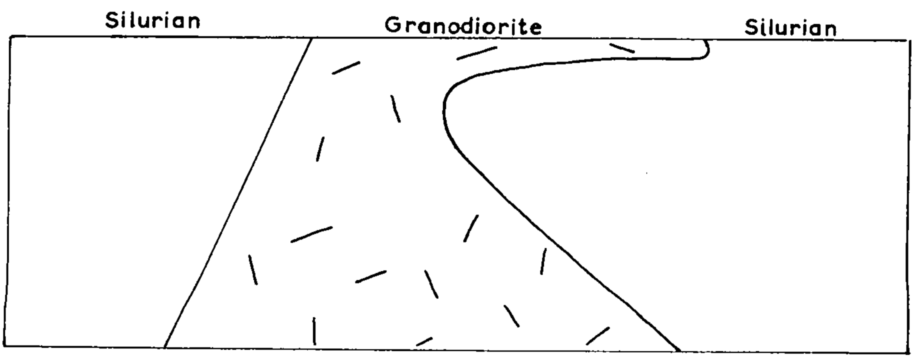


Fig. 6.3 Sketch of a possible configuration which might reproduce the main features of the observed anomaly

has been assumed to be of uniform density throughout. The depth to the base is taken as five miles, as suggested by the equation for the gravity effect of a vertical cylinder (equation 4 ii), using a density contrast of 0.08 gm./c.c.

Neither of the two models produces an anomaly resembling the observed profile: in each case the anomalies diverge in three important features. Firstly, the calculated anomaly is of shallower extent than the observed. Secondly, the lowest part of the calculated anomaly is centrally placed in relation to the granite contacts while the observed anomaly is markedly asymmetrical. Thirdly, the change in gradient of the calculated anomaly over the south eastern margin occurs much more rapidly than is observed.

While the amplitude of the anomaly can be matched by slightly increasing the depth of the model, the asymmetry of the gravity "low" can only be explained by a mass of denser material lying below the central and southern part of the granite. If the granite is still assumed to be of uniform density, the only conceivable way in which denser rock may occur under the centre of the mass is for the granite contact on the south eastern side to be of a sinuous nature as shown in the sketch (fig.6.3), thus bringing country rock under the centre of the granite at no great depth. This is, however, unlikely on geological grounds; for example the exposed angle of contact and the well defined regional foliation pattern which everywhere dip steeply outwards. The possibility has therefore been discounted as a likely interpretation.

There remain two possible means of explaining these observed features which cannot be satisfactorily accounted for by the simple models hitherto discussed. Either the granite is deeper in the north west than in the south east, or, alternatively, there is a horizontal density variation within the granite.

The idea that the granite is deeper in the north west would account for the asymmetry of the gravity "low", and, from a geological point of view may be feasible. However, it still does not explain the steady gravity gradient over the south eastern margin, since a sudden change of density at the contact is bound to produce a change in gradient reflecting the position of the contact. Thus, while a change in depth might account for some features of the anomaly, it is impossible to interpret the whole structure on this basis. Although it may be a contributory factor, this therefore is not the main reason for the peculiar shape of the anomaly.

It therefore remains to consider the possibility of a horizontal change in density within the granite. If this is the explanation of the characteristics of the anomaly, it is evident that the density increases towards the south eastern margin to account for the asymmetrical nature of the gravity minimum. The steady gradient over the south eastern margin, which could not be reproduced where the density change takes place suddenly, might be explained by a more gradual increase in density occurring over a wider part of the granite than just the contact zone itself. A rapid change in density would however still be expected over the north western edge of the granite where the gravity gradient shows a sharp increase at the contact. (The fact that the main increase in the gradient is over the country rock and not the granite itself also provides evidence of an outwardly sloping boundary to the granite in this north western region).

There is good geological evidence for such density changes within the rock. It has been shown in chapter 1 that the main mass of the intrusion is composed of light coloured porphyritic granodiorite, surrounded on all sides except the north west by the darker, main granodiorite. The density values of the minerals given on page 11 show that the lighter coloured minerals of which the porphyritic rock is largely composed are lower in density than the dark minerals which predominate in the main granodiorite. As the change from porphyritic to main granodiorite is only gradual, it is logical to assume that the change in density from one rock type to the other is also gradual, increasing towards the contact.

The measurement of actual rock specimens collected from widely scattered localities within the granodiorite provides striking proof of the existence of this density change, the

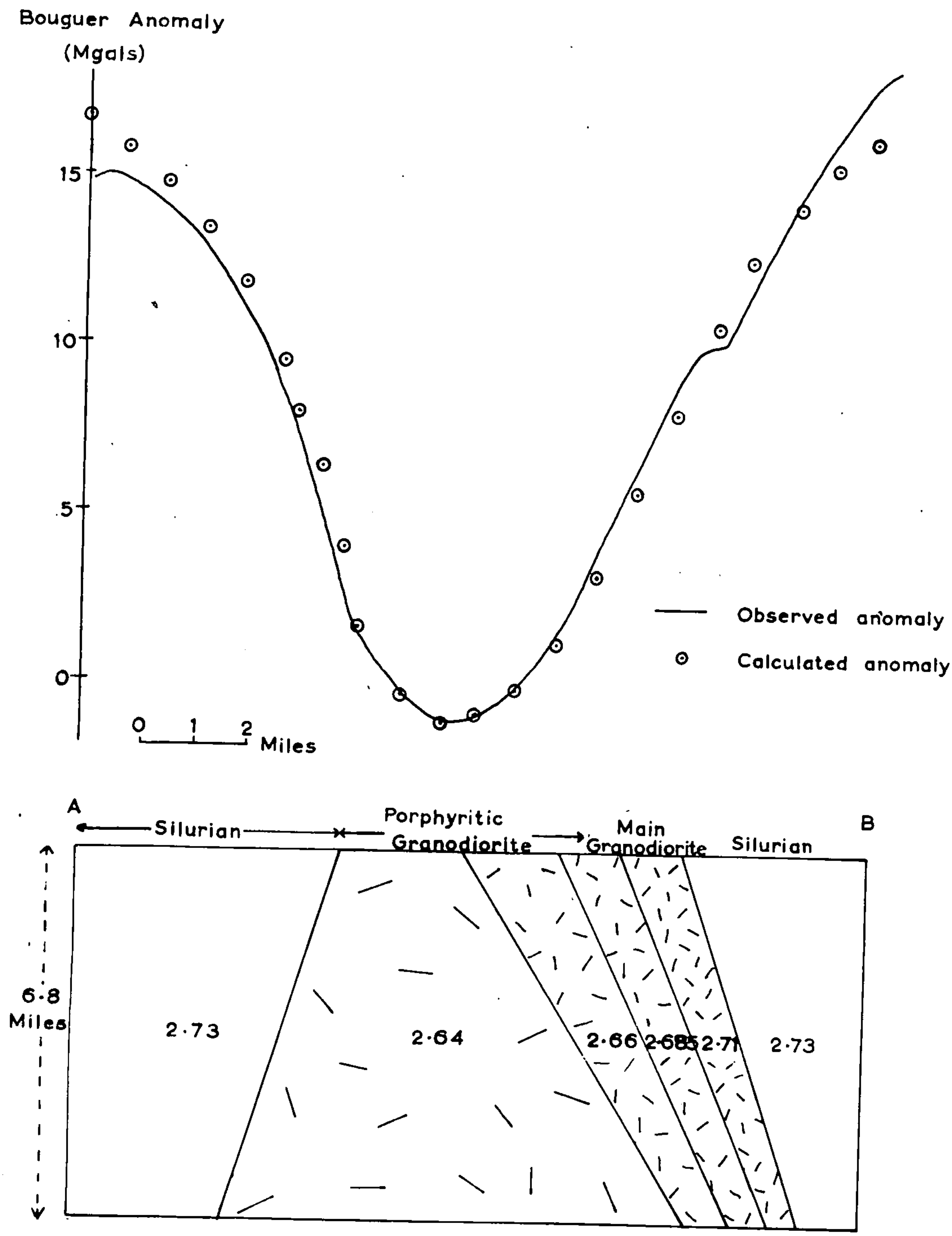


Fig. 6.4 Comparison of the anomaly due to the two dimensional model shown above with the observed anomaly over the granite (The dimensions of the model are based upon fig. 2, page 322 of Bott & Masson-Smith (1960))

values ranging from 2.64 gm./c.c. in the centre of the porphyritic mass to 2.70 gm./c.c. in the main granodiorite. Where this is absent, on the north western side of the complex, specimens from a marginal locality give a value of 2.66 gm./c.c demonstrating that there is little density gradation in this region, the change being more abrupt than on the south eastern side.

Using all the above observations, models of likely density distributions may be constructed and the calculated and observed anomalies compared, as before.

Figure 6.4 shows an example of such a model, based upon figure 2 of Bott and Masson-Smith (1960). It reproduces closely those features of the anomaly which the previous models could not do, namely, the position of the gravity "low" and the gradients over the boundaries. This has been achieved by extending the depth of the model to 6.8 miles and by using varying density contrasts as shown. These values have been derived by interpolation between localities where density values are known from measurements, bearing in mind the geological evidence of a gradational increase.

Figure 6.5 retains the same essential features as the model developed by Bott and Masson-Smith, but uses a density of 2.72 gm./c.c. for the country rock as indicated by the density specimens collected during the present survey. It has also been modified to include a wedge of denser rock on

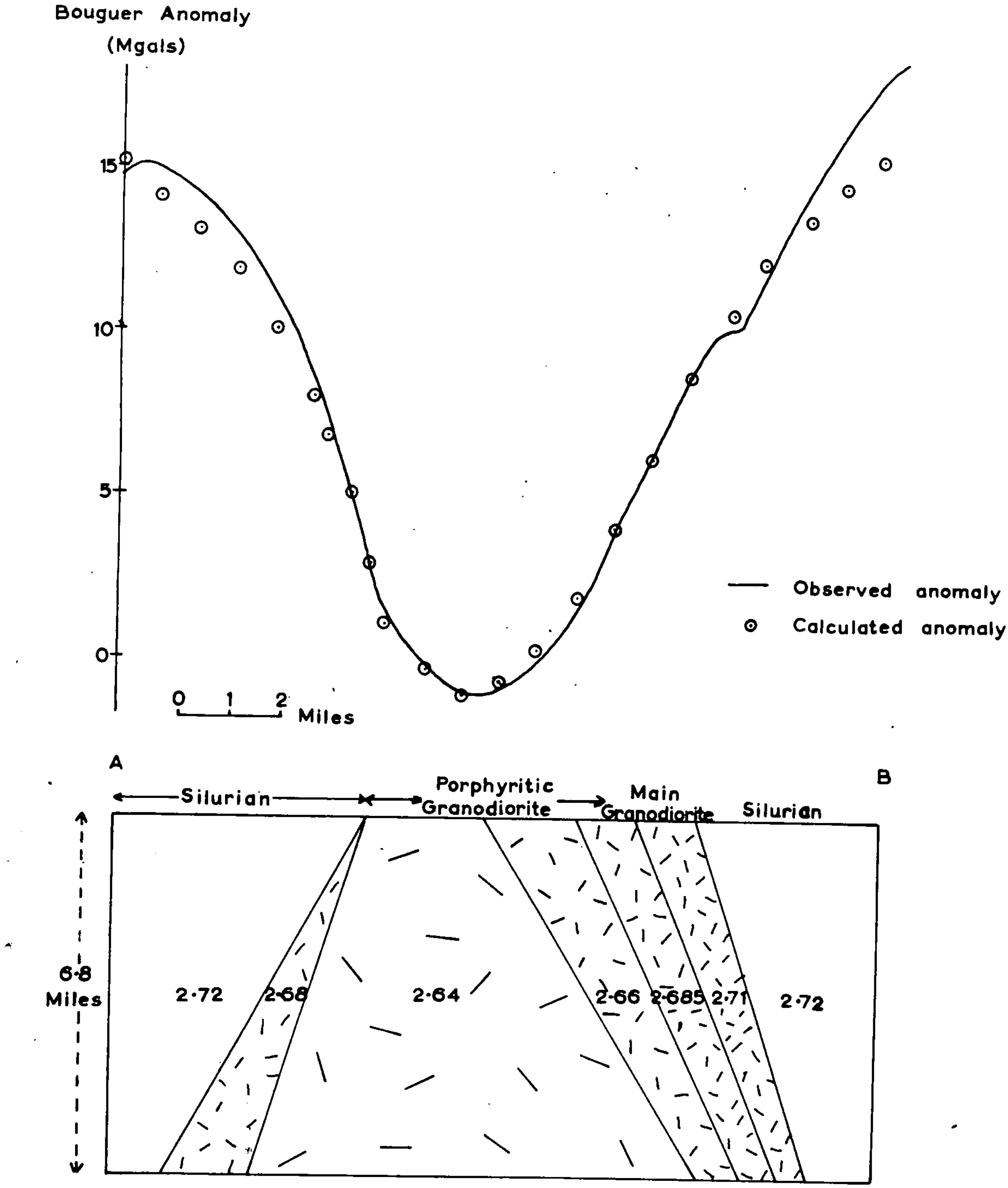


Fig. 6.5 An alternative model to fig. 6.4 showing an equally good fit between the observed and calculated anomalies. A wedge of denser rock has been included below the north-western margin of the porphyritic granodiorite.

the north western side. While there is no direct evidence from density specimens of the existence of such a wedge, it is reasonable to expect this by analogy with the southern margin. The resulting anomaly agrees closely with the observed anomaly and it is considered that this model provides a likely alternative explanation to that given by Bott and Masson-Smith.

ii) Three dimensional models.

In order to obtain the two dimensional profiles described above, it has been assumed that the model is of infinite extent in the plane at right angles to that of the profile. However, the geological map of the area (Map 2) shows that the Criffel granodiorite is only about twice as long as it is broad. It is evident that this assumption, ignoring the end effect, will lead to errors, and will result in a shallow estimate of depth to the base of the mass deficiency.

This difficulty is overcome by the use of three dimensional models which take into account the ends of the mass as well as just its detailed cross section. A satisfactory model is shown in figure 6.6., compiled after the manner described on page 50, the shape being represented by a pile of five horizontal slabs. The plan of the uppermost of these is shown in figure 6.7.

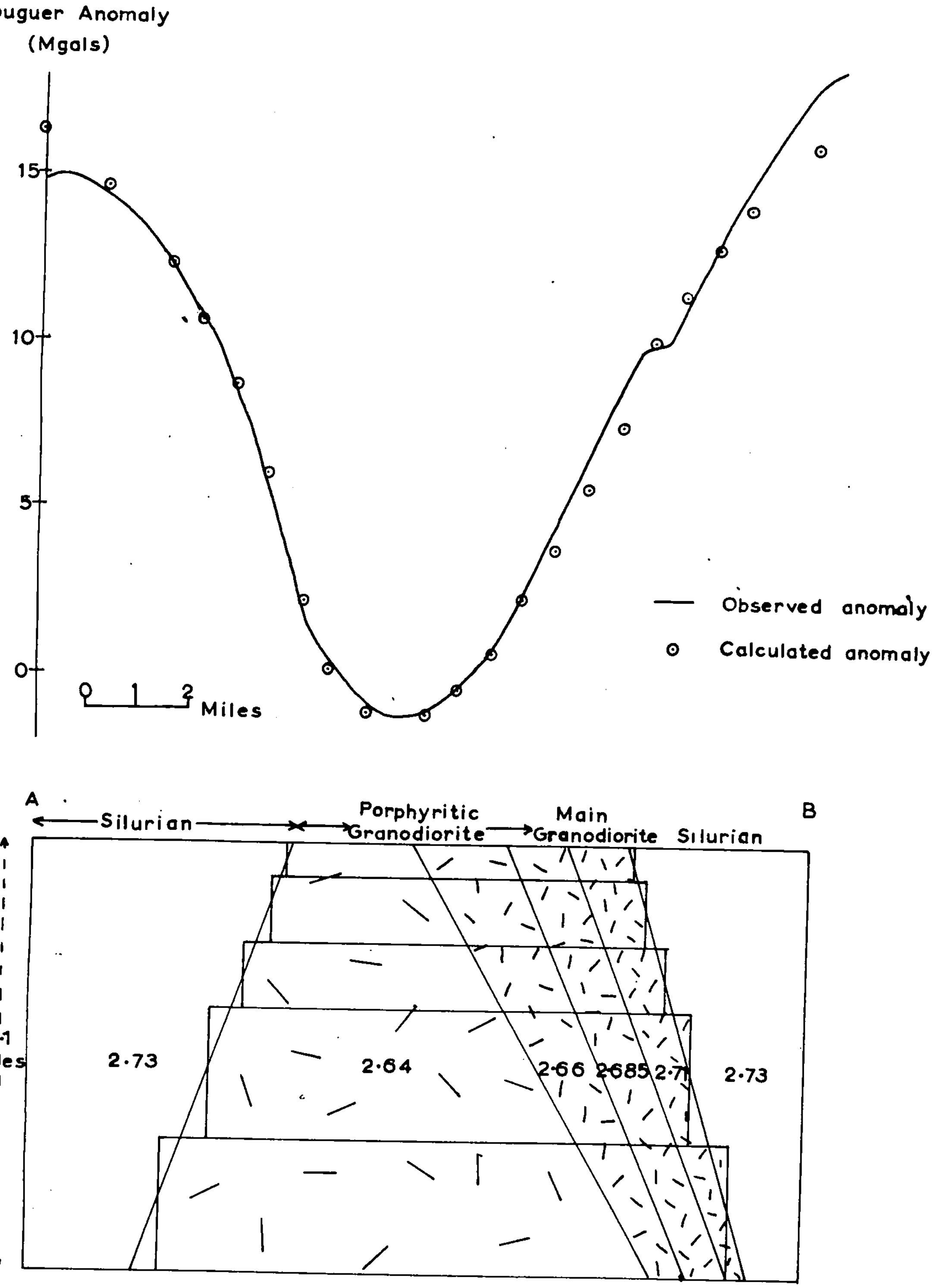


Fig. 6.6 Section across a three dimensional model of the Criffel granodiorite showing a good fit between the observed and calculated anomalies.

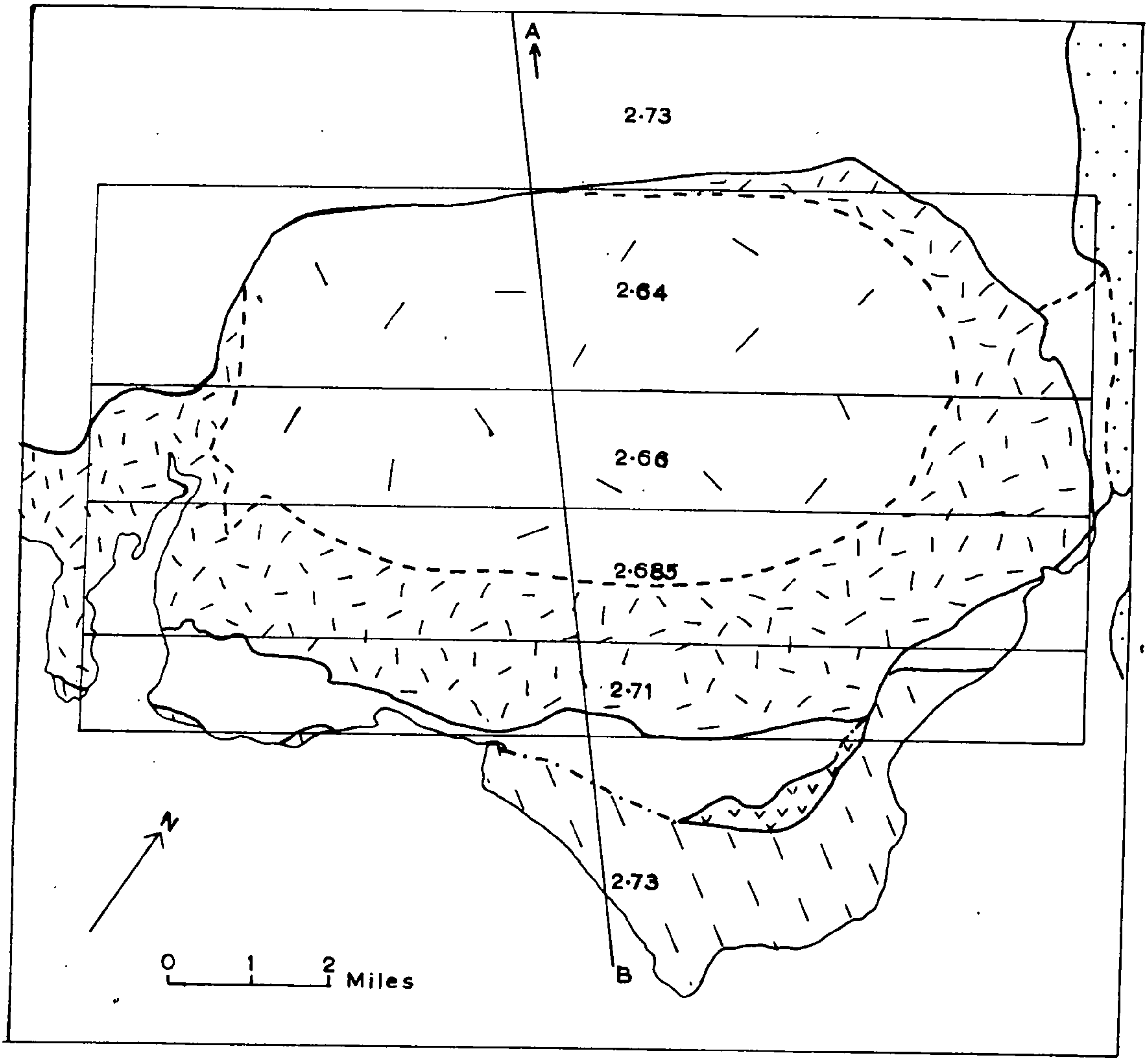


Fig. 6.7 Map of the Criffel granodiorite complex showing the outline of the topmost polygon of the three dimensional model whose cross section along the line AB is shown in fig. 6.6

The anomaly calculated for the model fits the observed anomaly as closely as do the better two dimensional models (figs. 6.4 and 6.5). The main difference from the two dimensional models lies in the increased depth to the base of the anomalous mass (now 8.1 miles). The density distribution remains the same as before. As the only major change has been to take into account the ends of the granodiorite, this error is entirely due to the so-called "end-effect" and it now becomes possible to assign a value to this hitherto rather vague quantity. In this case it represents an error of 1.3 miles, or 19% of the depth suggested by the two dimensional profile.

2) Local anomalies.

While the model shown in figure 6.6 provides a reasonable explanation of the mass distribution which causes the main features of the negative gravity field, the calculated anomaly diverges slightly in three respects from the observed curve, as follows:-

a) The anomaly in the region of Caulkerbush.

There is a local decrease in gradient in the Caulkerbush area, involving a drop in the anomaly of about half a milligal. As this part of the area is largely drift covered it is not possible to correlate the gravity field with the geology. The anomaly may be caused entirely by the existence of a thick drift deposit resting against the granite, or it may reflect faulting between the Silurian and Lower Carboniferous rocks which underlie the drift. If the anomaly were due to the drift alone, use of the slab formula ($A = 2 \pi G \rho t$) shows that for a density contrast of 0.4 gm./c.c. a thickness of approximately 100 feet would be necessary. If it were entirely the effect of downfaulting of the Carboniferous a thickness of about 400 feet would be required. It is possible that the anomaly is caused by a combination of both these features.

b) The decrease of background anomaly to the north west.

In both of the two dimensional and the three dimensional models (figs. 6.4, .5 or .6) the calculated background value on the north west side of the granite is consistently higher than is observed. Map 2 shows that this decrease in the observed anomaly is continued beyond the end of the line of profile. The gradient of the decrease is comparable to that of the outermost part of the Criffel anomaly and it is suggested that the Cairnsmore of Fleet granite, which comes to the surface a few miles to the west of the present area, may be the cause.

c) The increase in background value to the south east.

None of the models used so far reproduces exactly the rise in background value which takes place to the south east of the area. The value of 18.1 milligals at the very tip of Southerness Point (Map 1) is already higher than the background value to the north west of the granite and there is every indication that it is still increasing out into the Solway Firth. This increase in background is apparent all along the coast from Southerness to the limits of the survey at Kirkcudbright and thus appears to be a linear feature. (The apparent closure in the anomaly around Kirkcudbright itself is more likely to be due to the interaction of this regional rise with the Criffel anomaly rather than to a departure from the regional linearity).

The gradient of the rise is fairly steep, although not as pronounced as around the granite. The mass surplus which is responsible for the rise probably therefore lies within the upper part of the crust rather than near the base of it.

3) <u>The Auchencairn Anomaly</u>

The interpretation of the gravity anomaly over the complex south west corner of the granite mass has been approached by methods similar to those used on the main Criffel anomaly. The significant features which need to be

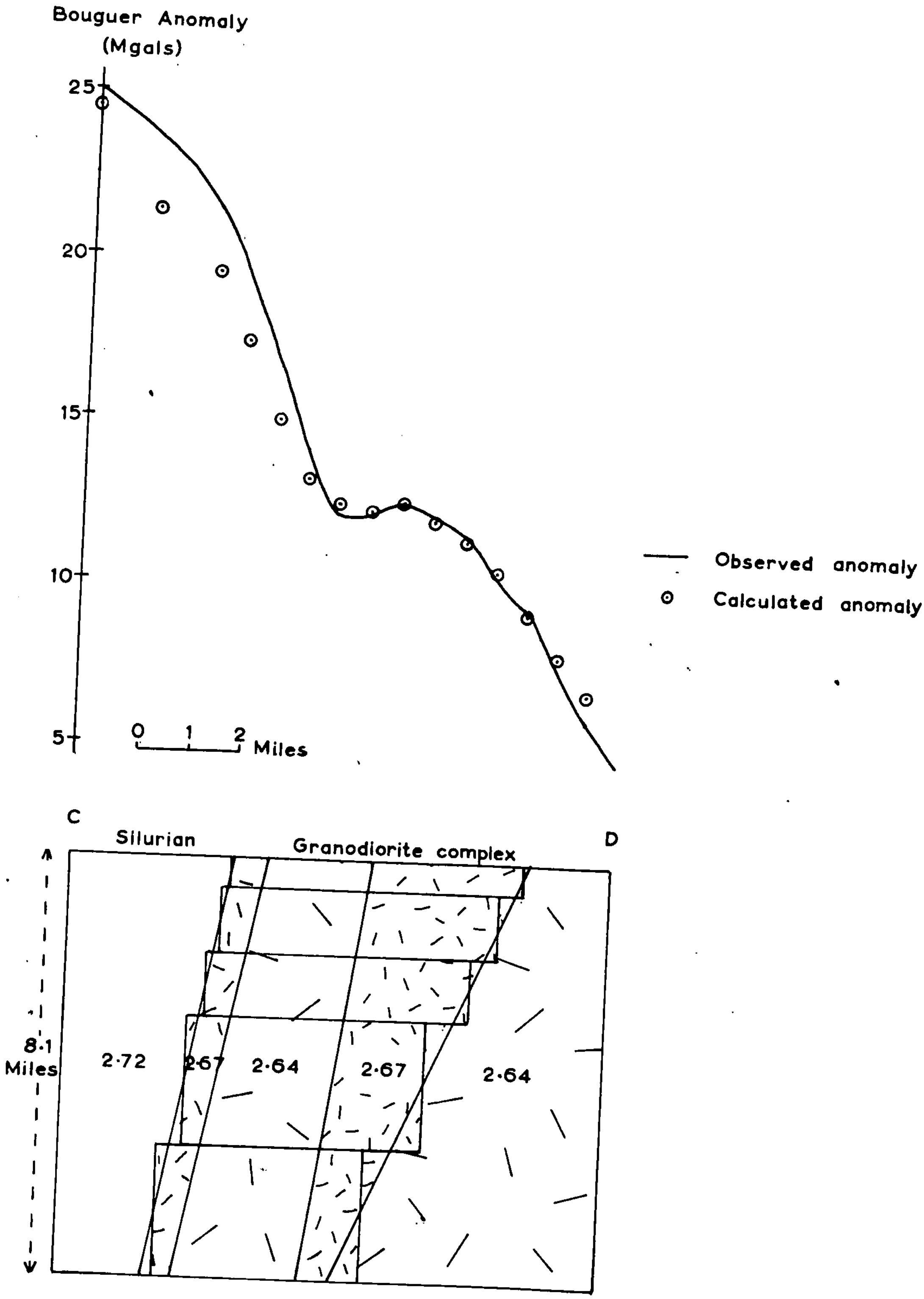


Fig. 6.8 Section across a three dimensional model of the granodiorites of the Auchencairn district showing a good fit between the observed and calculated anomalies.

explained are the steep gradient over the intermediate granodiorite to the south west of Auchencairn and the small positive anomaly over the main granodiorite between Auchencairn and the Urr Water.

In the first instance two dimensional models were constructed along the line CD (Map 2) assuming a depth of about five miles to the base of the granite. These were all unsatisfactory for the likely range of density values which could be used. On a two dimensional basis, the only model which gave an anomaly which fitted the observed curve was one with a variable depth to the base of the granite, ranging from five miles below the surface at C to 6·8 miles at D.

Construction of three dimensional models, however, shows that this sloping base may be in fact a spurious representation owing to the increasing end effect as the granite outcrop narrows to the south west.

A reasonable fit is provided by the three dimensional model whose cross section is shown in figure 6.8. The outline of the uppermost slab used in its construction is shown in figure 6.9, from which it will be seen that the whole of the main Criffel granite has been taken into consideration and not just the portion shown on the right hand side of the profile. The depth of the base of the model below the surface is 8.1 miles, as for the main granite (fig.6.6).

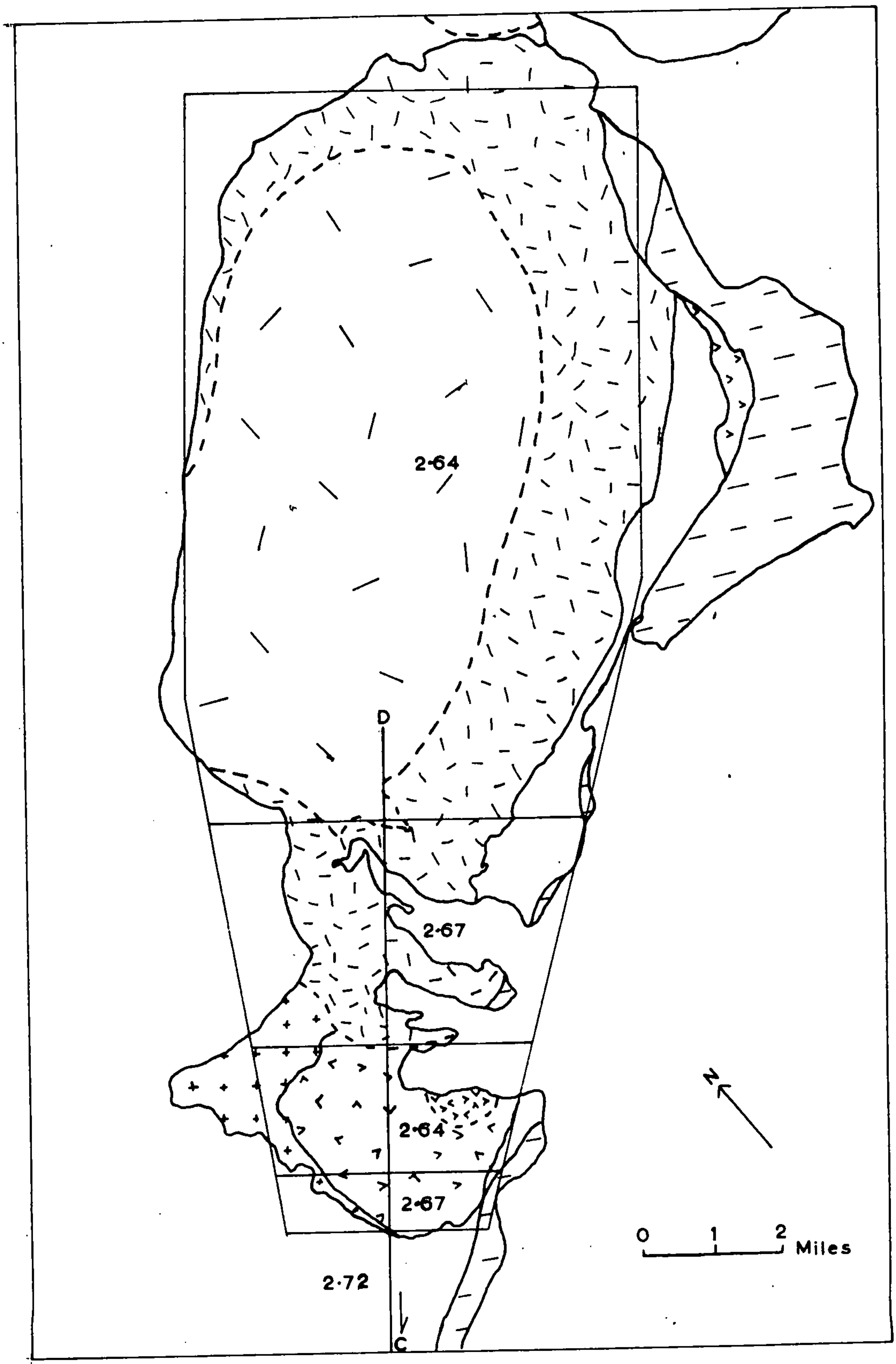


Fig. 6.9 Map of the Criffel granodiorite complex showing the outline of the topmost polygon of the three dimensional model whose cross section along the line CD is shown in fig. 6.8

The density values for the Silurian rocks and the porphyritic granodiorite are fairly well established, but values for the other rock types are tentative since these are based upon relatively few density determinations.

While the small positive anomaly of Orchardton Bay is explained by a slightly denser body lying beneath, as in figure 6.8, the fit between the calculated and observed anomalies is not exact on the south west side of the profile. Here, the calculated background value is less than the actual one and the gradient of the theoretical curve is also somewhat less than the observed. This latter feature may possibly be rectified by adjustments to the density or width of the narrow strip of denser rock which is thought to be present on this side. The failure of the calculated background value to attain the true one must again be attributed to the regional rise noted in the profile of the main Criffel granite.

Conclusions.

It is now possible to draw certain conclusions about the nature and distribution of the Criffel mass.

1) In the area of the large negative anomaly the granite extends to a depth of approximately eight miles below the surface, assuming that the density contrasts used in the model (fig.6.6) are consistent throughout the depth of the mass. Neglect of the effect of the ends of the mass in a

purely two dimensional interpretation results in a spurious figure being obtained for the depth, the granite being represented as 1.3 miles shallower than is indicated by the three dimensional method.

2) The main granite is not of uniform density throughout but exhibits a gradational increase in density from the edges of the porphyritic centre outwards to the contact with the country rock on the south-eastern side.

3) This gradation is not present on the north-western side, the light porphyritic granodiorite continuing right up to the contact. Some denser rock may be present in the contact region at depth but cannot be of greater extent than is shown in figure 6.5.

4) The granite contacts everywhere slope outward at a high angle, approximately parallel to the flow foliation.

5) The granodiorite in the region of Auchencairn is similar to the main Criffel mass in that it, too, could be about eight miles deep and exhibits density variation. Owing to the rapid narrowing of the outcrop to the south west, two dimensional methods of interpretation are grossly inaccurate.

6) Features outside the limits of the survey appear to be exerting a regional influence upon the anomalies. The drop in anomaly to the north west is regarded as being the effect of the Cairnsmore of Fleet granite, while the rise in anomaly to the south reflects a mass of denser material

under the part of the Solway Firth which borders this coast.

While this interpretation cannot be regarded as unique from a geophysical point of views, it does provide the only really satisfactory explanation of the features described in accord with the geological evidence.

Implications of the interpretation.

Having thus arrived at a picture of the possible form of the Criffel mass, it is interesting to see if any deductions may be made as to its mode of origin and to compare it to similar features elsewhere.

The fact that the models show that the granite extends to about eight miles depth is possibly not in accord with Phillips (1956) analogy with a "giant blister". This figure does however correlate well with depths determined for other British granites of comparable size of outcrop, e.g. The Dartmoor granite (Bott and others 1958). It is impossible to say with any certainty, from gravity evidence alone what changes occur at this depth of eight miles: all that can be concluded is that the density contrast between the granite and the country rock dies out. This might mean that there is a layer of rock below this depth of the same density as either the granite or the country rock or possibly of some other constant value. The fact that depth values obtained for other granites agree with that of the Criffel granite may perhaps be regarded as evidence for a widespread uniform layer at this depth.

The geophysical evidence may, perhaps, be used to throw some light upon the mode of emplacement of the granite. Geological observations, such as the flow foliation, the forcing aside of the country rocks and petrographical considerations suggest that the major part of the granite is of post-tectonic, magmatic origin at its present level. There is no suggestion of any "basic front" in the country rocks around the granite as would be expected if it were of metasomatic origin. This is supported by the gravity data, which shows no trace of any positive "hump" over the margin of the granite which would be present if a "basic front" existed (Bott, 1956).

The problem of the destiny of the country rock which originally filled the space now occupied by the Criffel mass is also of importance, as with most other large granite bodies. The two alternative theories usually advanced are a) forcible intrusion, whereby the country rocks are shouldered apart by the uprising magma b) stoping; a process where blocks of country rock are removed by sinking to below the base of the magma.

Although there is geological evidence of some forcing aside of the country rock, it is inconceivable that such a large body of rock could become emplaced in its present position by this means alone. While forcible intrusion may play some part therefore, it is not the main mechanism.

Stoping can only occur where the material which is being removed is denser than the magma; if this is not so it will not sink. It has been shown that the country rock is considerably denser than the granite and so from this point of view the process is feasible. The existence of quite large xenoliths within the granite may be taken as further evidence of the possibility of stoping. If the denser material has been removed from the surface layers to a depth below the base of the granite, it might still be expected to show a positive effect superimposed upon the main negative anomaly, as shown by Bott (1956). This however is obviously not the case, as the gravity anomaly attains a very definite "low" with no sign of a positive hump. Bott (1956) has noticed a similar lack of any positive anomaly in the granites he examines and concludes that the positive effect which a sunken mass of country rock would have is possibly offset by a corresponding crustal thickening below the area of the granite. This explanation may equally well apply to the Criffel granite.

There may however be an alternative explanation in part. The Criffel granite is the only British granite which is known to exhibit a pronounced gradation in density, possibly on account of its position on the edge of the

Southern Uplands tectonic unit and it is clear that a fair proportion of the country rock has been assimilated into the granite in these denser regions. This assimilation will only account for a part of the rock which has been removed, but as it is restricted to the south eastern side of the mass, it might be expected that the surplus mass lies further out, beyond the Solway coast. The rise in gravity anomaly over the coast may possibly be due to such a mass lying at depth, although it is also part of a regional rise towards the Solway Firth and Irish Sea which has been noted in other areas and is as yet not entirely satisfactorily explained (Whittow, 1958).

The gravity evidence lends support to Phillip's (1956) mapping of the asymmetrical nature of the granite. Phillip's explanation of a magma welling up in the north western part, assimilating country rock and "flowing" down on the south eastern side is also in accord with the geophysical results. It is interesting to find that this asymmetry is not merely a surface feature, but continues at depth: nowhere on the north western side is there a very great thickness of denser rock within the granite. The asymmetry is thus a feature of the original intrusion and is not by any means entirely the result of later uprise of the porphyritic block relative to the rest of the intrusion, although this undoubtedly did take place to a certain extent.

The fact that the granodiorite of the Auchencairn area could be of the same depth as the main granodiorite shows that it is not a thin offshoot of the main mass but forms an integral part of the complex.

ACKNOWLEDGMENTS.

I wish to thank Professor K.C.Dunham, F.R.S., for the opportunity to study at Durham which is an experience I greatly appreciate. I am extremely grateful to Dr.Bott for his kindly supervision of my work throughout the course and for allowing me to make use of his unpublished computer programmes. I should like to thank Mr.John Mansfield for his cheerful companionship and assistance with the routine field work and many other members of the Geology Department for much fruitful discussion.

I also wish to acknowledge the assistance rendered by the staff of the computing laboratory at King's College, Newcastle in sorting out many otherwise inexplicable tangles.

Finally, my thanks are due to the Department of Scientific and Industrial Research for the provision of a maintenance grant.

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APPENDIX A

GRAVITY BASE STATION NO: 1

TOWN: Auchencairn COUNTY: Kirkcudbrightshire

1" MAP: Sheet 81 6" MAP: NX 75 SE

DESCRIPTION: Meter opposite end window of shop, 5 ft. from wall. B.M.(74.76) on other end of wall. Auchencairn Square.

GRAVITY: +1.971 mgls.

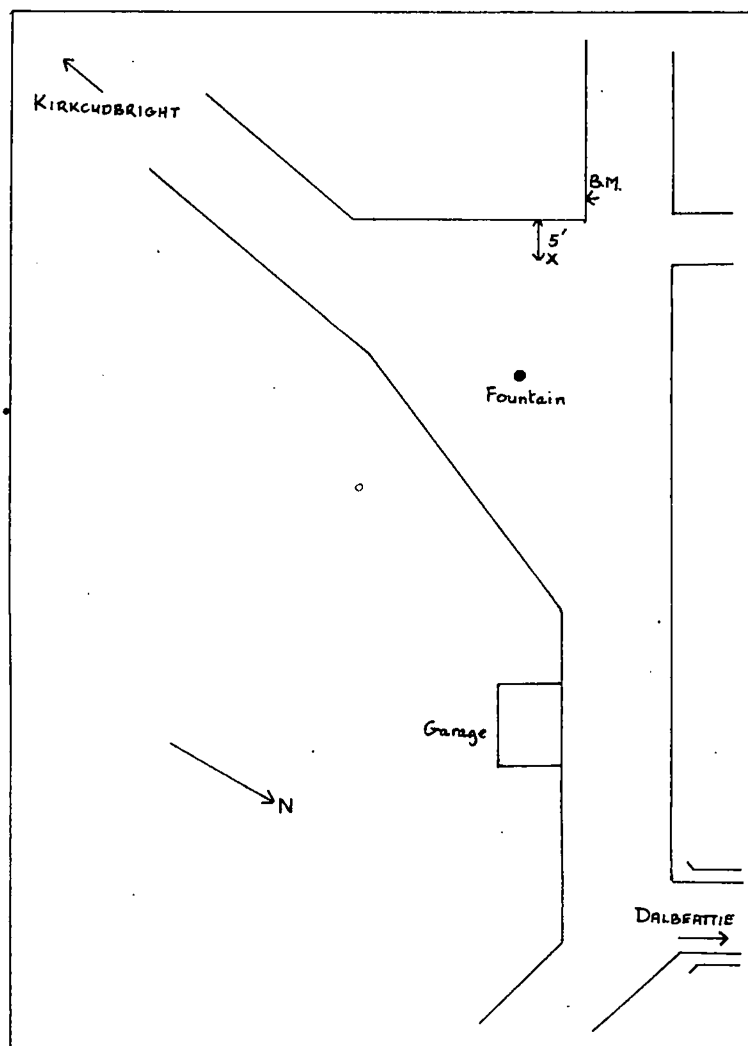
ELEVATION: 72.0 ft.

LATITUDE: 54 50' 35"

LONGITUDE: 3 52' 10" W.

DATE: 3/9/59

OBSERVER: P. Kennett



GRAVITY BASE STATION NO: 17

TOWN: Dalbeattie

COUNTY: Kirkcudbrightshire

1" MAP: Sheet 81

6" MAP: NX 86 SW

DESCRIPTION: Meter in line with edge of hedge opposite first of row of houses set back from road.

GRAVITY: +3.00 mgls.

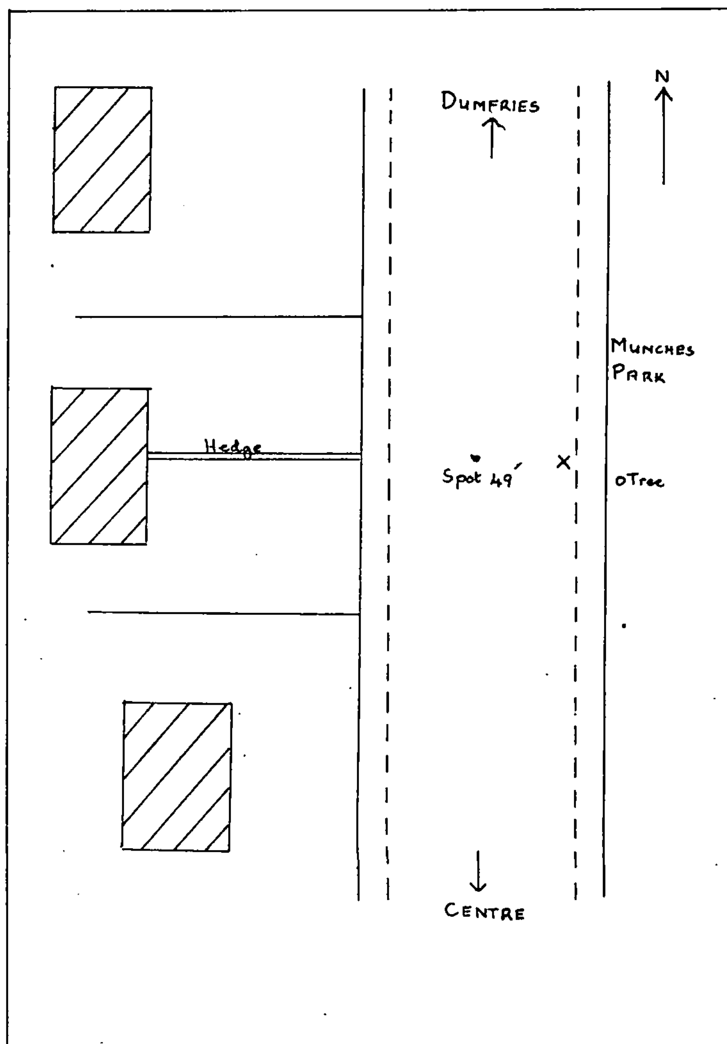
ELEVATION: 49 ft.

LATITUDE: 54 56'11"

LONGITUDE: 3 52' 11"

DATE: 3/9/59

OBSERVER: P.Kennett



GRAVITY BASE STATION NO: 18

TOWN: Caulkerbush

COUNTY: Kirkcudbrightshire

1" MAP: Sheet 81

6" MAP: NX 95 NW

DESCRIPTION: Meter opposite B.M.(35.42) on end wall of lodge house.

GRAVITY: +6.37 mgls.

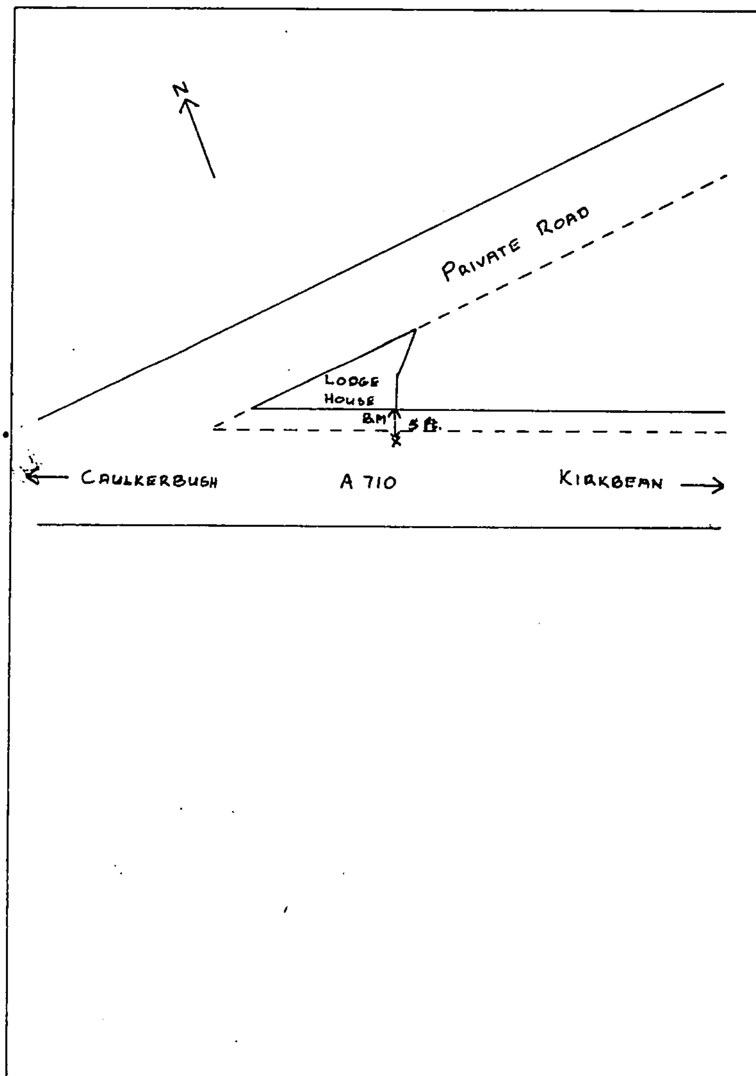
ELEVATION: 33.4 ft.

LATITUDE: 54 53' 53"

LONGITUDE: 3 40' 13" W.

DATE: 4/9/59

OBSERVER: P.Kennett



GRAVITY BASE STATION: Dumfries

TOWN: Dumfries

COUNTY: Dumfriesshire

1" MAP: Sheet 74

6" MAP:

DESCRIPTION: Meter aligned opposite buttress of end house in road, 3 feet from kerb. Road is a turning off the main Dumfriess to Locherbie road on the outskirts of the town.

GRAVITY: +12.39mgls.

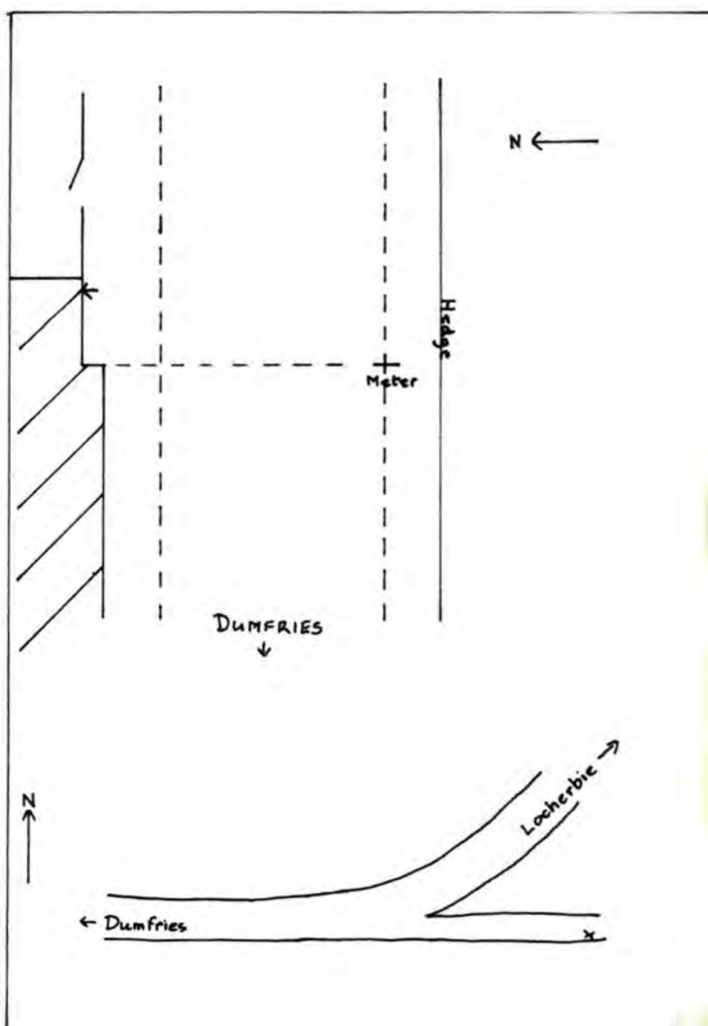
ELEVATION: 66.9 ft.

LATITUDE: 55°04′23″

LONGITUDE: 3°35′07″

DATE: 15/11/54

OBSERVER: Bott & Nairn



GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :-

1 OBSERVERS STATION NUMBER	2 LATITUDE N.	3 LONGITUDE (E. or W.)	4 ELEVATION feet (Newlyn O.D.)	5 STATION TO WHICH CONNECTED	6 GRAVITY DIFFERENCE MEAN VALUE (milligals)	6 DEVIATION	7 TOTAL GRAVITY MEAN VALUE	7 DEVIATION	8 FREE AIR ANOMALY (milligals)	9 BOUGUER ANOMALY ON I.G.F. (milligals)	10 DENSITY VALUES USED IN BOUGUER REDUCTION	11 TERRAIN CORRECTION (milligals)	11 ZONE	12 REMARKS	13 G.S.M. REFERENCE NO. OF STATION
1	54 50 35	3 52 10 W	72.0 ?				+1.97 mgl.			+12.2	2.65	0.28		GRAVITY VALUES IN	
2	54 50 34	3 51 33 W	23.2	1			+4.11			+11.4	2.65	0.29		COL. 7 ARE RELATIVE	
3	54 50 12	3 50 40 W	30.0	1			+4.64			+13.0	2.65	0.40		TO BASE STATION	
4	54 49 36	3 49 38 W	40.0	1			+6.60			+16.2	2.65	0.17		2000 AT NEWCASTLE.	
5	54 52 26	3 50 17 W	37.0	1			+5.67			+11.3	2.65	0.46		THE VALUE OF BASE	
6	54 52 2	3 50 05 W	29.6	1			+6.42			+12.2	2.65	0.44		2000 IS +0.83 MGL.	
7	54 51 49	3 49 56 W	50.0	1			+4.98			+12.3	2.65	0.42		HIGHER THAN THE GEOL.	
8	54 52 11	3 50 10 W	22.0	1			+6.76			+11.8	2.65	0.40		SURVEY PENDULUM	
9	54 48 44	3 54 43 W	407.0	1			−10.64			+21.9	2.73	0.25		STATION WHICH HAS	
10	54 48 19	3 54 35 W	402.5	1			−10.85			+22.3	2.73	0.49		AN ASSUMED VALUE	
11	54 47 59	3 54 55 W	283.0	1			−3.86			+22.8	2.73	0.64		OF 981.50608 CM.SEC.$^{-2}$	
12	54 48 00	3 55 35 W	301.0	1			−3.81			+23.7	2.73	0.38		BASE STATION 2000	
13	54 47 42	3 55 58 W	241.0	1			−0.62			+23.6	2.73	0.25		THEREFORE HAS THE	
14	54 50 25	3 51 13 W	21.0	1			+4.28			+11.7	2.65	0.29		ASSUMED VALUE OF	
15	54 50 00	3 50 17 W	28.0	1			+5.79			+14.2	2.65	0.31		981.50691 CM.SEC.$^{-2}$	
16	54 49 37	3 49 14 W	16.0	1			+7.63			+16.0	2.73	0.45			
17	54 56 11	3 49 08 W	49.0				+3.00			+3.9	2.65	0.27			
18	54 53 53	3 40 03 W	33.4				+6.37			+9.9	2.73	0.60			
19	54 55 18	3 50 03 W	32.0	1			+5.14			+6.3	2.65	0.37			
20	54 55 45	3 49 43 W	29.0	1			+4.82			+5.1	2.65	0.25			
21	54 52 23	3 35 40 W	14.0	18			+14.16			+18.1	2.60	0.08			
22	54 58 32	3 51 55 W	70.0	1			+14.62			+13.3	2.73	0.23			
23	54 57 59	3 51 02 W	63.0	1			+12.21			+11.4	2.73	0.38			
24	54 57 45	3 50 47 W	70.6	1			+10.83			+10.8	2.73	0.33			
25	54 57 19	3 50 26 W	76.0	1			+7.88			+8.9	2.73	0.48			
26	54 56 56	3 50 13 W	104.5	1			+4.26			+7.7	2.73	0.63			
27	54 56 32	3 50 03 W	123.0	1			+1.56			+6.3	2.73	0.29			
28	54 56 8	3 49 07 W	64.0	1			+3.57			+5.5	2.65	0.30			
29	54 55 27	3 48 56 W	45.0	17			+2.45			+4.1	2.65	0.21			
30	54 55 02	3 48 56 W	51.7	17			+2.01			+4.6	2.65	0.22			

GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :–

1 OBSERVER'S STATION NUMBER	2 LATITUDE N.	3 LONGITUDE (E. or W)	4 ELEVATION feet (Newlyn O.D.)	5 STATION TO WHICH CONNECTED	6 GRAVITY DIFFERENCE MEAN VALUE (milligals)	6 DEVIATION	7 TOTAL GRAVITY MEAN VALUE	7 DEVIATION	8 FREE AIR ANOMALY (milligals)	9 BOUGUER ANOMALY ON I.G.F. (milligals)	10 DENSITY VALUES USED IN BOUGUER REDUCTION	11 TERRAIN CORRECTION (milligals)	11 ZONE	12 REMARKS	13 G.S.M. REFERENCE NO. OF STATION
31	54 54 20	3 48 57 W	48.0	17			+2.96 mgl.			+6.3(5)	2.65	0.21		GRAVITY VALUES IN	
32	54 53 51	3 48 34 W	27.9	17			+3.95			+6.9	2.65	0.33		COL. 7 ARE RELATIVE	
33	54 53 19	3 48 12 W	135.5	17			-1.24			+8.8	2.65	0.20		TO BASE 2000 AT	
34	54 53 3	3 48 18 W	143.0	17			-1.45			+9.5	2.65	0.21		NEWCASTLE WHICH HAS	
35	54 52 36	3 48 42 W	17.5	17			+6.47			+10.6	2.65	0.35		A VALUE OF 981.50691	
36	54 59 49	3 49 53 W	275.0	17			+3.33			+12.3	2.73	0.14			
37	54 59 25	3 50 07 W	190.0	17			+7.63			+12.2	2.73	0.19			
38	54 58 53	3 49 57 W	176.0	17			+6.87			+11.2	2.73	0.12			
39	54 58 32	3 49 39 W	177.0	17			+4.97			+9.9	2.73	0.14			
40	54 58 4	3 49 25 W	174.0	17			+2.63			+8.1	2.73	0.19			
41	54 57 37	3 49 04 W	152.0	17			+1.04			+5.9	2.73	0.19			
42	54 57 30	3 49 03 W	141.0	17			+1.21			+5.5	2.73	0.19			
43	54 57 17	3 48 58 W	131.0	17			+0.68			+4.8	2.73	0.26			
44	54 57 11	3 48 49 W	126.0	17			-0.06			+3.9	2.73	0.22			
45	54 57 01	3 48 37 W	143.0	17			-2.25			+3.0	2.65	0.16			
46	54 56 56	3 48 43 W	125.2	17			-0.96			+3.3	2.65	0.14			
47	54 56 24	3 49 06 W	70.0	17			+1.79			+3.7	2.65	0.29			
48	54 56 39	3 49 02 W	98.0	17			+0.55			+3.6	2.65	0.19			
49	54 53 39	3 40 50 W	117.0	17			+0.84			+10.4	2.73	1.33			
50	54 53 20	3 41 34 W	91.0	17			+2.97			+10.8	2.73	0.70			
51	54 52 58	3 42 43 W	87.0	17			+4.12			+12.2	2.73	0.70			
52	54 52 52	3 43 37 W	38.0	17			+6.03			+11.2	2.65	0.51			
53	54 52 43	3 44 00 W	39.0	17			+6.88			+12.1	2.73	0.36			
54	54 52 32	3 44 28 W	133.0	17			+1.12			+12.0	2.73	0.20			
55	54 52 15	3 44 37 W	135.0	17			+1.36			+12.9	2.73	0.34			
56	54 52 8	3 44 36 W	140.5	17			+1.08			+13.2	2.73	0.40			
57	54 51 50	3 44 42 W	79.3 ?	17			+4.01			+13.6	2.60	0.91			
58	54 55 55	3 48 27 W	134.0	17			-3.64			+2.6	2.65	0.18			
59	54 55 36	3 47 43 W	146.0	17			-5.59			+1.9	2.65	0.16			
60	54 55 10	3 47 22 W	137.0	17			-5.59			+1.9	2.65	0.16			

GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :-

1 OBSERVER'S STATION NUMBER	2 LATITUDE N.			3 LONGITUDE (E. or W)				4 ELEVATION feet (Newlyn O.D)	5 STATION TO WHICH CONNECTED	6 GRAVITY DIFFERENCE MEAN VALUE (milligals)	6 DEVIATION	7 TOTAL GRAVITY MEAN VALUE	7 DEVIATION	8 FREE AIR ANOMALY (milligals)	9 BOUGUER ANOMALY ON I.G.F. (milligals)	10 DENSITY VALUES USED IN BOUGUER REDUCTION	11 TERRAIN CORRECTION (milligals)	11 ZONE	12 REMARKS	13 G.S.M. REFERENCE NO. OF STATION
61	54	54	51	3	46	35	W	155.0	17			-6.59 mgl.			+2.5	2.65	0.24		GRAVITY VALUES IN COL	
62	54	54	44	3	45	16	W	273.1	17			-13.17			+3.4	2.65	0.43		7 ARE RELATIVE TO	
63	54	54	56	3	44	12	W	411.0	17			-21.34			+3.2	2.65	0.32		BASE 2000 AT NEWCASTLE	
64	54	54	53	3	43	40	W	363.0	17			-17.93			+3.7	2.65	0.26		WHICH HAS A VALUE OF	
65	54	54	54	3	43	17	W	358.5	17			-17.37			+4.1	2.65	0.36		981.50691 cm.sec^{-2}	
66	54	54	56	3	42	15	W	256.0	17			-10.99			+4.4	2.65	0.50			
67	54	54	45	3	41	19	W	209.1	17			-6.60			+6.4	2.65	0.68			
68	54	54	20	3	40	34	W	99.0	17			+1.46			+8.6	2.65	0.93			
69	54	54	02	3	40	20	W	65.0	17			+4.53			+9.8	2.65	0.76			
70	54	52	20	3	44	57	W	147.5	18			+0.57			+12.7	2.73	0.26			
71	54	52	22	3	45	32	W	132.0	18			+1.00			+12.1	2.73	0.17			
72	54	52	18	3	46	02	W	124.3	18			+1.21			+11.9	2.73	0.12			
73	54	52	04	3	46	27	W	127.6	18			+1.01			+12.2	2.73	0.13			
74	54	51	36	3	47	02	W	90.0	18			+3.43			+13.1	2.73	0.20			
75	54	51	51	3	47	22	W	61.0	18			+4.35			+12.0	2.73	0.23			
76	54	52	02	3	47	47	W	65.0	18			+3.70			+11.4	2.73	0.35			
77	54	56	11	3	55	33	W	149.0	1			+8.67			+15.3	2.73	0.11			
78	54	55	21	3	55	12	W	146.0	1			+7.87			+15.5	2.73	0.16			
79	54	55	02	3	54	53	W	148.0	1			+7.03			+15.3	2.73	0.25			
80	54	54	19	3	53	47	W	154.7	1			+4.35			+14.4	2.73	0.60			
81	54	54	11	3	53	10	W	135.0	1			+4.36			+13.9	2.73	1.01			
82	54	53	57	3	52	44	W	87.0	1			+6.68			+13.9	2.73	1.19			
83	54	53	28	3	52	06	W	52.0	1			+7.60			+12.8	2.73	0.64			
84	54	53	17	3	51	57	W	42.0	1			+7.64			+12.8	2.73	0.89			
85	54	53	00	3	51	23	W	49.0	1			+5.62			+11.1	2.65	0.31			
86	54	52	46	3	50	53	W	97.0	1			+2.70			+11.2	2.65	0.16			
87	54	52	35	3	50	35	W	57.0	1			+4.96			+11.4	2.65	0.24			
88	54	53	21	3	50	30	W	51.4	1			+5.17			+10.2	2.65	0.29			
89	54	53	41	3	50	25	W	44.0	1			+5.47			+9.7	2.65	0.35			
90	54	53	51	3	50	25	W	52.5 ?	1			+4.51			+9.1	2.65	0.50			

GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :-

1 OBSERVER'S STATION NUMBER	2 LATITUDE N.	3 LONGITUDE (E. or W.)	4 ELEVATION feet (Newlyn O.D.)	5 STATION TO WHICH CONNECTED	6 GRAVITY DIFFERENCE MEAN VALUE (milligals)	6 GRAVITY DIFFERENCE DEVIATION	7 TOTAL GRAVITY MEAN VALUE	7 TOTAL GRAVITY DEVIATION	8 FREE AIR ANOMALY (milligals)	9 BOUGUER ANOMALY ON I.G.F. (milligals)	10 DENSITY VALUES USED IN BOUGUER REDUCTION	11 TERRAIN CORRECTION (milligals)	11 TERRAIN ZONE	12 REMARKS	13 G.S.M. REFERENCE NO. OF STATION
91	54 54 12	3 50 47 W	254·0	1			-7·53 mgl.			+8·6	2·73	0·58		GRAVITY VALUES IN COL. 7	
92	54 54 29	3 51 05 W	249·0	1			-7·12			+8·1	2·73	0·42		ARE RELATIVE TO BASE	
93	54 55 10	3 51 35 W	305·5	1			-7·06			+10·2	2·73	0·12		2000 IN NEWCASTLE	
94	54 55 42	3 52 17 W	201·0	1			+1·27			+11·9	2·73	0·40		WHICH HAS A VALUE OF	
95	54 55 35	3 50 15 W	33·0	1			+5·82			+6·8	2·65	0·52		981·50691 cm. sec^{-2}	
96	54 55 56	3 50 45 W	143·0	1			+0·71			+7·7	2·73	0·54			
97	54 55 30	3 51 00 W	259·0	1			-6·24			+8·2	2·73	0·43			
98	54 56 17	3 52 15 W	359·3	1			-6·85			+12·2	2·73	0·25			
99	54 56 58	3 52 25 W	129·7	1			+8·30			+12·7	2·73	0·17			
100	54 56 00	3 56 00 W	149·0	1			+8·77			+15·7	2·73	0·15			
101	54 55 18	3 56 12 W	221·6	1			+4·05			+16·2	2·73	0·08			
102	54 54 27	3 55 03 W	209·6	1			+3·29			+16·0	2·73	0·22			
103	54 54 12	3 54 40 W	250·6	1			-0·23			+15·3	2·73	0·22			
104	54 53 59	3 54 20 W	273·8	1			-2·53			+14·9	2·73	0·40			
105	54 53 48	3 54 08 W	345·2	1			-7·20			+14·7	2·73	0·40			
106	54 53 25	3 53 45 W	293·5	1			-4·93			+14·6	2·73	0·55			
107	54 52 30	3 52 17 W	56·0	1			+5·02			+12·3	2·65	0·99			
108	54 52 40	3 52 20 W	87·0	1			+3·92			+12·7	2·73	1·00			
109	54 52 58	3 52 58 W	203·0	1			-1·84			+13·5	2·73	1·08			
110	54 53 04	3 53 10 W	233·7	1			-3·08			+13·7	2·73	0·85			
111	54 52 28	3 51 56 W	30·0	1			+6·01			+11·3	2·65	0·53			
112	54 52 09	3 52 04 W	54·5	1			+4·71			+12·1	2·65	0·70			
113	54 51 44	3 52 00 W	49·0 ?	1			+4·54			+12·0	2·65	0·51			
114	54 51 10	3 51 05 W	33·7	1			+4·37			+11·4	2·65	0·26			
115	54 51 03	3 50 59 W	21·2	1			+4·70			+11·2	2·65	0·27			
116	54 53 09	3 47 45 W	152·0	1			-2·39			+9·1	2·65	0·33			
117	54 52 42	3 47 05 W	198·0	1			-4·58			+10·1	2·65	0·12			
118	54 52 25	3 46 21 W	108·0	1			+1·50			+11·7	2·65	0·72			
119	54 52 57	3 44 03 W	70·0	1			+4·00			+10·9	2·65	0·42			
120	54 53 03	3 44 24 W	83·0	1			+2·65			+10·2	2·65	0·48			

GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :-

1 OBSERVER'S STATION NUMBER	2 LATITUDE N.	3 LONGITUDE (E. or W.)	4 ELEVATION feet (Newlyn O.D.)	5 STATION TO WHICH CONNECTED	6 GRAVITY DIFFERENCE MEAN VALUE (milligals)	6 DEVIATION	7 TOTAL GRAVITY MEAN VALUE	7 DEVIATION	8 FREE AIR ANOMALY (milligals)	9 BOUGUER ANOMALY ON I.G.F. (milligals)	10 DENSITY VALUES USED IN BOUGUER REDUCTION	11 TERRAIN CORRECTION (milligals)	11 ZONE	12 REMARKS	13 G.S.M. REFERENCE NO. OF STATION
121	54 53 22	3 44 47 W	128·0	1			-0·89 mgl			+9·1	2·65	0·64		Gravity values in col. 7	
122	54 53 53	3 45 02 W	147·0	1			-3·45			+6·7	2·65	0·36		are relative to base	
123	54 54 15	3 45 37 W	122·0	1			-3·41			+4·7	2·65	0·31		2000 in Newcastle	
124	54 54 40	3 46 10 W	152·0	1			-6·16			+3·1	2·65	0·29		which has a value of	
125	55 00 01	3 47 18 W	267·3	17			+0·49			+8·7	2·73	0·15		981·50691 cm. sec.$^{-2}$.	
126	54 59 54	3 47 14 W	262·0	17			+0·13			+8·2	2·73	0·17			
127	54 59 44	3 47 07 W	254·0	17			-0·34			+7·5	2·73	0·16			
128	54 59 30	3 46 41 W	228·0	17			-0·48			+6·1	2·73	0·12			
129	54 59 18	3 46 40 W	231·0	17			-1·67			+5·4	2·73	0·13			
130	54 59 12	3 46 38 W	218·0	17			-1·34			+5·1	2·73	0·16			
131	54 58 54	3 46 20 W	184·0	17			-1·99			+2·9	2·73	0·22			
132	54 59 00	3 46 25 W	199·0	17			-1·67			+4·0	2·73	0·20			
133	54 58 48	3 46 24 W	181·0	17			-2·22			+2·7	2·73	0·22			
134	54 58 41	3 46 26 W	172·0	17			-2·32			+2·2	2·73	0·22			
135	54 58 34	3 46 27 W	173·0	17			-2·82			+1·9	2·73	0·23			
136	54 58 36	3 46 07 W	174·0	17			-3·92			+1·1	2·65	0·32			
137	54 58 42	3 45 47 W	220·0	17			-6·63			+1·0	2·65	0·26			
138	54 58 33	3 45 52 W	259·7	17			-9·46			+0·7	2·65	0·22			
139	54 58 07	3 46 06 W	281·4	17			-12·01			+0·1	2·65	0·22			
140	54 57 52	3 46 10 W	246·0	17			-10·25			+0·1	2·65	0·22			
141	54 57 36	3 46 16 W	255·0	17			-11·12			+0·2	2·65	0·27			
142	54 57 02	3 46 23 W	284·0	17			-14·17			-0·4	2·65	0·24			
143	54 56 48	3 46 03 W	293·2	17			-15·22			-0·5	2·65	0·23			
144	54 56 55	3 46 30 W	240·0	17			-11·69			-0·3	2·65	0·27			
145	54 56 59	3 46 45 W	235·0	17			-10·75			+0·3	2·65	0·34			
146	54 57 08	3 47 08 W	162·8	17			-5·59			+0·8	2·65	0·29			
147	54 56 14	3 44 52 W	312·0	17			-17·52			-0·4	2·65	0·70			
148	54 55 29	3 43 50 W	320·4	17			-17·02			+1·4	2·65	0·51			
149	54 53 23	3 41 40 W	126·0	17			+1·03			+11·0	2·65	0·74			
150	54 53 30	3 41 59 W	249·0	17			-6·49			+10·4	2·65	0·47			

GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :-

1 OBSERVER'S STATION NUMBER	2 LATITUDE N.	3 LONGITUDE (E. or W)	4 ELEVATION feet (Newlyn O.D)	5 STATION TO WHICH CONNECTED	6 GRAVITY DIFFERENCE MEAN VALUE (milligals)	6 DEVIATION	7 TOTAL GRAVITY MEAN VALUE	7 DEVIATION	8 FREE AIR ANOMALY (milligals)	9 BOUGUER ANOMALY ON I.G.F. (milligals)	10 DENSITY VALUES USED IN BOUGUER REDUCTION	11 TERRAIN CORRECTION (milligals)	11 ZONE	12 REMARKS	13 G.S.M. REFERENCE NO. OF STATION
151	54 53 47	3 42 15 W	309.0	18			-11.15 mgl.			+9.2	2.65	0.71		GRAVITY VALUES IN COL	
152	54 54 01	3 42 29 W	303.0	18			-11.82			+8.1	2.65	0.97		7 ARE RELATIVE TO	
153	54 54 14	3 42 50 W	347.0	18			-14.90			+7.1	2.65	0.62		BASE 2000 IN NEWCASTLE	
154	54 54 25	3 43 09 W	413.0	18			-19.29			+6.2	2.65	0.41		WHICH HAS A VALUE OF	
155	54 54 39	3 43 28 W	429.0	18			-21.23			+4.8	2.65	0.34		981.50691 cm. sec^{-2}	
156	54 54 10	3 44 24 W	366.9	18			-16.66			+6.4	2.65	0.44			
157	54 53 59	3 44 33 W	281.0	18			-11.36			+6.8	2.65	0.47			
158	54 53 38	3 44 47 W	177.0	18			-4.46			+8.0	2.65	0.48			
159	54 54 50	3 57 25 W	238.0	1			+2.99			+17.1	2.73	0.47			
160	54 54 16	3 57 13 W	309.1	1			-2.17			+16.6	2.73	0.09			
161	54 53 50	3 57 18 W	296.0	1			-1.84			+16.8	2.73	0.12			
162	54 53 30	3 57 25 W	290.0	1			-1.54			+17.3	2.73	0.16			
163	54 53 13	3 57 29 W	313.0	1			-3.45			+17.1	2.73	0.15			
164	54 52 47	3 57 17 W	348.0	1			-6.22			+17.1	2.73	0.19			
165	54 52 31	3 57 27 W	421.0	1			-11.24			+16.7	2.73	0.19			
166	54 52 10	3 57 12 W	419.0	1			-11.82			+16.7	2.73	0.32			
167	54 52 03	3 56 45 W	467.0	1			-15.39			+16.3	2.73	0.52			
168	54 51 47	3 56 40 W	528.0	1			-18.86			+16.8	2.73	0.44			
169	54 51 34	3 56 22 W	505.0	1			-18.15			+16.9	2.73	0.92			
170	54 51 26	3 55 55 W	434.0	1			-14.31			+16.5	2.73	0.71			
171	54 51 21	3 55 37 W	397.0	1			-12.53			+16.2	2.73	0.73			
172	54 51 17	3 55 17 W	366.0	1			-11.11			+15.9	2.73	0.74			
173	54 51 03	3 54 40 W	361.0	1			-11.63			+15.4	2.73	0.72			
174	54 50 51	3 54 12 W	288.2	1			-8.02			+15.0	2.65	0.46			
175	54 50 42	3 54 02 W	301.0	1			-9.05			+14.8	2.65	0.30			
176	54 50 31	3 54 02 W	300.0	1			-8.64			+15.5	2.65	0.33			
177	54 50 09	3 53 52 W	265.0	1			-6.16			+16.3	2.65	0.28			
178	54 48 47	3 53 25 W	364.0	1			-9.39			+20.7	2.73	0.37			
179	54 48 48	3 52 06 W	44.9	1			+7.81			+18.8	2.73	0.20			
180	54 48 51	3 52 03 W	36.0	1			+8.11			+18.5	2.73	0.22			

GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :-

1 OBSERVER'S STATION NUMBER	2 LATITUDE N.	3 LONGITUDE (E. or W)	4 ELEVATION feet (Newlyn O.D)	5 STATION TO WHICH CONNECTED	6 GRAVITY DIFFERENCE MEAN VALUE (milligals)	6 DEVIATION	7 TOTAL GRAVITY MEAN VALUE	7 DEVIATION	8 FREE AIR ANOMALY (milligals)	9 BOUGUER ANOMALY ON I.G.F. (milligals)	10 DENSITY VALUES USED IN BOUGUER REDUCTION	11 TERRAIN CORRECTION (milligals)	11 ZONE	12 REMARKS	13 G.S.M. REFERENCE NO. OF STATION
181	54 48 49	3 51 48 W	14.5	1			+9.23 mgl.			+18.5	2.60	0.24		GRAVITY VALUES IN COL. 7.	
182	54 50 12	3 52 25 W	145.3	1			-0.89			+14.2	2.65	0.15		ARE RELATIVE TO BASE	
183	54 50 21	3 52 27 W	151.0	1			-1.71			+13.5	2.65	0.16		2000 IN NEWCASTLE	
184	54 50 03	3 52 44 W	125.0 ?	1			+0.55			+14.6	2.65	0.18		WHICH HAS A VALUE OF	
185	54 49 26	3 54 05 W	331.2	1			-7.71			+19.7	2.65	0.25		981.50691 CM. SEC.$^{-2}$	
186	54 49 13	3 54 33 W	387.4	1			-10.42			+20.3	2.73	0.27			
187	54 48 55	3 54 30 W	399.0	1			-10.56			+21.3	2.73	0.23			
188	54 48 41	3 54 00 W	409.6	1			-11.75			+21.2	2.73	0.37			
189	54 51 15	3 59 34 W	329.0	1			-3.58			+20.7	2.73	0.10			
190	54 51 34	3 59 15 W	345.0	1			-4.96			+19.9	2.73	0.17			
191	54 51 41	3 58 55 W	372.0	1			-6.84			+19.4	2.73	0.18			
192	54 51 52	3 58 37 W	386.0	1			-8.28			+18.5	2.73	0.13			
193	54 52 02	3 58 13 W	391.0	1			-9.01			+17.9	2.73	0.18			
194	54 52 18	3 57 54 W	419.0	1			-10.90			+17.2	2.73	0.14			
195	54 53 02	3 56 55 W	327.0	1			-4.78			+16.9	2.73	0.22			
196	54 53 16	3 56 42 W	316.0	1			-3.77			+17.0	2.73	0.24			
197	54 53 33	3 56 25 W	303.0	1			-2.78			+16.8	2.73	0.25			
198	54 53 48	3 56 13 W	287.0	1			-1.65			+16.6	2.73	0.18			
199	54 54 03	3 55 51 W	266.0	1			-0.22			+16.4	2.73	0.16			
200	54 54 14	3 55 43 W	241.0	1			+1.29			+16.2	2.73	0.17			
201	54 54 18	3 49 53 W	42.0	1			+5.19			+8.7	2.65	0.63			
202	54 54 16	3 49 48 W	24.0	1			+6.36			+8.6	2.65	0.37			
203	54 54 16	3 49 41 W	23.0	1			+6.05			+8.2	2.65	0.34			
204	54 54 17	3 49 38 W	25.0	1			+5.76			+7.9	2.65	0.27			
205	54 54 16	3 49 26 W	28.0	1			+5.02			+7.3	2.65	0.21			
206	54 54 17	3 49 12 W	18.5	1			+5.28			+7.0	2.65	0.23			
207	54 54 51	3 49 53 W	39.0	17			+4.82			+7.0	2.65	0.28			
208	54 54 47	3 50 11 W	30.0	17			+6.37			+8.2	2.65	0.42			
209	54 54 48	3 50 23 W	37.6	17			+6.24			+8.9	2.65	0.73			
210	54 54 18	3 48 57 W	55.0	17			+2.57			+6.4	2.65	0.19			

GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :–

1 OBSERVER'S STATION NUMBER	2 LATITUDE N.	3 LONGITUDE (E. or W)	4 ELEVATION feet (Newlyn O.D)	5 STATION TO WHICH CONNECTED	6 GRAVITY DIFFERENCE MEAN VALUE (milligals)	6 DEVIATION	7 TOTAL GRAVITY MEAN VALUE	7 DEVIATION	8 FREE AIR ANOMALY (milligals)	9 BOUGUER ANOMALY ON I.G.F. (milligals)	10 DENSITY VALUES USED IN BOUGUER REDUCTION	11 TERRAIN CORRECTION (milligals)	11 ZONE	12 REMARKS	13 G.S.M. REFERENCE NO. OF STATION
211	54 54 19	3 49 03 W	51·0	17			+2·57 mgl.			+6·1	2·65	0·20		GRAVITY VALUES IN COL 7.	
212	54 54 13	3 48 51 W	43·0	17			+3·24			+6·5	2·65	0·18		ARE RELATIVE TO BASE	
213	54 54 50	3 49 01 W	51·0	17			+2·28			+5·1	2·65	0·20		2000 IN NEWCASTLE	
214	54 55 51	3 44 30 W	314·0	17			−17·77			+0·1	2·65	0·82		WHICH HAS A VALUE OF	
215	54 56 30	3 45 15 W	321·4	17			−17·84			−0·9	2·65	0·38		981·50691 CM. SEC⁻²	
216	54 54 59	3 42 42 W	251·0	17			−12·04			+3·8	2·65	0·39			
217	54 53 41	3 40 10 W	18·0	18			+6·77			+9·6	2·73	0·52			
218	54 53 29	3 40 23 W	17·0	18			+7·05			+10·0	2·73	0·41			
219	54 53 23	3 40 32 W	20·3	18			+7·15			+10·4	2·73	0·38			
220	54 53 12	3 40 24 W	21·0	18			+7·44			+10·9	2·60	0·29			
221	54 53 08	3 40 09 W	18·0	18			+7·98			+11·3	2·60	0·25			
222	54 52 58	3 40 01 W	20·0	18			+8·28			+11·9	2·60	0·21			
223	54 52 51	3 40 06 W	18·0	18			+8·44			+12·1	2·60	0·19			
224	54 52 49	3 39 40 W	20·0	18			+8·85			+12·7	2·60	0·18			
225	54 52 48	3 39 26 W	20·0	18			+9·08			+12·9	2·60	0·17			
226	54 52 42	3 36 26 W	40·0	18			+11·45			+16·6	2·60	0·11			
227	54 53 17	3 37 20 W	69·0	18			+8·81			+14·8	2·60	0·21			
228	54 53 42	3 38 00 W	119·0	18			+3·94			+12·4	2·73	0·38			
229	54 53 40	3 38 16 W	78·0	18			+6·26			+12·5	2·73	0·38			
230	54 53 39	3 38 54 W	63·0	18			+6·29			+11·7	2·73	0·42			
231	54 53 46	3 39 37 W	23·0	18			+6·57			+9·6	2·73	0·59			
232	54 54 31	3 40 53 W	148·0	17			−1·98			+7·6	2·65	0·60			
233	54 54 54	3 41 44 W	239·0	17			−8·95			+5·3	2·65	0·41			
234	54 55 30	3 52 48 W	346·0	17			−6·65			+12·6	2·73	0·13			
235	54 55 17	3 53 11 W	310·0	17			−4·38			+13·0	2·73	0·08			
236	54 55 07	3 53 30 W	315·0	17			−3·83			+14·1	2·73	0·08			
237	54 54 51	3 53 45 W	285·5	17			−2·11			+14·5	2·73	0·13			
238	54 49 00	3 54 56 W	397·5	1			−10·11			+21·5	2·73	0·20			
239	54 49 05	3 55 46 W	369·0	1			−7·79			+21·9	2·73	0·14			
240	54 48 26	3 56 51 W	222·0	1			+1·99			+23·9	2·73	0·15			

GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :-

1	2	3	4	5	6		7		8	9	10	11		12	13
OBSERVER'S STATION NUMBER	LATITUDE N.	LONGITUDE (E. or W.)	ELEVATION feet (Newlyn O.D.)	STATION TO WHICH CONNECTED	GRAVITY DIFFERENCE MEAN VALUE (milligals)	DEVIATION	TOTAL GRAVITY MEAN VALUE	DEVIATION	FREE AIR ANOMALY (milligals)	BOUGUER ANOMALY ON I.G.F. (milligals)	DENSITY VALUES USED IN BOUGUER REDUCTION	TERRAIN CORRECTION (milligals)	ZONE	REMARKS	G.S.M. REFERENCE NO. OF STATION
241	54 51 09	3 52 13 W	73·0	1			+2·23 mgl.			+11·7	2·65	-0·29		GRAVITY VALUES IN COL. 7	
242	54 51 17	3 52 02 W	47·0	1			+3·59			+11·3	2·65	0·27		ARE RELATIVE TO BASE	
243	54 52 43	3 51 42 W	27·0	1			+6·63			+11·3	2·65	0·49		2000 IN NEWCASTLE	
244	54 52 56	3 51 38 W	32·0	1			+6·61			+11·3	2·65	0·44		WHICH HAS A VALUE OF	
245	54 53 19	3 51 17 W	63·0	1			+4·76			+10·5	2·73	0·30		981·50691 cm. sec^{-2}	
246	54 53 24	3 50 35 W	57·0	1			+4·97			+10·2	2·65	0·17			
247	54 53 55	3 50 16 W	41·0	1			+5·07			+8·6	2·73	0·24			
248	54 53 59	3 50 12 W	47·0	1			+4·56			+8·3	2·73	0·23			
249	54 55 56	3 49 22 W	36·0	1			+4·03			+4·4	2·65	0·21			
250	54 55 52	3 49 05 W	37·0	1			+3·20			+3·7	2·65	0·21			
251	54 56 06	3 49 43 W	60·0	1			+3·50			+5·1	2·65	0·21			
252	54 55 25	3 41 20 W	274·7	18			-12·25			+4·6	2·65	1·52			
253	54 55 12	3 43 15 W	272·3	18			-13·17			+2·8	2·65	0·50			
254	54 58 02	3 47 21 W	165·0 ?	18			-2·49			+2·7	2·65	0·18			
255	54 58 21	3 47 40 W	260·7	18			-5·91			+4·3	2·73	0·20			
256	54 58 36	3 48 06 W	245·9	18			-2·37			+6·6	2·73	0·19			
257	54 58 56	3 48 43 W	219·9	18			+2·41			+9·3	2·73	0·15			
258	55 00 02	3 50 20 W	355·4	17			-0·28			+13·2	2·73	0·18			
259	55 00 34	3 50 18 W	415·0 ?	17			-2·62			+13·6	2·73	0·23			
260	55 00 58	3 51 40 W	349·0	17			+3·18			+14·8	2·73	0·11			
261	55 00 43	3 51 56 W	346·7	17			+3·13			+15·0	2·73	0·09			
262	55 01 28	3 52 50 W	381·9 ?	17			+1·69			+14·6	2·73	0·15			
263	55 02 54	3 53 49 W	553·0	17			-7·99			+13·3	2·73	0·38			
264	55 02 25	3 53 34 W	533·5	17			-7·35			+13·6	2·73	0·46			
265	55 02 02	3 52 40 W	478·5	17			-3·76			+14·1	2·73	0·16			
266	55 02 09	3 51 02 W	496·0	17			-4·36			+14·5	2·73	0·26			
267	55 02 08	3 49 42 W	393·3	17			+1·84			+14·5	2·73	0·16			
268	55 01 43	3 49 48 W	411·5	17			+0·19			+14·5	2·73	0·11			
269	55 01 26	3 49 42 W	413·4	17			-0·75			+14·1	2·73	0·12			
270	55 01 07	3 48 05 W	400·0	17			-2·30			+12·1	2·73	0·09			

GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :-

1 OBSERVER'S STATION NUMBER	2 LATITUDE N.	3 LONGITUDE (E. or W)	4 ELEVATION feet (Newlyn O.D)	5 STATION TO WHICH CONNECTED	6 GRAVITY DIFFERENCE MEAN VALUE (milligals)	6 DEVIATION	7 TOTAL GRAVITY MEAN VALUE	7 DEVIATION	8 FREE AIR ANOMALY (milligals)	9 BOUGUER ANOMALY ON I.G.F. (milligals)	10 DENSITY VALUES USED IN BOUGUER REDUCTION	11 TERRAIN CORRECTION (milligals)	11 ZONE	12 REMARKS	13 G.S.M. REFERENCE NO. OF STATION
271	55 01 07	3 47 50 W	388.0	17			-1.76 mgl.			+12.0	2.73	0.08		GRAVITY VALUES IN	
272	55 01 32	3 56 53 W	292.0	17			+5.16			+12.8	2.73	0.26		COL. 7 ARE RELATIVE TO	
273	55 01 12	3 56 28 W	218.0	17			+9.57			+13.3	2.73	0.24		BASE 2000 IN NEWCASTLE	
274	55 01 12	3 56 01 W	202.0	17			+10.84			+13.7	2.73	0.33		WHICH HAS A VALUE OF	
275	55 00 39	3 55 33 W	236.0	17			+8.98			+14.5	2.73	0.20		981.50691 CM. SEC^{-2}	
276	55 00 05	3 55 21 W	228.0	17			+9.51			+15.4	2.73	0.21			
277	54 59 32	3 54 50 W	193.0	17			+11.03			+15.6	2.73	0.19			
278	54 59 03	3 53 40 W	148.0	17			+12.59			+15.1	2.73	0.16			
279	54 58 54	3 52 54 W	134.1	17			+12.63			+14.6	2.73	0.20			
280	55 00 01	4 01 52 W	157.0	17			+8.83			+10.6	2.73	0.26			
281	54 59 27	3 59 47 W	156.0	17			+9.83			+12.4	2.73	0.34			
282	54 58 55	3 59 15 W	160.0	17			+9.96			+13.4	2.73	0.20			
283	54 58 25	3 58 39 W	181.0	17			+9.42			+14.8	2.73	0.17			
284	54 57 40	3 57 45 W	155.0	17			+10.92			+15.8	2.73	0.12			
285	54 57 18	3 57 07 W	166.0	17			+9.80			+15.8	2.73	0.08			
286	54 56 56	3 56 37 W	162.0	17			+9.50			+15.8	2.73	0.07			
287	54 56 43	3 56 17 W	165.0	17			+8.90			+15.6	2.73	0.07			
288	54 55 48	3 57 00 W	179.0	17			+7.07			+15.9	2.73	0.06			
289	54 55 14	3 58 26 W	149.0	17			+8.67			+16.6	2.73	0.09			
290	54 52 30	4 03 54 W	98.0	17			+10.01			+19.1	2.73	0.38			
291	54 52 53	4 03 07 W	76.0	17			+11.14			+18.3	2.73	0.31			
292	54 54 19	4 03 17 W	97.0	17			+9.88			+16.5	2.73	0.55			
293	54 54 42	4 03 20 W	147.0	17			+7.52			+16.5	2.73	0.54			
294	54 55 33	4 04 08 W	221.0	17			+2.52			+14.4	2.73	0.27			
295	54 56 24	4 04 05 W	238.0	17			+1.42			+13.1	2.73	0.18			
296	54 57 12	4 04 00 W	259.0	17			+0.16			+11.9	2.73	0.15			
297	54 57 24	4 01 10 W	283.0	17			+1.20			+14.0	2.73	0.06			
298	54 57 16	4 00 33 W	265.0	17			+2.67			+14.6	2.73	0.06			
299	54 56 58	4 00 45 W	225.0	17			+4.81			+14.8	2.73	0.07			
300	54 56 14	4 00 55 W	221.0	17			+4.82			+15.6	2.73	0.06			

GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :–

1 OBSERVER'S STATION NUMBER	2 LATITUDE N.	3 LONGITUDE (E. or W.)	4 ELEVATION feet (Newlyn O.D.)	5 STATION TO WHICH CONNECTED	6 GRAVITY DIFFERENCE MEAN VALUE (milligals)	6 DEVIATION	7 TOTAL GRAVITY MEAN VALUE	7 DEVIATION	8 FREE AIR ANOMALY (milligals)	9 BOUGUER ANOMALY ON I.G.F. (milligals)	10 DENSITY VALUES USED IN BOUGUER REDUCTION	11 TERRAIN CORRECTION (milligals)	11 ZONE	12 REMARKS	13 G.S.M. REFERENCE NO. OF STATION
301	54 55 24	4 00 10 W	167.0	17			+7.46 mgl.			+16.2	2.73	0.09		GRAVITY VALUES IN	
302	54 54 59	3 59 07 W	153.0	17			+8.19			+16.7	2.73	0.09		COL. 7 ARE RELATIVE TO	
303	54 56 35	4 00 11 W	143.0	17			+8.19			+16.8	2.73	0.18		BASE 2000 IN NEWCASTLE	
304	54 54 12	4 01 28 W	171.0	17			+6.31			+17.1	2.73	0.14		WHICH HAS A VALUE OF	
305	54 50 34	3 52 54 W	150.0	17			−2.08			+12.9	2.65	0.30		981.50691 cm. sec.$^{-2}$	
306	54 51 30	3 51 12 W	56.9 ?	17			+4.20			+12.1	2.65	0.17			
307	54 52 17	3 51 30 W	59.2	17			+4.29			+11.4	2.65	0.33			
308	54 52 36	3 50 15 W	44.0	17			+5.55			+11.3	2.65	0.37			
309	54 54 44	3 58 14 W	204.2	17			+4.94			+16.8	2.73	0.09			
310	54 54 21	3 58 55 W	162.2	17			+7.17			+17.2	2.73	0.15			
311	54 54 06	3 59 07 W	162.2	17			+6.89			+17.3	2.73	0.22			
312	54 53 37	3 59 30 W	194.0	17			+4.14			+17.1	2.73	0.19			
313	54 53 11	4 00 10 W	187.0	17			+4.36			+17.6	2.73	0.26			
314	54 52 41	4 00 42 W	207.0	17			+3.21			+18.4	2.73	0.26			
315	54 52 22	4 00 52 W	224.0	17			+1.82			+18.4	2.73	0.23			
316	54 51 30	4 02 30 W	18.0	17			+15.07			+20.8	2.73	0.23			
317	54 50 46	4 02 23 W	26.0	17			+14.83			+22.0	2.73	0.29			
318	54 50 17	4 02 47 W	23.6	17			+15.24			+23.0	2.73	0.28			
319	54 48 17	3 57 02 W	245.0	1			+0.49			+24.2	2.73	0.35			
320	54 48 09	3 58 03 W	402.0	1			−8.60			+24.5	2.73	0.26			
321	54 48 11	3 58 30 W	366.0	1			−6.01			+24.9	2.73	0.22			
322	54 48 08	3 59 10 W	317.0	1			−2.91			+25.3	2.73	0.31			
323	54 48 22	4 00 17 W	290.0	1			−1.01			+25.1	2.73	0.16			
324	54 48 33	4 01 12 W	325.0	1			−2.81			+25.1	2.73	0.17			
325	54 48 52	4 02 17 W	61.0	1			+13.55			+25.5	2.73	0.26			
326	54 49 05	4 02 40 W	22.0	1			+15.89			+25.2	2.73	0.27			
327	54 50 34	4 05 50 W	115.0	1			+9.43			+22.0	2.73	0.16			
328	54 49 58	4 05 25 W	92.0	1			+11.58			+23.6	2.73	0.13			
329	54 47 07	3 57 05 W	111.0	1			+7.70			+25.0	2.73	0.21			
330	54 47 27	3 57 02 W	100.0	1			+8.75			+25.0	2.73	0.30			

GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :-

1 OBSERVER'S STATION NUMBER	2 LATITUDE N.	3 LONGITUDE (E. or W.)	4 ELEVATION feet (Newlyn O.D.)	5 STATION TO WHICH CONNECTED	6 GRAVITY DIFFERENCE MEAN VALUE (milligals)	6 DEVIATION	7 TOTAL GRAVITY MEAN VALUE	7 DEVIATION	8 FREE AIR ANOMALY (milligals)	9 BOUGUER ANOMALY ON I.G.F. (milligals)	10 DENSITY VALUES USED IN BOUGUER REDUCTION	11 TERRAIN CORRECTION (milligals)	11 ZONE	12 REMARKS	13 G.S.M. REFERENCE NO. OF STATION
331	54 48 13	3 59 51 W	254.0	1			+1.13 mgl.			+25.3	2.73	0.35		GRAVITY VALUES IN	
332	54 47 36	4 00 15 W	216.0	1			+3.24			+26.0	2.73	0.16		COL. 7 ARE RELATIVE TO	
333	54 47 36	4 01 05 W	242.0	1			+1.79			+26.1	2.73	0.17		BASE 2000 IN NEWCASTLE	
334	54 47 42	4 02 00 W	283.0	1			-0.43			+26.2	2.73	0.19		WHICH HAS A VALUE OF	
335	54 47 16	4 01 57 W	225.0	1			+2.63			+26.7	2.73	0.41		981.50691 cm.sec^{-2}	
336	54 46 57	4 02 41 W	146.6	1			+7.25			+26.9	2.73	0.19			
337	54 47 13	4 03 11 W	154.1	1			+7.31			+27.1	2.73	0.24			
338	54 48 09	4 03 13 W	31.0	1			+15.20			+26.3	2.73	0.20			
339	54 52 54	3 49 40 W	49.4	1			+4.26			+10.1	2.73	0.50			
340	54 53 00	3 49 45 W	102.4	1			+0.60			+9.5	2.65	0.60			
341	54 49 37	3 54 02 W	308.0	1			-7.09			+18.7	2.65	0.25			
342	54 47 16	3 58 43 W	269.0	1			-1.03			+25.4	2.73	0.17			
343	54 47 39	3 58 38 W	334.0	1			-4.14			+25.6	2.73	0.20			
344	54 48 33	3 58 01 W	443.0	1			-10.69			+24.3	2.73	0.23			
345	54 49 33	3 57 05 W	354.0	1			-5.66			+22.6	2.73	0.23			
346	54 49 28	3 58 58 W	367.0	1			-5.46			+23.6	2.73	0.16			
347	54 49 48	3 59 52 W	298.0	1			-1.00			+23.5	2.73	0.17			
348	54 49 34	4 01 23 W	75.0	1			+12.37			+24.3	2.73	0.41			
349	54 49 16	4 01 43 W	56.0	1			+13.53			+24.9	2.73	0.63			
350	54 49 46	3 52 15 W	141.5	1			+0.29			+15.7	2.65	0.12			
351	54 49 30	3 50 17 W	87.7	1			+3.79			+16.4	2.65	0.15			
352	54 49 25	3 50 40 W	137.8	1			+0.87			+16.6	2.65	0.18			
353	54 50 07	3 57 49 W	370.0	1			-6.20			+22.1	2.73	0.12			
354	54 50 44	3 58 16 W	386.0	1			-7.14			+21.3	2.73	0.14			
355	54 50 57	3 58 53 W	337.0	1			-4.16			+21.0	2.73	0.11			
356	54 50 10	3 48 29 W	[illegible]9.0	17			+7.78			+14.6	2.65	0.07			
357	54 50 19	3 48 31 W	[illegible]-50	17			+8.63			+14.4	2.73	0.08			
358	54 50 29	3 48 31 W	-5.0	17			+8.90			+14.4	2.73	0.08			
359	54 52 34	3 36 05 W	35.0	17			+12.83			+17.9	2.60	0.10			
Dumfries	55 04 23	3 35 07 W	66.9				+12.39			-	-	-			

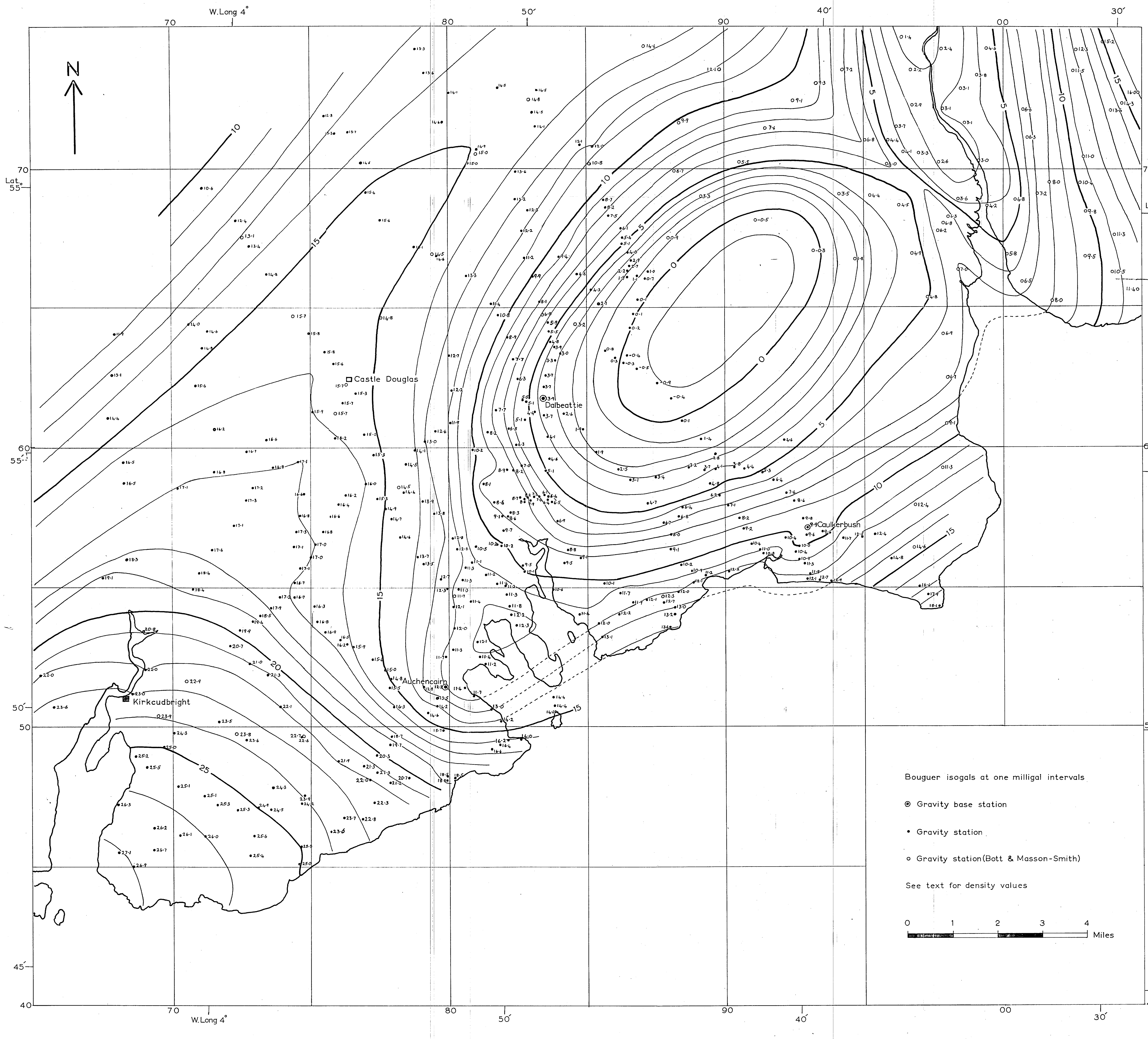
GRAVIMETER SURVEY : *GRAVITY DATA SHEET*

FILE REF. :-

1 OBSERVER'S STATION NUMBER	2 LATITUDE N.	3 LONGITUDE (E. or W)		4 ELEVATION feet (Newlyn O.D.)	5 STATION TO WHICH CONNECTED	6 GRAVITY DIFFERENCE MEAN VALUE (milligals)	6 DEVIATION	7 TOTAL GRAVITY MEAN VALUE	7 DEVIATION	8 FREE AIR ANOMALY (milligals)	9 BOUGUER ANOMALY ON I.G.F. (milligals)	10 DENSITY VALUES USED IN BOUGUER REDUCTION	11 TERRAIN CORRECTION (milligals)	11 ZONE	12 REMARKS	13 G.S.M. REFERENCE NO. OF STATION
331	54 48 13	3 59 51	W	254.0	1			+1.13 mgl.			+25.3	2.73	0.75		Gravity values in	
332	54 47 36	4 00 15	W	216.0	1			+3.24			+26.0	2.73	0.16		Col. 7 are relative to	
333	54 47 36	4 01 05	W	242.0	1			+1.79			+26.1	2.73	0.17		Base 2000 in Newcastle	
334	54 47 42	4 02 00	W	283.0	1			-0.43			+26.2	2.73	0.19		which has a value of	
335	54 47 16	4 01 57	W	225.0	1			+2.63			+26.7	2.73	0.41		981.50691 cm. sec.$^{-2}$	
336	54 46 57	4 02 41	W	146.6	1			+7.25			+26.9	2.73	0.19			
337	54 47 13	4 03 11	W	154.1	1			+7.31			+27.1	2.73	0.24			
338	54 48 09	4 03 13	W	31.0	1			+15.20			+26.3	2.73	0.20			
339	54 52 54	3 49 40	W	49.4	1			+4.26			+10.1	2.73	0.50			
340	54 53 00	3 49 45	W	102.4	1			+0.60			+9.5	2.65	0.60			
341	54 49 37	3 54 02	W	308.0	1			-7.09			+18.7	2.65	0.25			
342	54 47 16	3 58 43	W	269.0	1			-1.03			+25.4	2.73	0.17			
343	54 47 39	3 58 38	W	334.0	1			-4.14			+25.6	2.73	0.20			
344	54 48 33	3 58 01	W	443.0	1			-10.69			+24.3	2.73	0.23			
345	54 49 33	3 57 05	W	354.0	1			-5.66			+22.6	2.73	0.23			
346	54 49 28	3 58 58	W	367.0	1			-5.46			+23.6	2.73	0.16			
347	54 49 48	3 59 52	W	298.0	1			-1.00			+23.5	2.73	0.17			
348	54 49 34	4 01 23	W	75.0	1			+12.37			+24.3	2.73	0.41			
349	54 49 16	4 01 43	W	56.0	1			+13.53			+24.9	2.73	0.63			
350	54 49 46	3 52 15	W	141.5	1			+0.29			+15.7	2.65	0.12			
351	54 49 30	3 50 17	W	87.7	1			+3.79			+16.4	2.65	0.15			
352	54 49 25	3 50 40	W	137.8	1			+0.87			+16.6	2.65	0.18			
353	54 50 07	3 57 49	W	370.0	1			-6.20			+22.1	2.73	0.12			
354	54 50 44	3 58 16	W	386.0	1			-7.14			+21.3	2.73	0.14			
355	54 50 57	3 58 53	W	337.0	1			-4.16			+21.0	2.73	0.11			
356	54 50 10	3 48 29	W	[illegible]9.0	17			+7.78			+14.6	2.65	0.07			
357	54 50 19	3 48 31	W	[illegible]-50	17			+8.63			+14.4	2.73	0.08			
358	54 50 29	3 48 31	W	-5.0	17			+8.90			+14.4	2.73	0.08			
359	54 52 34	3 36 05	W	35.0	17			+12.83			+17.9	2.60	0.10			
Dumfries	55 04 23	3 35 07	W	66.9				+12.39			-	-	-			

APPENDIX B

BOUGUER ANOMALY MAP OF THE CRIFFEL GRANODIORITE



BOUGUER ANOMALIES & GEOLOGY OF THE CRIFFEL GRANODIORITE