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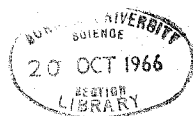
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Gravity and Magnetic Investigations of the Deep Structure
of
The North Irish Sea.

A Thesis submitted for the Degree of Doctor of Philosophy
In the Faculty of Science
of
The University of Durham.

University College,
Durham.
1965.

David G.G. Young.



Summary

This thesis describes and analyses the results of surveys conducted during the summer months of 1963, 1964, and 1965 with an underwater North American gravimeter in the Irish Sea, together with certain detailed magnetic data obtained using a sea-borne proton magnetometer. In addition use has been made of the Aero-magnetic Maps prepared by the Geological Survey in order to co-ordinate and qualify the observed gravity field.

For the purpose of this work the North Irish Sea has been defined as that area bounded in the south by a line approximately from Holyhead in North Wales to Dublin. A line running from the Mourne Mountains to the Calf of Man, and from Ramsey on the east coast of the Isle of Man to Fleetwood formed the northern limit of operation. The surveys were directed towards extending the gravity coverage already accomplished in the north-east of the area. They provide further evidence relevant to the evaluation of the deep structure of the Irish Sea Basin.

The low Bouguer Anomaly values known to exist in the north-east of the area as a result of an earlier marine gravity survey have been shown to extend over a wide area in the eastern part of the North Irish Sea. The original interpretation in terms of a deep sedimentary basin containing low density sediments was confirmed. A large negative anomaly was also discovered in the Dublin Bay area and this was again interpreted as a large sedimentary basin.

A linear magnetic anomaly that appears on the Aero-magnetic Maps in the vicinity of Morecambe Bay was the subject of detailed traverses using the sea-borne proton magnetometer. It was concluded that a sill or lavas dipping to the north with a direction of magnetisation towards the south could best account for the observed anomaly.

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Chapter 1.

The Geological Environment.

1. General Introduction.

This chapter contains a summary of the geological setting of the area under investigation. The major stratigraphical divisions are systematically described according to the separate regions in which they occur. The rocks surrounding the North Irish Sea can be divided into four main stratigraphical units, namely the Pre-Cambrian, Lower Palaeozoic, Carboniferous, and Permo-Triassic. These units are normally separated by major unconformities.

The distribution of the Pre-Cambrian and Lower Palaeozoic rocks is of importance in connection with interpretation of the magnetic data. Lower Palaeozoic strata form the structural framework of the area and a knowledge of their composition and distribution is necessary for analysis of the gravity field. Carboniferous and Permo-Triassic sediments occur in sedimentary basins in several widely separated localities bordering the marine area. A simplified geological map is presented in conjunction with the Bouguer Anomaly map (Plate 1). The names of the majority of the localities referred to in the text of this chapter are also included on this map which is contained inside the back cover.

2. The Pre-Cambrian.

2.1 Anglesey.

The oldest rocks exposed on land adjacent to the North Irish Sea are of Pre-Cambrian age. A great development of these rocks forms the Mona Complex of Anglesey, which comprises one or more series of highly altered rocks.



Greenly (1919) distinguished three major subdivisions, the Gneisses, the Bedded Series, and the Coedana Granite which he considered to have formed successively, with the Gneiss constituting the basal group.

Further work (Shackleton, 1952) has suggested that Greenly's view of the age relationship is incorrect and that the Gneisses are the highly altered equivalent of the Bedded Series. In a development of about 20,000 feet the Bedded Series contains typical geosynclinal sediments including grits, grey-wackes, conglomerates, shales and muds. The apparent dimensions of this crustal downwarp are comparable with those of the later Lower Palaeozoic geosyncline.

The folds affecting the rocks of the Mona Complex trend approximately north-east, south-west (Shackleton 1952). The style of tectonics is still uncertain. The Coedana Granite was probably intruded towards the end of the large scale folding. The long axis of this granite is aligned in a north-east to south-west direction similar to the structural trend of the strata over a wide area in Anglesey.

2.2. Pre-Cambrian rocks elsewhere.

The other rocks of possible Pre-Cambrian age immediately bordering the North Irish Sea are found in Ireland where the Bray Series of widely accepted Cambrian age has occasionally been assigned to the Pre-Cambrian. The Bray Series is described in section 3.4.

3. Lower Palaeozoic rocks and Caledonian folding.

3.1 Southern Scotland.

Southern Scotland constitutes the most northerly area adjacent to the Irish Sea in which Lower Palaeozoic strata are present. This region is bounded

to the north by the faulted southern margin of the Midland Valley and to the south by the Solway Firth and the Cheviot Hills. Between these boundaries the upland region extends almost continuously from the North Sea to the North Channel. For the purpose of this chapter it is only that part lying to the north of the Solway Firth and westward to the Mull of Galloway that is of interest.

Most of this area is occupied by highly folded Ordovician and Silurian rocks, mainly of marine origin (Pringle, 1935). Although some tectonic movement occurred at the close of the Arenig, the major folding took place at the end of Silurian time when the region suffered intense lateral pressure which folded the rocks in a north-east to south-west (Caledonian) direction throughout the area. As a result of this folding and associated faulting the rocks of the Southern Uplands form three distinctive belts, comprising a northern belt of highly folded Arenig, Glenkiln, and Hartfell rocks, a broad central area composed mainly of similarly folded Llandovery greywackes and shales, and a southern belt in which isoclinally folded Wenlock rocks occur.

3.2 The Lake District.

Lower Palaeozoic rocks form most of the Lake District where strata ranging from the Upper Cambrian to the Upper Silurian are present. The base of the succession is made up of the Skiddaw Slates of Upper Cambrian and Lower Ordovician age comprising 6,500 feet of slates, shales, and mudstones (Mitchell, 1956). The general tendency is for younger rocks to outcrop steadily southwards with the Skiddaw Slates overlain by a thickness in excess of 10,000 feet consisting mainly of andesitic lavas and pyroclastics known as the Borrowdale Volcanic Series. The succession is continued by a thin Upper Ordovician and

Lower Silurian group of sediments followed by approximately 13,000 feet of Middle and Upper Silurian shales and greywackes.

The main structural features of the Lake District rocks were established during the subsequent Caledonian movements which appear to have initiated intense pressures directed along south-south-east and north-north-west lines. The strike impressed upon the rocks is arcuate, changing from south-west in the south-west of the region to east-west and finally to south-east in the south-east of the Lake District. A broad anticlinal structure was developed through Skiddaw and a complementary syncline through Scafell. Numerous minor folds with similar trends accompany these major structures.

3.3 North Wales.

Continuing further south, the Lancashire coastal plain is composed entirely of Mesozoic rocks and it is in North Wales that the next extensive outcrop of Lower Palaeozoic rocks occurs along the margin of the Irish Sea. Rocks of Cambrian age form an elliptically-shaped outcrop running parallel with the Menai Straits separating Anglesey from the Mainland, and at a distance of about three miles from that passage. The oldest rocks are represented by coarse basal conglomerates resting with great unconformity upon Pre-Cambrian strata (Smith and Neville George, 1935). The succession consists of a series of fine grits, mudstones and shales. The rocks of the Cambrian system suffered minor earth movements which folded them into gentle synclines and anticlines before the succeeding Ordovician sediments were laid down.

Outcrops of Ordovician rocks occupy large areas in North Wales. The outcrops closest to the Irish Sea occur in the coastal section stretching from the base of the Great Ormes' Head to the entrance of the Menai Straits,

and in parts of Anglesey itself. In Anglesey large outliers of Ordovician rock rest on Pre-Cambrian strata. Rocks of Silurian age cover very large areas in North Wales. In the northern part, bordering the Irish Sea, they are to be found over most of the Denbighshire moors and in the Clwydian Range. The strata display considerable lateral variation with arenaceous and conglomeratic material forming the unconformable base of the system in the eastern part of the area. In the south-west and west, fine grained sediments pass without break from the Ordovician into the Lower Silurian.

The Lower Palaeozoic period was terminated as elsewhere by the earth movements of the Caledonian Orogeny. The result of these movements was to fold the rocks about a north-east to south-west axis. This was accompanied by faulting and thrusting, the Carmel Head Thrust in Anglesey which causes rocks of the Mona Complex to override Ordovician sediments providing a notable example (Greenly, 1919).

3.4 Ireland.

From the detailed work conducted over many years it has become apparent that, geologically, Ireland forms a natural western continuation of Great Britain (Charlesworth, 1963). It has been suggested that some of the geological problems occurring in England may be solved as a result of study of structures in Ireland, and attention has frequently been drawn to the apparent continuity of structural lines and features which can be traced across the Irish Sea Depression. In the north of Ireland the Caledonoid trend of the structures has been linked with similar occurrences in Scotland, in particular the Boundary Faults of the Midland Valley, while further south a similar structural exercise has projected the dominant strike lines of the Lower

Palaeozoic rocks of the Lake District into the areas north and west of Dublin.

The framework of the country is largely composed of Lower Palaeozoic rocks forming the existing high ground with a wide plain occupying the interior which is underlain by Carboniferous material, predominantly limestone. The rocks bordering the Irish Sea which are widely accepted as being of Cambrian age are known as the Bray Series and outcrop in three separate areas, namely the Hill of Howth on the north side of Dublin Bay, the Bray and Greystones area itself, and a long strip stretching south-westwards from Cahore Point to the south coast of County Wexford which is outside the relevant area. The second two occurrences form the Bray Anticlinorium in the north and the Cahore Anticlinorium in the south, separated by the Arklow Synclinorium made up almost entirely of Ordovician strata. A dominant direction of folding with a Caledonoid trend exists in this south-eastern part of Ireland with the elongate outcrop of the Leinster Granite extending south-south-west from near Dublin, flanked on both sides by the Lower Palaeozoic sediments and associated igneous rocks to form a great Caledonian Anticline (Smyth et al., 1939). The Cambrian succession is made up of hard purple and green greywackes, highly cleaved and crushed slates, massive quartzites, together with conglomerates or breccias of local rocks. The total thickness is apparently several thousand feet (Charlesworth, 1963). At Howth the rocks consist of massive quartzites and greywackes with breccias and well-cleaved green and variegated slates which are intensely folded and crushed. The closely spaced anticlines and synclines plunge steeply east and were later affected by longitudinal and transverse faults. Similar rocks, equally distorted, outcrop in Ireland's Eye approximately two miles to the north of Howth.

The Ordovician rocks which lie near to the east coast occur in Leinster and in inliers in the Central Plain. In Leinster, as mentioned above, the Ordovician rocks display a Caledonoid trend where they flank both sides of the Leinster granite which reaches the coast in the vicinity of Dun Laoghaire. In general, the Ordovician consists of slates with thin fine-grained greywackes with interspersed volcanic and hypabyssal rocks. To the east of the Leinster Granite at the south-western margin of the Bray Anticlinorium the strata consists of alternating sandstones and siltstones with slates making up a thickness of 1,500 feet (Tremlett, 1959). North of Dublin, Ordovician rocks outcrop in Portrane where they consist of a volcanic suite with intercalated shales, unconformably overlain by bedded limestones followed by a crush conglomerate at the contact with the succeeding greywackes of estimated Silurian age. In Lambay Island the limestones and shales were deposited around a centre of vulcanism with which they are probably for the most part contemporaneous. Fragmentary igneous rocks and disturbed sediments accumulated to form massive conglomerates which became covered by calcareous mud. The accompanying tuffs are succeeded by brown slates and andesitic lavas, followed by a limestone containing a similar fauna to that found in Portrane. This is followed by a conglomerate and slates with impure limestone.

The main Silurian outcrop occurs in a large triangular area bordering the east coast from near Drogheda northwards to the Holywood Hills south of Belfast. Westwards the outcrop narrows to an apex near the River Shannon. Within this large area occur more recent granites and a series of small inliers of Ordovician age lying in a Caledonian orientation. The rocks include grey and green greywackes, grits, flags, siltstones, a few coarse quartz conglomerates, and some thick graptolitic mudstones.

Minor tectonic movements occurred throughout the Lower Palaeozoic in Ireland but these were merely the forerunners of the Caledonian Orogeny which folded the Lower Palaeozoic rocks and caused the Caledonian trend to be indelibly impressed upon the geology. This can be seen in the boundaries of the Ordovician and Silurian rocks together with those of the Leinster and Newry granites. The Leinster Granite was intruded following the main Caledonian Orogeny in this area and is about 70 miles in length, with a maximum width of approximately 12 miles at outcrop (Smyth et al., 1939). This igneous mass forms high ground with the summits between 1,500 and 3,000 feet above sea-level. The age has been given as Devonian and although the contact with the Carboniferous at the northern end is not exposed, the flow form has been taken to indicate that the granite ends a short distance north of the existing outcrops and a faulted margin has been suggested for this contact (Cole, 1921; Turner, 1950; Charlesworth, 1963).

3.5 The Isle of Man.

The Manx Slate Series (Lamplugh 1903) which forms the central massif of the Island has been divided into eleven formations having a collective thickness of about 25,000 feet (Simpson, 1963). The succession is a complex sequence of slates, flags, and greywackes which display many similarities with much of the Lower Palaeozoic strata on the mainland. A Cambrian to Ordovician age has been suggested for the series and the Island thus formed part of the Caledonian orogenic belt suffering multiple deformation during a long tectonic history. The major structure that affects the whole Island is the acute Caledonoid Isle of Man syncline which was formed during the initial stages of the earth movements.

4. Devonian.

There are only a few insignificant outcrops of Old Red Sandstone sediments in the area adjacent to the North Irish Sea. In Southern Scotland, eastwards from the Criffell region, the Silurian and Lower Carboniferous strata are occasionally separated by thin Upper Old Red Sandstone deposits (Pringle, 1935). No rocks of Old Red Sandstone age are present on the Isle of Man or in North-west England apart from the possibility of certain dubious conglomerates in the Lake District. An indication of the tremendous erosion which occurred during Devonian times is seen in the fact that Upper Palaeozoic rocks in the Lake District rest on all members of the Lower Palaeozoic from the Upper Ludlow to the Skiddaw Slates.

Sediments of Devonian age occur as a small outcrop on the north-east coast of Anglesey and include unfossiliferous conglomerates, purple and red sandstones, a few calcareous cornstones, and wind blown dust (Smith and Neville George, 1935). Deposition was not continuous however, since the overlying Carboniferous strata rest with marked unconformity upon the Old Red Sandstone.

In Ireland rocks of this age are almost completely absent from the east coast with the exception of a small outcrop in the middle of the Swords Anticline approximately six miles north of Dublin (Charlesworth, 1963).

A very important feature of Old Red Sandstone times was the post-tectonic emplacement of numerous large intrusions. In Southern Scotland these form the Criffell, Cairnsmore of Fleet, and Loch Dee granite masses. The first two cut through Silurian strata, while the Loch Dee mass is intruded into Ordovician rocks (Pringle, 1935). The Criffell mass rises abruptly from the Solway Firth to form an elevated area with the longer axis running in a north-east to south-

west direction, coinciding with the strike of the Silurian rocks. Radiometric age determinations of the major intrusions of the Lake District including the Shap, Eskdale, and Skiddaw granites together with the Ennerdale granophyre indicated a Devonian age (Brown, Miller and Soper, 1964) and suggested that their emplacement followed the main phase of the Caledonian orogeny. The Leinster granite in Southern Ireland was discussed in section 3.4. Further examples are found on the Isle of Man where the Foxdale granite and the Dhoon granodiorite were intruded during this time.

5. Carboniferous.

5.1 Southern Scotland.

Because of the Caledonian earth movements Carboniferous rocks frequently overlie the Lower Palaeozoic strata with major unconformity. In the north-east of this area as earlier defined in section 3.1, rocks of the Lower Limestone Group overlie members of the Calciferous Sandstone Series, while to the south and south-west of the Criffell Granodiorite strata of the Calciferous Sandstone Series form a discontinuous outcrop along the north coast of the Solway Firth.

5.2 The Lake District.

Rocks of Lower Carboniferous age flank the Lake District except in the south-west. The succession which borders the Cumberland coalfield is divided into a lower part made up of 780 feet of dominantly limestone material followed by an upper part consisting of 100 to 1,600 feet of shales and sandstones with sub-ordinate limestones (Eastwood, 1930; Eastwood et al., 1931). This outcrop of Carboniferous limestone is succeeded by a narrow strip of Millstone Grit and forms a border to the coalfield beneath which both formations dip generally seawards.

The Coal Measures, consisting mainly of estuarine sandstones, mudstones, shales, and clays with coal seams and clay-ironstones are made up of two groups, the Lower Productive Measures, which may attain a thickness of about 1,000 feet, and the Upper Whitehaven Sandstone Series which is a reddish colour and almost devoid of coal seams and has a minimum thickness of 700 feet. The two groups are separated by an unconformity.

To the south in Furness and South Cumberland, the Lower Carboniferous succession consists of basement beds a few hundred feet thick, followed by about 2,000 feet of limestone and 1,400 feet of Yoredale facies comprising the Gleaston Group. In this area the Carboniferous appears to have been tilted in a southerly direction (Dunham and Rose, 1949).

5.3 North Wales.

As a result of the Caledonian earth movements, a marked unconformity separates rocks of the Carboniferous system from those of the Lower Palaeozoic in North Wales (Smith and Neville George, 1935). The main outcrops of Lower Carboniferous strata occur in two approximately parallel arcs, running in the first case from the Great Orme south-eastwards along the western side of the Vale of Clwyd, and in the second from Prestatyn along the eastern flank of the Clwydian Range to Llandegla. Here the limestone reaches its greatest development in North Wales attaining a thickness of nearly 3,000 feet, while to the north around Prestatyn the formation is much thinner and composed in general of purer limestone. In the most northern mainland exposure of the Great Orme, the sequence appears similar to the main outcrop in the east, although a peculiarity is present in the form of a series of dolomitic beds at the base. To the west in Anglesey the Carboniferous Limestone unconformably overlies the

Old Red Sandstone, overstepping this to rest on Lower Palaeozoics and rocks of the Mona Complex.

In North Wales the 'Millstone Grit' outcrops extensively only in Flintshire and Denbighshire where it extends from Prestatyn to Oswestry, a distance of over thirty miles. A marked lithological change occurs in this formation from north to south passing from predominantly shale to sandstone in this direction. Coal Measures are found from the Point of Air southwards to near Oswestry, the generally easterly dip causing the strata to disappear beneath the New Red Sandstone of the Cheshire Plain. In Flintshire the Productive Measures attain a maximum thickness of nearly 2,000 feet which includes eighteen workable coalseams. The succession is made up of shales and clays with coal seams, together with an occasional impersistent coarse sandstone. The Upper Coal Measures, tracable from near Flint southwards to Oswestry differ from the Productive Measures in being without workable coal seams, and in the character of the shales and sandstones which tend to be predominantly red in colour. In Anglesey the Coal Measures contain a similar development of red strata 700 feet thick, overlying about 1,000 feet of Productive Measures which have been mined for coal although they do not outcrop, being concealed beneath a considerable thickness of alluvium and glacial drift.

5.4 Ireland.

The Carboniferous system occupies a special position in the geology of Ireland since rocks of this age underlie approximately two-thirds of the country (Charlesworth, 1963). Carboniferous rocks outcrop along the east coast from Dublin, where they are in contact with the Leinster Granite, northwards to Skerries where Silurian strata appear. Carboniferous rocks are again encountered

in the region of Drogheda, north of which the Silurian outcrop together with intrusive granites are predominant. The maximum thickness is not known but a detailed study of the Lower Carboniferous succession between Rush and Skerries on the coast just north of Dublin yielded a thickness of 2,000 feet (Matley and Vaughan, 1906-1909).

The Central Plain covering the interior of Ireland was completely submerged during Carboniferous times and covered by a thick deposit of limestones, Coal Measures, and Mesozoic strata. Subsequently, severe erosion removed the Mesozoic cover and most of the Coal Measures, so that Carboniferous Limestone now forms the most characteristic rock exposed.

5.5 The Isle of Man.

Strata of Carboniferous age occupy small and isolated outcrops on the Isle of Man where they lie unconformably on the Manx Slates. In the south near Castletown a thin basal conglomerate is succeeded by the Castletown Limestone approximately 350 feet thick, and this is overlain by a thin basic lava (Lamplugh, 1903).

The Peel Sandstone which occurs near the town of that name on the west coast, includes red and mottled sandstones and thin impure limestones, and is thought to be of Lower Carboniferous age. These strata are faulted against the Manx Slates and have a predominantly west-north-west dip.

In the north of the Isle of Man, borings through the drift and Permian-Triassic deposits revealed the presence of a Lower Carboniferous succession made up of about 800 feet of Basement Group together with Lower and Middle Limestone Groups which showed similarities with the West Cumberland succession, followed by approximately 700 feet of material similar to the Upper Limestone

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Group of North-East Cumberland (Smith, 1927). The Carboniferous rocks overlie the Manx Slates with strong unconformity. They appear to be more disturbed than in the south but dip generally northwards.

6. Permo-Triassic.

6.1 Southern Scotland.

The main outcrops of Permo-Triassic rocks in Southern Scotland occur in Nithsdale and Annandale where they consist of red sandstones with rounded grains and interbedded breccias similar in lithology to the Penrith Sandstone (Pringle, 1935). Near Stranraer an area of similar sandstones with interbedded breccias occurs. Gravity surveys in the Dumfries area (Bott and Masson-Smith, 1960) and over the Stranraer region (Mansfield and Kennett, 1963) have yielded estimates for the thicknesses of at least 3,000 feet.

6.2 The Carlisle Basin.

The Carlisle Basin containing Permo-Triassic strata is situated at the head of the Solway Firth between the Palaeozoic rocks of the Lake District, the Pennines, and the Southern Uplands. The basin disappears beneath the sea in a south-westerly direction (Dixon et al., 1926).

The oldest rocks exposed at the surface belong to the St. Bees Shales. These pass upwards into the St. Bees Sandstone which is a thick group of fine red sandstone with interbedded shale. The St. Bees Sandstone passes vertically and laterally into the Kirklington Sandstone which may be coarse-grained and without interbedded shale. The Stanwix Shales containing gypsum conformably overlie the Kirklington Sandstone. The general sequence of Permo-Triassic rocks in the Cumberland and Westmorland region is as follows:

Stanwix Shales - about 950 feet

Kirklington and St. Bees Sandstones - 2,000 feet

St. Bees Shales	-	300 feet
Magnesian Limestone	-	0 - 10 feet.
Hilton Plant Beds	-	possibly 150 feet
Penrith Sandstone and Brocknam	-	possibly 1,500 feet.

6.3 The Lake District.

Much of the area between the western part of the Lake District and the Irish Sea lies below the 300 feet contour and is composed of New Red Sandstone strata largely concealed by glacial drift (Trotter et al., 1937). A general sequence for the New Red Sandstone rocks in the West Cumberland and Furness area may be summarised as follows:

Keuper: Marls with Rock Salt and Gypsum - about 600 feet.

Bunter: Kirklington type sandstone. } Proved in boreholes up to 3,200 feet.

St. Bees Sandstone.

Permian: St. Bees Shale.

Magnesian Limestone } up to 500 feet.

Brockram.

The lower part of the formation consists of a basal breccia up to 400 feet thick succeeded by the St. Bees Shales, and the St. Bees Sandstone which is over 3,000 feet thick. In the Whitehaven area the St. Bees Shales range in thickness from 100 feet to 375 feet and contain thick beds of gypsum and anhydrite.

The succeeding St. Bees Sandstone is usually a dull red sandstone of medium grain. The considerable thickness of the sandstone has been proved by borings. A boring at Seascale penetrated St. Bees and Kirklington sandstones to a depth of 3,200 feet without reaching the base (Gregory, 1915). Further south, near Bootle, another deep boring penetrated 2,249 feet of red sandstone again without

reaching the base of the formation (Trotter et al., 1937). At Haverigg Haws a borehole reached the bottom of the Permo-Triassic succession overlying Lower Carboniferous at approximately -2,300 O.D. (Dunham and Rose, 1941) while at Barrow-in-Furness in the south of the coastal area under consideration, 2,080 feet of St. Bees Sandstone were shown to be present.

A north-north-westerly fault system downthrowing to the west separates the Lower Palaeozoic rocks and the Eskdale Granite from the New Red Sandstone, and in South Cumberland and Furness the Permo-Triassic rocks dip generally south-westwards (Dunham and Rose, 1949).

6.4 The Lancashire Coastal Plain.

This area extends from Fleetwood in the north to Liverpool in the south, and the solid rocks exposed, or lying immediately beneath the superficial deposits are all of Triassic age. Because of the great development of glacial and later deposits most of the available information has been obtained from borehole evidence (Wray and Wolverson Cope, 1948). Several boreholes were sunk by the D'Arcy Exploration Company near Formby in connection with the occurrence of an oil seepage in that area. Of these, wells number 1 and 3 passed through several thousand feet of Triassic marls and sandstones before entering older rocks. The thickness and divisions of Triassic rocks mapped in the Southport and Formby district are as follows:

Keuper Marl - Up to 2,000 feet.

Keuper Sandstone - (400 feet at Liverpool, 970 feet at Formby,
and 650 feet at Scarisbrick) 400-1,000 feet.

Bunter (proven by borings) 2,300 feet.

Evidence of strata of Permian age which do not outcrop in the area has been obtained from the borehole information. These rocks immediately underlie

the Bunter and the sequence is as follows:

Manchester Marls - 400-740 feet.

Collyhurst Sandstone - 1,160-2,350 feet.

The thickness of the Permian rocks is greatly in excess of that known to be present elsewhere. In the type locality near Manchester, the maximum known thickness is 852 feet (Tonks et al., 1931). The Collyhurst Sandstone is underlain by hard red silicified shales and marls with recrystallised and dolomitised sandstones of Carboniferous age.

6.5 North Wales.

The Vale of Clwyd had come into existence by this time and was filled with Triassic sediments. A borehole at Foryd near Rhyl penetrated 100 feet of drift and 500 feet of Bunter Sandstone before entering what appeared to be Upper Carboniferous Barren Measures (Powell, 1955). Geophysical work in the area invoked an interpretation assuming a northward thickening of these Triassic sediments to 1,000 feet just offshore (Ibid).

6.6 Ireland.

Severe erosion preceded the deposition of Permian strata in Ireland and a marked unconformity exists between them and the underlying Carboniferous rocks. Permian strata now remain in very small areas in the north-east. A boring under east Belfast revealed the following succession (Charlesworth, 1963).

Upper Permian Marls. - 142 feet.

Magnesian Limestone - 60 feet.

Basal Permian Sandstone and Brockram. - 146 feet.

Triassic rocks are also restricted to North-East Ireland. The main outcrop occurs at the Head of Belfast Lough and from the evidence of several borings

in Belfast (Lamplugh et al., 1904) the succession in the Belfast area appears to be as follows:

- Keuper Marl. - 1,000 feet.
- Upper Sandstone - 1,250 feet.
- Bunter Marls - 360 feet.
- Lower Sandstone - 275 feet.

The total thickness is 2,885 feet. However, the thickness rapidly decreases eastwards and at Newtownards, at the head of Strangford Lough, the succession is no more than 400 feet thick.

6.7 The Isle of Man.

In the extreme north of the Isle of Man a succession similar to the generalised sequence tabulated in section 6.3 above but lacking the Magnesian Limestone is known from borehole information. In this area the strata attains a maximum observed thickness of 2,585 feet (Gregory, 1920).

7. Post-Triassic.

Post Triassic sediments are extremely rare in the area surrounding the North Irish Sea with a thin patch of Lower Lias forming an outlier in the Carlisle Basin. In Ireland the Post-Triassic rocks occur mainly in the extreme north-east where their preservation is normally due to the covering of Tertiary Lavas.

Further evidence becomes somewhat speculative, but it has been suggested from the indications of the erratics present along the northern coast of Anglesey that the floor of the Irish Sea, east of the Isle of Man, might be underlain by Jurassic rocks in addition to possible Triassic material (Greenly, 1919). Further, the presence of much flint was taken to indicate that chalk might still form a section of the floor. The area was visualized by Greenly as a broad, slightly undulating plain over which Triassic sediments had the greatest areal distribution. Overlying these was an outlier or several outliers of Jurassic rocks succeeded by a more substantial outcrop of chalk. On the western edge of the plain Coal Measures were visualized

as emerging unconformably from beneath the Trias with Carboniferous Limestone below them. The Coal Measure outcrop was thought to be rapidly overlapped, with the Mesozoic boundary trending in a northerly direction towards the Isle of Man. Finally, since Triassic or older strata occurred everywhere along the margins of this part of the sea, and assuming the approximately central position of Jurassic and Cretaceous rocks, it was suggested that the composite area possessed the structure of a gentle synclinal fold.

The other Post-Triassic sediments that outcrop along the coastal margin are of Pleistocene and recent age. On the coastal plain of Lancashire the glacial deposits have a maximum thickness of 200 feet (Wray and Wolverson Cope, 1948). Drift in the form of stratified and unstratified Boulder Clay, sands and gravel, attain a thickness of about 400 feet on the northern plain of the Isle of Man (Gregory, 1920). In the Central Plain of Ireland the superficial deposits consist mainly of glacial gravels in the form of moraines and eskers but are not expected to exceed 650 feet at the absolute maximum (Murphy, 1952).

8. Summary

The rocks surrounding the North Irish Sea can be divided into four major stratigraphical units which are normally separated by unconformities. A broad division of this kind is useful for analysis of the gravity data where large scale structures are involved.

The oldest rocks in the area form the highly disturbed Pre-Cambrian Mona Complex of Anglesey. The Bedded Series of this complex contains about 20,000 feet of geosynclinal sediments in which the dominant fold direction is approximately north-east to south-west.

Lower Palaeozoic rocks are widespread in the region bordering the North

Irish Sea and on the Isle of Man, and form the structural framework of the area under investigation. The thickness of these rocks may again be of the order of 20,000 feet. The Lower Palaeozoic period was terminated by major earth movements which folded the rocks along a predominantly north-east to south-west or Caledonian trend. The main phase of tectonic activity was followed by the intrusion of several large granite bodies which are often observed to occupy areas of relatively high ground at the present day.

Because of the Caledonian earth movements Carboniferous rocks frequently succeed the Lower Palaeozoic with major unconformity. The largest area of Carboniferous rocks is of predominantly limestone facies and occupies the Central Plain of Ireland, reaching the east coast between Dublin and Skerries.

Permo-Triassic rocks occupy several widely separated, and with the exception of the Lancashire coastal area, relatively restricted areas bordering the North Irish Sea. Borehole data has provided information concerning the thickness of these rocks in certain areas. Near Formby in Lancashire a thickness of approximately 7,000 feet of Permo-Triassic rocks has been proved.

The presence in the coastal regions of large post-tectonic granites and great thicknesses of Permo-Triassic sediments, both of which are known to characteristically possess relatively low densities, is of major importance in connection with features appearing on the Bouguer Anomaly map of the North Irish Sea.

Chapter 2

Previous Geophysical Work.

1. Introduction

This chapter reviews the geophysical work that has already been completed in the North Irish Sea, on land in the coastal region surrounding the marine area, and on the Isle of Man. The coastal areas are described in order, commencing in Southern Scotland and moving in a clockwise sense around the Irish Sea basin. The subject is considered systematically in three sections comprising gravity, seismic, and magnetic.

2. Gravity.

2.1 The Stranraer Basin.

A detailed gravity survey in the Stranraer district of South-West Scotland revealed the presence of a negative gravity anomaly of seventeen milligals amplitude associated with the Carboniferous and New Red Sandstone basin at Stranraer (Mansfield and Kennett, 1963). It was suggested that low density sediments within the valley contrasted with the denser Lower Palaeozoic rocks to produce the observed negative anomaly and on this assumption a detailed interpretation was conducted to obtain the shape of the basin.

A range of possible density contrasts was used and it was concluded that the basin had a depth of greater than 3,000 feet and probably 4,500 feet or

* by Mansfield and Kennett

more below O.D. It was further concluded that the great thickness of sediments was formed by contemporaneous sinking and infilling of the basin floor during New Red Sandstone and possibly Carboniferous times. It was suggested that the downward movement was accomplished partly by faulting along the eastern margin, and partly by downwarping from the western margin which acted as a hinge-line.

Gravity work at sea has shown that a negative gravity anomaly, forming the south-eastern extension of the gravity 'low' associated with the Stranraer sediments, occupies Luce Bay (Bott, 1964). The marine observations indicate that the anomaly closes near the mouth of Luce Bay. It was suggested by Bott that the interpretation put forward for the Stranraer Basin also held for the continuation into Luce Bay.

2.2 The Criffell Granodiorite and the New Red Sandstone deposits near Dumfries.

A gravity survey along the north shore of the Solway Firth was made by Bott and Masson-Smith (1960) to investigate the deep structure of the Criffell granodiorite mass and the New Red Sandstone deposits near Dumfries. A negative gravity anomaly of about twenty milligals amplitude was shown to exist over the Criffell granodiorite, the relatively low density of which was shown to be the cause of the anomaly. The interpretation suggested a batholithic form with a floor at a minimum depth of seven miles. It was further shown that

the mass deficiency represented by the granite as calculated from the anomalies was of the same magnitude as the additional surface load of the corresponding high ground. It was suggested that the ground had risen isostatically in response to an intrusion of relatively low density.

The New Red Sandstone deposits near Dumfries and Lochmaben were found to be associated with negative anomalies of about fifteen milligals amplitude. For an assumed density contrast of 0.4 gm./cm^3 , it was shown that a thickness of 3,500 feet of sandstone was needed to account for the anomalies, but that if Carboniferous rocks were present beneath the New Red Sandstone strata, the depth to the floor of the Carboniferous would be greater than this estimate. It was concluded that the basin formed by contemporaneous downwarp and infilling, while the similarity of large depth and general shape with other New Red Sandstone basins in Great Britain was emphasized. Finally a regional increase of the Bouguer Anomaly towards the Irish Sea was noted.

2.3 The Carlisle Basin.

Gravity data obtained by the Anglo-American Oil Company Ltd. in Northern England provide further information in connection with structures in the adjacent regions to the North Irish Sea (White, 1949). The surveys were directed towards the discovery and interpretation of concealed structures.

In the Carlisle area it was shown that the Permo-Triassic basin was

responsible for gravity minima of approximately 20 milligals amplitude, but it was concluded that much of the gravity effect was caused by structural anomalies within the underlying Carboniferous. Along the southern margin of the basin the steep gravity gradients were taken to indicate extensive faulting, not necessarily confined to the Triassic-Carboniferous contact but possibly also affecting the Carboniferous outcrop. White estimated a thickness of nearly 10,000 feet for the Lower Carboniferous sediments to explain the observed anomaly, but information about the thickness of the Permo-Triassic rocks is necessary in order to separate the contribution from the two systems.

2.4 The Lake District.

Gravity investigations in the Lake District have revealed interconnecting negative gravity anomalies between the exposed granites (Bott, personal communication). The Permo-Triassic rocks along the Furness and South-west Cumberland coasts also cause a gravity 'low' which was found to merge near Seascale with the negative gravity anomaly associated with the Eskdale granite. The anomaly associated with the sediments was found by Bott to fall towards the coast. Away from the granites and Permo-Triassic rocks, a rise in the Bouguer Anomaly was observed as the Irish Sea was approached both across the Cumberland coalfield and in Furness.

2.5 The Lancashire Coast and Adjacent Area.

Analysis of the data in Lancashire and Cheshire by White (1949) indicated that while the Trias of the Lancashire coastal area is disposed in the form of a half-basin open to the west, the Cheshire area displays the complete basin form with older rocks occurring towards the margins. In both cases the eastern edges are known to be bounded by large faults downthrowing several thousand feet to the west. A zone of steep gravity gradients is associated with this faulted eastern margin in the Cheshire area, and the new observations discovered a similar feature on the opposite side of the basin to the west, which by analogy was interpreted as a major fracture. It was concluded by White that this evidence indicated that the Cheshire Basin was a rift structure bounded by parallel north-easterly ^{trending} normal faults. The Trias west of the Cheshire Basin was therefore considered to occupy a separate structural environment, being essentially part of the North Wales massif.

2.6 North Wales

i. Introduction.

A gravity survey covering North Wales has been conducted by Powell (1955). A regional rise in the Bouguer Anomaly from south-east to north-west was shown to be best explained by an arch in the crust. The Bouguer Anomaly over a wide area of the Denbigh Moors made up of thick Lower Palaeozoic rocks that

border the Irish Sea between Menai and Rhyl was found to be between +35 and +40 milligals. The Triassic and Upper Carboniferous deposits of the Vale of Clwyd were found to be associated with two gravity 'lows' and the northern 'low' was seen to transgress the coastal margin near Rhyl.

ii. The interpretation of the Bouguer Anomalies in North Wales.

The main features of the gravity field in North-west and Central Wales include the alignment of the anomalies parallel to the Caledonian trend, and the regional anomaly which increases from +10 milligals in the south-east to over +40 milligals in the Menai region to the north-west, and then decreases across Anglesey to +25 milligals (Powell, 1955). In the south-east of the area the Bouguer Anomaly values range from +10 to +15 milligals both over the Lower Palaeozoic which may attain a thickness of 20,000 feet and over the Pre-Cambrian of the Longmynd. Similarly in the north and north-west the Bouguer Anomalies are from +35 to +40 milligals both over the thick Lower Palaeozoic rocks of the Denbigh Moors and Snowdonia, and over the Pre-Cambrian in Anglesey. Powell showed that there was as great an anomaly change over the Pre-Cambrian as over the Lower Palaeozoics and that the changes over the latter were not correlated on a regional scale with its thickness. These facts established that the regional gravity increase from south-east to north-west must be due to a deeper density contrast than that between the Pre-Cambrian

and Lower Palaeozoic.

It was suggested by Powell that the anomalies might be caused by the structure of the earth's crust. The normal crust was assumed to include two layers, namely an upper granitic and sedimentary layer 15 kilometres thick with an average density of 2.7 gm./cm^3 , and a lower intermediate layer 20 kilometres thick and density 3.0 gm./cm^3 . The underlying layer was considered to have a density of 3.3 gm./cm^3 .

If the crust was arched under the Menai region so that the intermediate layer and substratum were about 10,000 feet nearer the surface than under Holyhead and Bala, then the gravity gradients of 1 mgal./mile and 0.75 mgal./mile to the north-west and south-east respectively would be explained. Alternatively, it was suggested that there might be a flexure in the crust passing upwards into a thrust fault in the Menai-Lleyn belt.

In the Vale of Clwyd it was shown that the gravity anomalies enabled an estimate to be obtained for the thickness of the concealed Upper Carboniferous rocks if the thickness of Trias cover was known (Powell, 1955). Borehole information which proved the presence of 100 feet of drift overlying 500 feet of Trias in the northern part of the Vale of Clwyd provided the basis for correcting the observed anomaly for the cover of Trias and drift, the residual being interpreted as due to the thickness of Upper Carboniferous.

Assuming a thickening of the Trias to 1,000 feet just north of Rhyl from the geological evidence on the Lancashire Coast, it was shown that a maximum thickness of 2,500 feet of Upper Carboniferous rocks was required to explain the observed anomaly. The steep marginal gravity gradients suggested faulted boundaries for this basin of deposition and the evidence was taken to indicate the existence of a Triassic Basin under the sea.

Magnetic work in North Wales showed that the anomalies reached a maximum in areas where the Pre-Cambrian was close to the surface and decreased towards areas of thick Lower Palaeozoic Sediments. It was suggested therefore that in this area the magnetic anomalies were a better indication of basement relief than the gravity anomalies since the densities of the two divisions were likely to overlap.

2.7 The East Coast of Ireland.

i. Introduction.

Gravity data collected in Ireland show that the Bouguer Anomaly over the undisturbed Lower Palaeozoic rocks of Central and Northern Ireland is close to +20 milligals over wide areas (Murphy, 1952; Cook and Murhpy, 1952). The Bouguer Anomalies are lowered over low density granite masses, and in areas of Coal Measures and Mesozoic deposits. It has been suggested by

Murphy that increases in the Bouguer Anomaly within certain areas of Lower Palaeozoic rocks may be due to local igneous activity. The very high Bouguer Anomalies in the north were shown to be due to high density Tertiary igneous rocks (Cook and Murphy, 1952). A further example of a rise in the Bouguer Anomalies as the sea is approached occurs over the Lower Palaeozoic rocks of south-east Ireland (Thirlaway, 1951).

ii. Description of the major Bouguer Anomalies.

Many of the major Bouguer Anomaly variations in Ireland have been explained in terms of granite intrusions and by a series of warps which alternatively depress and elevate the dense Lower Palaeozoic rocks (Thirlaway 1951). It was concluded from observations over a wide area that deep-seated rocks were exercising the primary influence on the gravity field, and that in areas where Silurian and older rocks were exposed or expected to be at no great distance below the surface, the anomalies were relatively high, ranging from +15 to +40 milligals.

Observations in South-east Ireland (Ibid) revealed that the increase in anomaly that occurs as the Welsh Coast is approached was repeated on this part of the Irish Coast. The magnitude of the gradients was considered to indicate that the dense material responsible for the rise in anomaly was not deeper than the sedimentary rocks. Assuming that the disturbing masses on opposite sides of the channel were related to one cause, it was suggested

that the increase in anomaly could be due to a thickening of Lower Palaeozoic sediments filling the geosyncline which would imply that the Welsh and Irish geosynclines were separated for long periods by a land mass on the site now occupied by the Irish Channel. This interpretation requires the Lower Palaeozoic rocks to be consistently denser than the Pre-Cambrian basement, a hypothesis that has doubtful validity (Powell, 1955).

While acknowledging that the conditions north of Dublin were not the same as along the south-east flank of the Leinster Granite, it was nevertheless anticipated that the Ordovician-Silurian strata would be thick and give rise to a Bouguer Anomaly of similar size (Murphy, 1952). From over the Leinster granite the anomaly was found to rise very rapidly to a value of +30 milligals just north of Dublin. From density considerations it was concluded that the increase in anomaly was produced by Ordovician strata lying beneath the Carboniferous rocks which have been shown to have a thickness at Dublin in excess of 1,000 feet decreasing rapidly to the north. The gradient over the contact between the Leinster granite and Carboniferous Limestone is consistent with a steep and possibly faulted margin, and eliminates the possible presence of the granite below Dublin and invalidates an earlier suggestion that the granite might extend northwards to reappear in the small island of Rockabill (Cole and Hallissy, 1924). Further north where Silurian

rocks outcrop the Bouguer Anomaly was found to be fairly constant with a value close to +20 milligals.

Work in the North of Ireland has shown that over large areas the average Bouguer Anomaly does not depart much from +20 milligals (Cook and Murphy, 1952). This is apparent over areas where Lower Palaeozoic or Dalradian rocks, having a density of approximately 2.75 gm./cm.^3 , outcrop. The low values in County Down are associated with granite bodies of density 2.65 gm./cm.^3 or less, while in Antrim and north Down the low values appear to be due to deposits of Coal Measures and Mesozoic rocks with densities less than 2.5 gm./cm.^3 . The areas of very high values were shown to be associated with Tertiary igneous rocks possessing densities of up to 3.0 gm./cm.^3 , which are located in the Carlingford and Slieve Gullion districts.

2.8 The Isle of Man.

A gravity survey over the Isle of Man revealed that the average Bouguer Anomaly over the Island is close to +40 milligals (Bell, 1959).

Three negative anomalies were discovered and found to be disposed along the main north-east to south-west axis of the Island. The centres of two of these anomalies, designated the Foxdale and Dhoon anomalies, approximately correspond with known outcrops of granitic rock. Density considerations clearly indicated that the emplacement of the granite bodies within the Manx Slates was sufficient

to cause the observed anomalies.

The Foxdale Anomaly in the south was found to be the largest, both in area and magnitude, on the Isle of Man. It was described as being roughly elliptical in shape with a major axis of nine miles in length extending in a north-east to south-west direction, and a minor axis of six miles (Cornwell, 1960). The anomaly therefore dominates much of the south-western area of the Island. A third negative feature was found to exist in the Calf of Man region in the extreme south, and in the absence of any surface feature which might cause the anomaly, an interpretation in terms of an unexposed granite was suggested. The apparent continuity of the Foxdale and Calf of Man anomalies along the same structural trend was put forward as an argument in support of the hypothesis.

At the Point of Ayre, in the north of the Island, the Bouguer Anomaly was found to drop to a value of only +32.7 milligals with the isogals running in an east-west direction.* Using information available from borehole data it was suggested that this anomaly was caused by a trough of Lower Carboniferous and Permo-Triassic sediments which thickened northwards.

A residual Bouguer Anomaly map of the Peel area on the west coast yielded an anomaly of -1.5 milligals. Using the known geological evidence,

* Bell, 1959.

and making an assumption for the density contrast, it was suggested that a faulted trough of Lower Carboniferous sandstone and conglomerates totalling approximately 1,500 feet was present in the Peel area.

2.9 The North-East Irish Sea.

All the existing marine gravity work in the North Irish Sea was completed in 1961 (Bott, 1964). The area investigated by this earlier survey extended from the Solway Firth westwards into Luce Bay and southwards to a line running approximately from Douglas on the Isle of Man to Fleetwood. A single traverse was also established from Peel on the west coast of the Isle of Man to Ardglass in Northern Ireland. Interest had been directed to the area by the frequent observation that in many places bordering the Irish Sea a steady rise in the Bouguer Anomaly is encountered as the margins of the land are approached until a value close to +35 milligals is attained in certain areas. It was concluded that the undisturbed background Bouguer Anomaly over the North Irish Sea was 25 - 30 milligals higher than ^{on} the surrounding land.

The gravity data at sea revealed the existence of several large negative anomalies superimposed upon the high regional background. Evidence from the coastal geology, together with the shape of the anomalies suggested a sedimentary basin structure as the most acceptable interpretation, in which Carboniferous and New Red Sandstone deposits formed the main 'fill', although the possibility

that rocks of Old Red Sandstone or Post-Triassic age might contribute was also acknowledged. The Isle of Man was visualised as a stable block structure of Lower Palaeozoic age, the sub-parallel coastlines of which were controlled by the adjacent sedimentary basins. A mechanism for formation was sought in terms of isostatic movements with mountain regions rising in response to stress differences caused by mass deficiencies, thereby tending to restore equilibrium. Erosion of the massif provided the 'fill' for adjacent subsiding basins, while flow movement in the Upper Mantle completed this 'Tectonic Cycle'.

2.10 The cause of the high regional anomaly over the Irish Sea.

The regional rise of the Bouguer Anomaly on approaching the Irish Sea has been observed in several widely separated areas surrounding the Irish Sea basin. It can be seen in South-west Scotland at Burrow Head, the Mull of Galloway (Bullerwell and Phemister - quoted by Bott, 1964), and on the north coast of the Solway Firth (Bott and Masson-Smith, 1960). Similarly in Northern Ireland, east of Strangford Lough, (Bullerwell, 1961), and westwards across the Cumberland coalfield, a seaward rise in the Bouguer Anomaly is again apparent. On the Isle of Man the maximum Bouguer Anomaly over the Lower Palaeozoic rocks is +48 milligals (Cornwell and Bell, 1960).

Several possible reasons for this regional rise have been suggested including density changes within the Lower Palaeozoic and underlying Pre-Cambrian

rocks, or deeper seated variations in crustal density or thickness (Bott, 1964). A regional rise of the Bouguer Anomalies from south-east to north-west across North Wales has been observed by Powell (1955). A crustal upwarp of approximately 10,000 feet under the Menai region was suggested in order to explain the observed regional gradients, (Section 2.6 ii). In South-east Ireland Thirlaway (1951) showed that a similar rise in the Bouguer Anomaly occurred in a seaward direction across the Lower Palaeozoic rocks south of Bray. A thickening of dense Lower Palaeozoic rocks was suggested as an interpretation for the observed gradients.

It is probable that no single interpretation is valid for all the observed occurrences of the regional rise of the Bouguer Anomaly towards the Irish Sea. It is possible that more than one of the suggested causes may combine to produce the observed effect in different areas.

3. Seismic

A fully reversed seismic traverse has been established about four miles south-east of Douglas, Isle of Man (Barnes, personal communication). The position of the traverse is indicated in Plate 2. A refracted P wave velocity of approximately 7,800 feet/second was indicated at a depth of 3,300 feet. Although the detailed interpretation was not available the results indicate an absence of Lower Palaeozoic sediments down to that depth.

Seismic work conducted in the East Irish Sea under the auspices of the U.K.A.E.A. has yielded evidence to support the idea of a thinner crust in the area. Depth charges were fired in the North Sea and Irish Sea in July 1962, and the seismic arrivals recorded by the U.K.A.E.A. linear array at Eskdalemuir, and by a borehole seismometer near Durham (Agger and Carpenter 1964). In the Irish Sea the line of shots extended from near Holyhead to the Solway Firth.

Arrivals considered to be refractions from the Mohorovicic discontinuity gave a value of 7.99 ± 0.10 kilometres /second for the sub-crustal compressional wave velocity, and depth estimates derived for the same surface suggested an average depth in the area of about 25 kilometres. This is about 3 kilometres less than the figure associated with the surrounding land areas. The results further suggested that the East Irish Sea is a region of thick sedimentary deposits.

4. Magnetic.

4.1 The Aero-magnetic Surveys.

An Aeromagnetic Survey has recently been made over the British Isles by the Geological Survey and includes much of the Irish Sea (Geological Survey and Museum 1964). Reference has been made to the isogam maps in order to substantiate the gravity data of the present work, and to indicate areas where further investigation using sea-borne proton magnetometer could provide

data for detailed interpretation. Discussion of several large features on the Aero-magnetic Map in conjunction with the gravity data forms the content of Chapter 7.

4.2 The Morecambe Bay Anomaly.

A particularly sharp anomaly that appears on the Aero-magnetic Maps in the vicinity of Morecambe Bay was the subject of a single sea-borne proton magnetometer traverse during the 1961 season. The data were examined but quantitative interpretation was not completed, although it was realised that the shape of the magnetic profile did not readily lend itself to interpretation in terms of a simple dyke model as would seem to be the case at first sight. Further investigation was considered necessary and six additional traverses were run across the strike of the anomaly in August 1964. The interpretation forms the subject of Chapter 8.

The Marine Surveys

1. General Introduction

This chapter contains a description of the conduct and reduction of the surveys made by the author. One hundred and eighty-one new marine gravity stations form the basis of this work and were established during the summer field seasons of 1963, 1964 and 1965 using a North American gravimeter modified for remote control from the surface. In addition, approximately two hundred miles of detailed magnetic lines have been obtained using a sea-borne proton-magnetometer.

The northern boundary of the area investigated extends from near Ramsey on the east coast of the Isle of Man to Fleetwood on the Lancashire coast. From there the Lancashire and North Wales coastlines form the border of the marine area as far as Holyhead. A line running from Holyhead to Bray in Eire establishes the southern limit of operation. The coast of Ireland borders the area on the west as far as the Mourne Mountains, from where an east-west line to the Calf of Man completes the closure. Plate 1, the Bouguer Anomaly Map, which may be found inside the back cover illustrates the above description. In this area the underwater gravity measurements form the most important part of the work.

The first survey in 1963 was carried out using the S.Y. Sheila, and the following two seasons were conducted from the M.V. Hamburg. Both vessels were chartered from Hydrographic Services Ltd., of Brighton. The much superior speed

of the second vessel made her considerably more suitable for the work because the time involved in travelling between stations is an important aspect of operational efficiency.

Since the preliminary objective was to make a regional survey of the area, station positions were initially spaced at intervals of approximately five miles, decreasing to a mile or less only when anomalous features involving steep gradients emerged.

2. Installation.

2.1 The Instrument.

As mentioned earlier the instrument used was a North American gravimeter adapted for remote control on the sea-bed. The gravimeter was contained in a watertight bell which was connected to the control console on the ship by means of a multi-core electrical cable. The instrument was levelled before making an observation by means of a fully automatic, servo-operated levelling system. The gravity dial position was altered by means of a selsyn motor, and the position of the beam detected by means of a displacement transducer, the signal from which was observed on the control panel. The depth of water was recorded by a pressure sensitive transducer mounted on the outside of the watertight bell and facility for clamping and unclamping the gravimeter was provided in the form of a simple reversible D.C. motor.



PLATE 4

2.2 Location of the equipment on the ship.

The bell was lowered to the seabed by a heavy winch powered by a hydraulic motor. The winch was made up of a movable carriage supporting an A-frame with a cradle slung beneath to hold the bell steady during transportation between stations, and which lowered to the water surface before release of the bell was permitted. It was found that a stern position was most suitable for the mounting of this heavy equipment, both for reasons of deck space available and also ease of lowering. In both vessels, but particularly in the M.V. Hamburg the amount of freeboard was least at the stern which allowed a conveniently small vertical movement of the cradle to reach water level. The carriage and A-frame could be moved aft on steel runners so that the cradle and bell were overhanging the stern before the A-frame was lowered as described. Plate 4 illustrates the above description.

The control console was bolted to a bulkhead in cabin-space as near to the stern as possible, but in a position adequately sheltered from flying spray. It was necessary to place this equipment so that visual contact between the winch and console operators could be maintained at all times during operation at sea. A roller, approximately eight inches in diameter, was bolted immediately over the stern to enable the electrical remote control cable, linking the instrument in the bell to the control console, to be payed

out and hauled in without any abrasion of the outer rubber casing.

2.3 Calibration of the Instrument.

The instrument was calibrated, soon after delivery, in March 1963, and again in April 1964 by observing between accurately established values at York and Newcastle. Intermediate stations at Durham and Northallerton were also occupied using the looping technique (Nettleton, 1940) to obtain an accurate estimation of the drift. The value of .10215 millgals/division obtained in the first calibration was used in the reduction of the readings obtained during the first survey in 1963. Unfortunately the lower mainspring ligature fractured at the beginning of the 1964 season and a new calibration constant was supplied following repair of the instrument by the Makers. This value of .10252 milligals/division was adopted throughout the following reductions. The instrument was further calibrated in October 1965 in order to obtain an estimate of the magnitude of error that may be present in the final Bouguer Anomalies due to changes in the value of the calibration constant.

The values obtained by calibration and as supplied by the Makers are as follows:

Original value as supplied by the Maker.	-----	.10251 mgals./div.
Calibration constant obtained on the 15th March 1963.	-----	.1025 [±] .00004 mgals./div.
Calibration constant obtained on the 16th April 1964.	-----	.10214 [±] .00011 mgals./div.
Value supplied by the Maker 29th May 1964.	-----	.10252 mgals./div.
Calibration constant obtained on the 21st October 1965.	-----	.10283 [±] .00036 mgals./div.

3. Marine Operation.

3.1 The Base Network.

The gravity measurements at sea were 'tied-in' to base positions on the seabed in harbours at Douglas ^{in the} Isle of Man, Fleetwood, Liverpool, Holyhead, and Dun Laoghaire in Eire. The nature of the installation did not permit the meter to be observed on the quayside and the value of gravity on the seabed was calculated from the observed value on the quay which was 'tied-in' to the land base station network. ^(Geological Survey and Museum) This was accomplished by the looping method, and diagrams of the main base positions together with the established quayside values are contained in Appendix 2. The values of gravity on the seabed are therefore relative to Pendulum House Cambridge where the value was assumed to be $981.2650 \text{ cm./sec}^2$. Diagram 1 assists the description of the corrections necessary to obtain the value of gravity on the seabed.

The difference in gravitational attraction between positions A and B is due to three different effects, namely, the free air effect, and the differences in attraction of the slab of material Q and the sheet of water P at the two positions. The free air effect was obtained by multiplying the free air correction factor by the vertical distance between A and B. The gravitational attraction at the two positions for both the quay Q, and the sheet of water P, was obtained using a graticule based on King Hubbert's (1948) line integral method. The effect of all mass below the level of B was assumed to be the same at both positions. A model example to illustrate the process is given for the value established at Holyhead. The appropriate measurements are indicated in diagram 2.

The density of sea water was taken as 1.03 gm/cm^3 .

The density of the quayside material was taken as 2.0 gm/cm^3 .

BASE STATION CORRECTIONS.

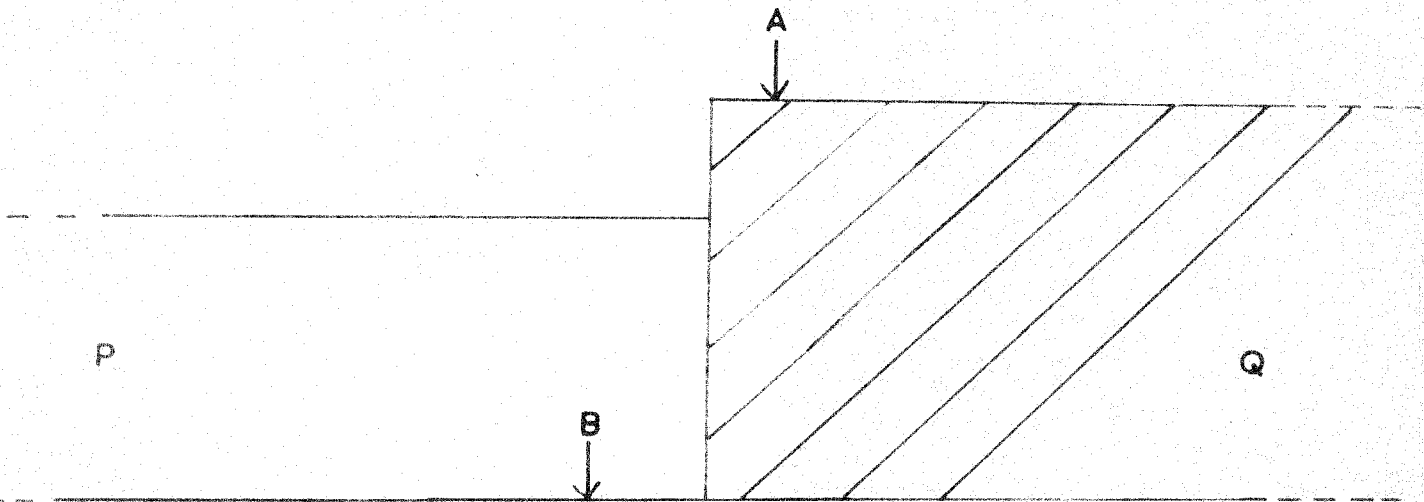


DIAGRAM 1

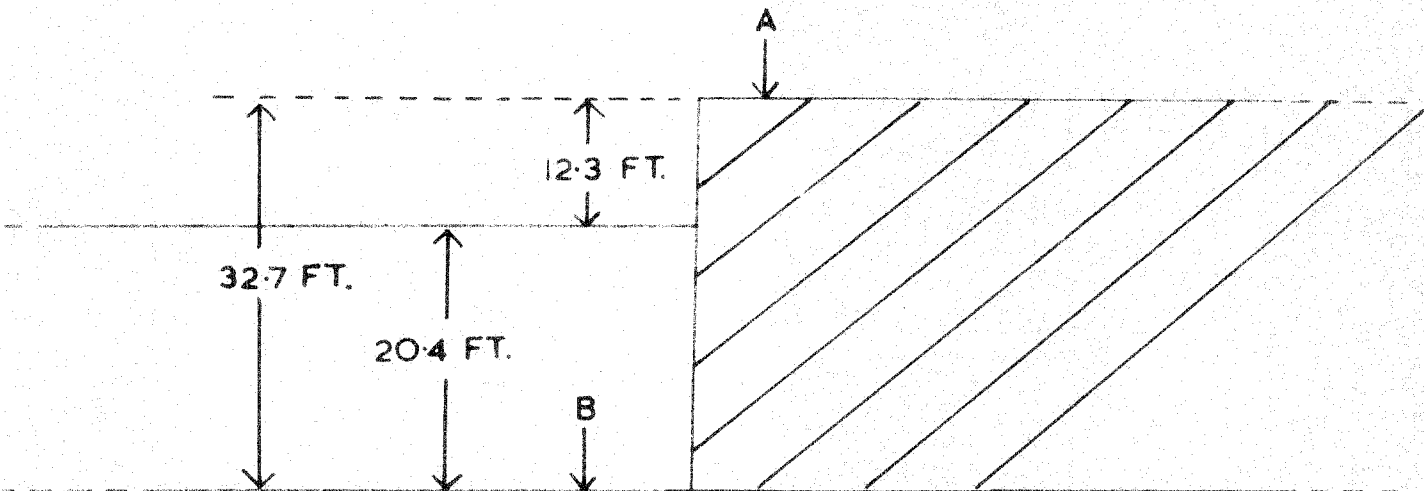


DIAGRAM 2

The difference in the Free Air correction between A and B was
calculated to be:----- +3.08 mgals.

The difference in effect of the quay was estimated to be:
----- -0.71 mgals.

The difference in effect of the sea was estimated to be:
----- -0.32 mgals.

Consequently the calculated difference in gravity between
A and B is ----- 2.05 mgals.

The value established on the quayside by the looping method was
+128.37 mgals.

Therefore the value on the seabed is given by 128.37 + 2.05 mgals.
=130.42 mgals.

This value is only valid for the state of the tide shown in the illustration,
and allowance was made for changes in the height of the tide.

3.2 Marine Stations.

i. Ideal Conditions.

At each marine station the vessel was anchored and allowed to swing
to a stable position. The gravimeter was then lowered rapidly but smoothly
to within about ten fathoms of the bottom as indicated by the echo-sounder
equipment. The lowering rate was then gradually reduced until the bell settled
gently onto the seabed.

The instrument was now levelled by means of the automatic levelling system.
With the instrument in a level position the meter was unclamped and a reading
of the gravity dial obtained as quickly as possible. The instrument was then
clamped and the depth of water as recorded by the pressure-sensitive transducer
on the bell was noted. The bell was now raised to the surface, and after a

record of the ship's position had been obtained using the Decca Navigator it was possible to proceed to the next position.

ii. Difficult Conditions.

Satisfactory measurements were only possible in relatively calm conditions and it was found in practice that a wind speed of Force 4 on the Beaufort Scale provided an upper limit for gravity operation. As already stated the vessel was anchored and allowed to swing before the bell was lowered onto the sea-floor. In conditions of slack water or upper limiting wind speed the ship may be held across wind and current such that variation of either causes oscillation about a focus situated a short distance forward of the bow. Consequent movement of the stern through a wider arc may cause the bell to be dragged across the seabed, and close contact between the winch and control console operators was essential in such conditions.

A further working difficulty was commonly encountered in the strength of the tidal currents which caused drag on the remote control cable and were sufficient in some cases to set up vigorous oscillation with the disturbance reaching down to the bell itself. This was observed on the control panel in an unsteady movement of the level indicators. Such effects could usually be reduced by slowly releasing additional cable until the level dials indicated a minimum of mechanical disturbance. If disturbance was experienced while the meter was unclamped it almost invariably inhibited the attainment of a satisfactory reading. In such cases the only available course was to clamp immediately and attempt to secure more stable conditions.

Poor anchoring ground has also presented difficulty in certain areas. In such instances the ship occasionally dragged the anchor and slipped astern until the gravimeter on the seabed was under the ship with the remote control and steel lifting cables in danger of fouling the propellers. As soon as it was noticed that the cables were tending to swing under the stern the bell was raised a few fathoms off the bottom and more anchor chain released before replacement of the instrument on the seabed. The gravity reading was always secured as quickly as possible in order to minimize the period that the instrument remained unclamped, particularly in the type of difficult conditions outlined above.

4. Method of Position Location.

The positions of gravity stations at sea were fixed using the Decca Navigator system. This is a radio system that uses phase differences between shore based transmitting stations to obtain the position.

The accuracy of the system depends upon several factors including distance from the Decca stations, nearness to coastal regions, and night time variations. There are two types of error that affect the accuracy of a Decca fix, fixed and variable errors. Fixed errors are due to distortion of the position line patterns and occur mainly as a result of the signal passing over ground of low conductivity. Since the distortion does not vary it is possible to make allowance for this error. Correction figures are supplied for relevant areas as fractions of a position lane width, and are classified into two groups. Class A contain well established figures which will imply systematic position line errors of less than 100 yards, at a 95% probability level. Class B include figures which do not qualify for the above but which give a better average fix in

the area in which they are applicable. In the area of operation the majority of the fixed error corrections fell into the first category.

The variable error is caused by interference between the direct radio signals from the Decca stations and the signals reaching the ship by a 'skywave' reflection path. The effect of these errors is usually small under daylight conditions but tends to become greater with distance from the station and at night. It is possible to obtain an estimate of the magnitude of the error at a given distance from the station, and to judge the direction in which the Decca fix is likely to be displaced from the true position. The Data Sheets available indicate the magnitude of the error that may occur at various places, and the directions of maximum and minimum accuracy by day and night. In most of the area under consideration the maximum error that might be anticipated under daylight conditions is one cable, or approximately ± 600 feet.

5. Reduction of the Observations.

5.1 Drift.

Over an operational day a difference in reading of five dial divisions or less, equivalent to approximately 0.5 milligals, between the known value of the return base and the measured value relative to the starting base, was considered satisfactory. The intermediate marine stations were then corrected by assuming a linear drift characteristic with time. However, on certain isolated days a difference of several milligals was recorded upon return to the base position. Instrumental 'jumps' of this nature are believed to be caused in the main by mechanical disturbance of the meter whilst it remains unclamped during an observation. The problem was overcome by systematic

This is made up of a Free Air Correction, $-ft$, the effect of the mass of sea water, $+4\pi G\rho_s t$, and that due to the imagined rock infill, $+2\pi G(\rho_m - \rho_s)t$, where f is the free air correction factor, ρ_s is the density of sea water, ρ_m the density of the rocks below the seabed, and t the depth.

Substituting values of 1.03 gm./cm.^3 for ρ_s the density of seawater, and 2.50 for ρ_m , a choice that will be critically examined later, the following simple expression is obtained.

$$\underline{C(\text{depth}) = -0.04902t \text{ milligals.}} \quad (t \text{ in feet.})$$

Similarly, the tidal correction is made up of $+ftD$, the additional free air correction where tD is the difference between the existing level and mean sea level, and $-2\pi G\rho_m tD$, the effect of removing an imaginary thin slab of rock. Here tD is taken to be positive when the existing level is higher than mean sea level.

$$\text{Thus } C(\text{tide}) = (f - 2\pi G\rho_m)tD. \quad (tD \text{ in feet.})$$

Substituting as before:

$$\underline{C(\text{tide}) = 0.06216tD \text{ milligals}}$$

A table was produced for depths up to 300 ft. to speed the approximate computation of results at sea, although these combined corrections were finally processed by computer since the derivation of the marine tide for over a hundred stations is a somewhat tedious calculation. The necessary data for the calculation of the marine tide were obtained from 'The Admiralty Tide Tables Volume 1' for the current year and Chart No. 5058, 'Co-tidal and Co-range lines.' It was not considered necessary to make Terrain Calculations since their magnitude does not exceed that of other sources of error.

5.4 Latitude Correction.

From the measured value of gravity at each station was subtracted the theoretical value at that latitude as calculated from the International Gravity Formula of 1930.* The values of theoretical gravity accurate to .01 mgal, were obtained from a pamphlet listing the values at intervals of 0.1 minute of arc between latitudes 40°N. and 85°N. (Tanner, 1962).

5.5 Tidal Gravity Corrections.

Since the time interval between base readings was usually several hours it was necessary to apply a further correction to allow for the changes in tidal attraction of the sun and moon and for the Earth Tides. This was obtained from tables published as a supplement to the December issue of Geophysical Prospecting for the preceding year (Goguel, Geophysical Prospecting 196-).

6. Errors.

The errors affecting the work are of two distinct types, random and systematic.

6.1 Systematic Errors.

Systematic errors involve the calibration constant of the instrument itself, and the density value adopted for the Bouguer Correction. Inspection of calibration results under section 2.3 reveals that the greatest change in the value of the calibration constant over the period of a survey was only of the order of 0.3% and since the entire range of the meter is only 100 milligals this may be considered a negligible source of error.

Scrutiny of density data for a range of possible rock types indicates that a density as low as 2.25 gm./cm.^3 may be encountered in some Mesozoic Sandstones,

* Nettleton, 1940.

while certain Lower Palaeozoic strata attain a value of 2.75 gm./cm.^3 . Thus, an error of $\pm 0.25 \text{ gm./cm.}^3$ may be present in the value of ρ_m , giving rise to an error of ± 0.95 milligals in the Bouguer Correction for a depth of 300 feet. A working limit of 50 fathoms or 300 feet was adopted in this area, and consequently the possible error in the Bouguer Correction from this cause will not exceed one milligal and will generally be much lower.

6.2 Random Errors.

Random errors arise from errors in the measurements themselves and include positional errors, drift errors, and depth and marine tide uncertainties. Fixed Error Corrections were applied to the Decca readings using the available information, and station positions using the equipment under normal daylight conditions are considered to **involve** a maximum error of 600 feet. The Latitude Correction may therefore introduce an error of up to ± 0.14 milligals. The depth transducer is considered to be sensitive to a change in water height of one foot, and the marine tide can be estimated from tables to a similar degree of accuracy. The error involved in these uncertainties is about ± 0.1 milligals. Ten of the gravity stations were later re-occupied and the differences between the reduced readings yielded an estimate for the standard deviation of a station Bouguer Anomaly of ± 0.69 milligals. This is probably ^{mainly} caused by a lack of linear behaviour in the drift.

7. Presentation of Results.

The final reduced data are presented both in the form of a Bouguer Anomaly Map, contoured at five milligal intervals, indicating the detailed profile lines, and also as a table listing the station numbers and other relevant information which is included in Appendix 1.

8. The Magnetic Surveys.

8.1 Introduction

The instrument used for the magnetic work at sea was a Gray Proton Magnetometer MK.IV. This was used selectively to obtain detailed traverses across anomalies appearing on the Aeromagnetic Maps of part of Great Britain and Northern Ireland produced by the Geological Survey. Data was also collected in areas where the gravity field suggested that magnetic information might provide assistance in the interpretation.

8.2 Field Operation.

The magnetometer 'fish' containing the bottle and pre-amplifier was towed at ^{more than} two ships' length astern with the vessel maintaining a normal cruising speed of 12 knots. The automatic timing circuit of the instrument was adjusted at the beginning of a season to take measurements at approximately 15 second intervals and this setting was maintained throughout the surveys.

The position of a traverse was fixed using the Decca Navigator which was usually observed at five minute intervals. The exact time was noted for all Decca observations and for the magnetic readings at approximately five minute intervals. Radio time checks were made for the wrist-watches used by the Decca Navigator and magnetometer observers in order to ensure accurate correlation between the magnetic readings and the position of the vessel.

8.3 Reduction of Observations.

The field data were reduced by computer using a programme which calculates the values of the magnetic field at specified positions having corrected for diurnal and regional variations (Johnson, Personal communications). The Decca readings at five minute intervals are used to calculate the position of the magnetic readings by interpolation. The magnetic readings are then

converted to gamma and corrected for diurnal and regional variation again by interpolation. Finally the programme prints out the value and position of the magnetic field at all the points of measurement.

8.4 Presentation of Results.

The results obtained during the investigation of a specific anomaly are discussed in chapter 8, where the data appear in the form of scaled profiles.

Chapter 4

Description of the Bouguer Anomaly map.

1. Introduction

The distribution of the Bouguer Anomalies in the coastal areas surrounding the North Irish Sea and on the Isle of Man was discussed in Chapter 2. A significant aspect that emerged from this review of previous geophysical work was the widespread tendency for a rise in the Bouguer Anomaly to occur on approaching the North Irish Sea. It is apparent that a background anomaly close to +40 milligals may be present over much of the existing marine area under investigation.

Superimposed upon this high regional background anomaly are several areas of low Bouguer Anomaly values. The amplitude of these local negative anomalies varies between 20 and 40 milligals. An extensive area of relatively low Bouguer Anomalies is found in the eastern part of the North Irish Sea forming the East Irish Sea 'low'. Between Peel on the west coast of the Isle of Man and Northern Ireland an area of low Bouguer Anomalies has been named the Peel-Ardglass 'low' (Bott, 1964). Finally a negative anomaly of 40 milligals amplitude has been located in the vicinity of Dublin Bay and is called the Dublin Bay-Kish Bank 'low'. The interpretations of the Dublin Bay-Kish Bank

'low' and the East Irish Sea 'low' are discussed in Chapter 5 and 6 respectively.

The Bouguer Anomalies over the area investigated by the author are now described in terms of the several large scale features which have been discovered. Throughout the chapter the reader is referred to the Bouguer Anomaly map (Plate 1) which is to be found inside the back cover.

2. The East Irish Sea 'low'

The East Irish Sea 'low' occupies the area bounded to the north by a line extending from Ramsey on the Isle of Man to Whitehaven on the Cumberland coast, and in the south by the coast of North Wales. In the east the low Bouguer Anomaly values transgress the Lancashire coastal plain. A region of high positive Bouguer Anomalies in excess of +40 milligals forms the western boundary between the Isle of Man and Anglesey.

The main area of minimum Bouguer Anomalies occurs in the north approximately midway between the Isle of Man and the Furness coast. A minimum of -3.6 milligals was recorded. The regional background anomaly is considered to be approximately +36 milligals over this part of the North Irish Sea and the amplitude of the local anomaly is therefore about 40 milligals. A shallow low occurs in the southern half of the area where a measured minimum of +16.1 milligals was observed. The amplitude over this part of

the anomaly with respect to the centrally disposed minimum of +16.1 milligals must be approximately 20 milligals assuming a background anomaly of +40 milligals from the evidence on Anglesey and the marine measurements to the north-west. This is only half the value estimated for the main minimum region in the north of the area.

As stated above the area of minimum anomaly lies approximately midway between the Isle of Man and the Furness Coast, and the eastern boundary of the feature has been taken as the gravity low along the coastal margin of south-west Cumberland and Furness. To the south-east of the central minimum the gradients are shallow and a large area exists in the vicinity of Morecambe Bay where the anomaly varies by only 2-3 milligals. The southern half of the East Irish Sea is characterized by relatively gentle gradients over much of the area with the Bouguer Anomaly values generally higher in the west, and decreasing gradually towards the Lancashire Coast. This tendency is interrupted by the shallow 'low' in the central part of the area in which the measured minimum was +16.1 milligals. This disturbance causes the 20 milligal isogal to swing round in the approaches to the Ribble Estuary and produce a pronounced nosing to the west, while the isogals immediately to the north of Rhyl appear to be strongly influenced by the Vale of Clwyd 'low' on the North Wales Coast. Over a wide area extending from Fleetwood in the north

to Liverpool in the south, the marine Bouguer Anomalies display values that vary little from those measured on the Lancashire coastal plain and no marked gravity gradients are present on this side of the feature.

A large positive anomaly occurs within the overall gravity 'low' approximately ten miles to the south-east of Douglas, Isle of Man. This feature is elliptical in shape and is approximately fifteen miles long in a south-east to north-west direction. The feature is about ten miles in length from south-west to north-east. The measured maximum Bouguer Anomaly was +37.7 milligals which is closely comparable with the values observed along the coast of the Isle of Man.

The northern boundary of the East Irish Sea 'low' was established by Bott as being the gravity ridge of relatively high Bouguer Anomalies which separates the gravity low under discussion from the 'Solway low' further north (Bott, 1964). The boundary is marked by steep gravity gradients and a detailed profile was obtained during the 1965 season in order to investigate the shape and magnitude of the gradients more accurately.

Steep gradients are again present within 3-4 miles of the eastern seaboard of the Isle of Man where the isogals tend to run almost parallel with the existing coastline and form the boundary of the 'low' in the west. From a value of about +40 milligals on the coastal margin, the anomaly falls to +20 milligals within four miles of the shore between Douglas and Laxey. The gradient reaches

a measured maximum of 7 mgals./mile near Laxey, and 10 mgals./mile to the south-east of Douglas.

The presence of steep gradients over the margin of the East Irish Sea 'low' in the south-west must be inferred from the existence of Bouguer Anomalies in excess of +40 milligals on Anglesey together with the knowledge that the value decreases to +25 milligals five miles to the north of the Great Ormes' Head. To the north of Holyhead the boundary of the anomaly is vague due to the scarcity of data, but the existence of a pronounced marginal gravity feature in this region is suggested by the further occurrence, only a few miles to the west, of a large area in which the Bouguer Anomalies exceed +40 milligals (Section 3).

Three detailed traverses have been established across significant gravity features of the East Irish Sea 'low'. Profile EE' was planned to investigate the shape and magnitude of the gravity gradients across the northern boundary and extends from Ramsey Bay in a south-easterly direction towards Fleetwood (Plate 1). Proceeding from north-west to south-east along the profile, it was found that after initially maintaining a constant value of approximately +36 milligals for more than three miles, the Bouguer Anomaly suddenly slumped by fourteen milligals in a mile and a quarter giving a maximum gravity gradient of about 11 mgals./mile. The gradient decreased

gradually in a south-easterly direction to a value of 2 mgals./mile as the central minimum was approached.

Profile DD''' across the local positive anomaly south-east of Douglas indicated that the steepest gradients associated with the feature occur in the north-east where a gravity gradient of 8 mgals./mile was recorded across the margin of this local anomaly. To the south-west the gradient has a value of 3-4 mgals./mile and the Bouguer Anomaly falls to a measured value of +16.6 milligals, after which the profile indicated a very gradual rise towards the extensive area of high gravity values situated between the Isle of Man and Anglesey.

Profile FF' extends from near Douglas in the north-west to a position south-east of the local positive anomaly. The Bouguer Anomaly near Douglas is approximately +40 milligals, but this value falls rapidly within about four miles from the coast to a measured minimum of +18.9 milligals. The maximum observed gravity gradient over this section of the profile was found to be approximately 10 mgals./mile. From the minimum of +18.9 the Bouguer Anomaly was found to rise at approximately 3-4 mgals./mile in a south-easterly direction until the measured maximum of +37.7 milligals was reached at the centre of the local positive anomaly.

Thus it is apparent that a large area in the eastern half of the North Irish Sea is occupied by a composite gravity 'low', the continuity of which is interrupted by a conspicuous gravity 'high' situated ten miles to the south-east of Douglas, Isle of Man. The major feature is delineated to the north-west and south west by steep gravity gradients, and to the west by an extensive area of high Bouguer Anomalies similar in value to those encountered over much of the Isle of Man. In the north-east the anomaly is bordered by a gravity 'low' along the coastal margin of Cumberland, while in the south-east of the area there appears to be structural continuity with the coastal plain of Lancashire. It is suggested that the term 'East Irish Sea Low' be used in reference to the above anomaly.

3. The 'Central High'.

As already noted in Section 2 of the chapter, a large area of relatively high Bouguer Anomalies is located to the west of the 'East Irish Sea Low', between the Isle of Man and Anglesey. The highest measured value was 41.8 milligals and although the 40 milligal isogal is adequately defined, the position of the 35 milligal isogal is doubtful to the south and west due to lack of data. This region of high Bouguer Anomaly values forms a western boundary to the 'East Irish Sea Low' and appears to lie on an extension of the structural axis of the Isle of Man.

4. The 'Peel-Ardglass Low'.

Situated to the north of the 'Central High' and occupying a position between the west coast of the Isle of Man and the Mourne Mountains, is an elongate gravity 'low' with a long axis aligned in a north-east to south-west or Caledonoid direction. The existence of this low was first detected in 1961 as the result of a single traverse from Peel on the Isle of Man towards Ardglass in Northern Ireland (Bott, 1964).

The maximum width of the anomaly is approximately fifteen miles, and the length in excess of twenty miles, a more accurate estimate being impossible without additional data in the north. The minimum observed Bouguer Anomaly was +16.8 milligals although a lower value might have been obtained had readings been possible in the central area which is occupied by very deep water. An estimate of the amplitude of the anomaly is therefore difficult. The problem is complicated by the fact that the background anomaly over the Lower Palaeozoic rocks of Northern Ireland is about +20 milligals (Cook and Murphy, 1952), compared with a value of approximately +40 milligals over the Isle of Man. Nevertheless it is probable that an amplitude of at least 15 milligals exists over the central part of the anomaly. The maximum gradient from the limited data available would appear to be approximately 5 mgals./mile in the area immediately to the west of Peel. South-east of the 'Peel-Ardglass

Low' the Bouguer Anomalies display a general tendency to decrease gradually towards the coast of Ireland, and no significant anomaly was discovered until the station coverage reached the approaches to Dublin.

5. The Dublin Bay-Kish Bank 'Low'.

The Dublin Bay-Kish Bank 'low' extends from a position approximately five miles south of Lambay Island in the north to near Bray in the south. The feature is rectangular in outline and elongate in a north-east to south-west or Caledonoid direction. The axis of the feature in this direction is about 20 miles in length and the width is nearly 15 miles.

The minimum observed Bouguer Anomaly is -6.6 milligals and the amplitude of the anomaly is estimated to be 40 milligals. The anomaly possesses a simple, elongate minimum region.

The boundary of the anomaly in the north is marked by very steep gravity gradients and two detailed profiles have been established across this margin to investigate the shape and magnitude of these gradients. Steep gravity gradients also delineate the south-western boundary near Bray Head. The isogals on land in the vicinity of Bray show a steady rise in value in a south-easterly direction as the sea is approached. It is apparent therefore, that the isogals must change direction abruptly upon crossing the coastal margin.

The station density to the east of the minimum region is not sufficient to allow an accurate estimate of the magnitude of the gradients to be made.

The available data suggests that the gradients over this margin are more gradual with the Bouguer Anomalies rising to a measured maximum of +30 milligals.

The detailed profiles across the northern boundary revealed a measured maximum gradient of approximately 11 mgals./mile along Profile AA', and 15 mgals./mile along BB'. The existence of the Dublin Bay-Kish Bank 'low' was not suspected from the gravity field on land and the interpretation forms the subject of Chapter 5.

Chapter 5.

The Dublin Bay-Kish Bank Gravity 'Low'

1. Introduction

A large negative gravity anomaly has been shown to exist in the area of Dublin Bay. The minimum observed Bouguer Anomaly was -6.6 milligals and the amplitude of the anomaly has been estimated to be approximately 40 milligals. It is the interpretation of this gravity anomaly that forms the subject of this chapter. The chapter begins with a description of the methods that have been used in the interpretation.

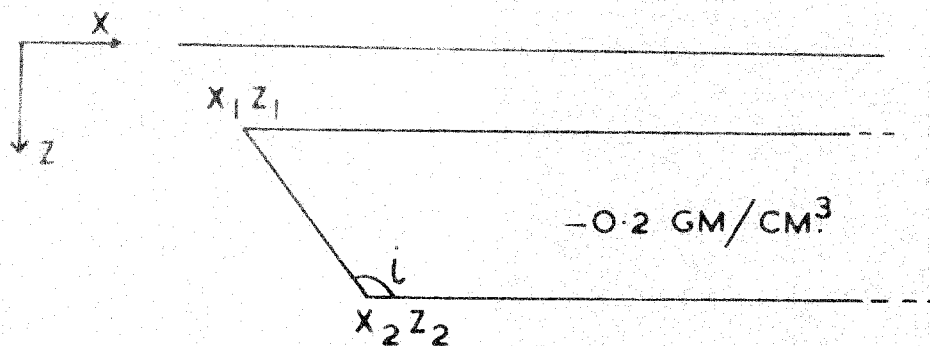
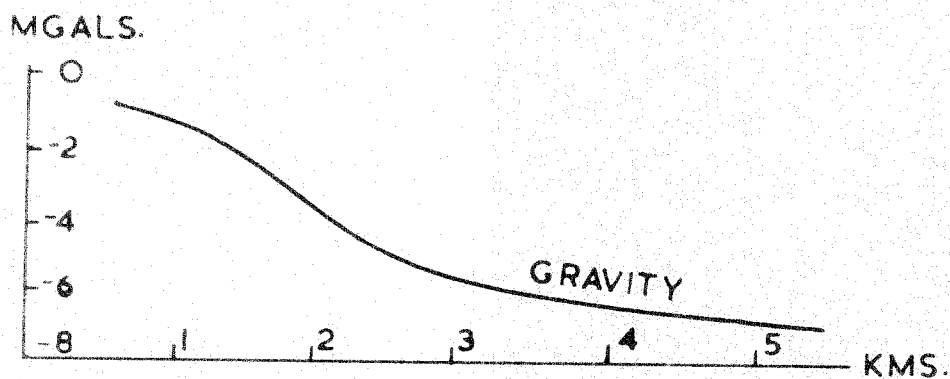
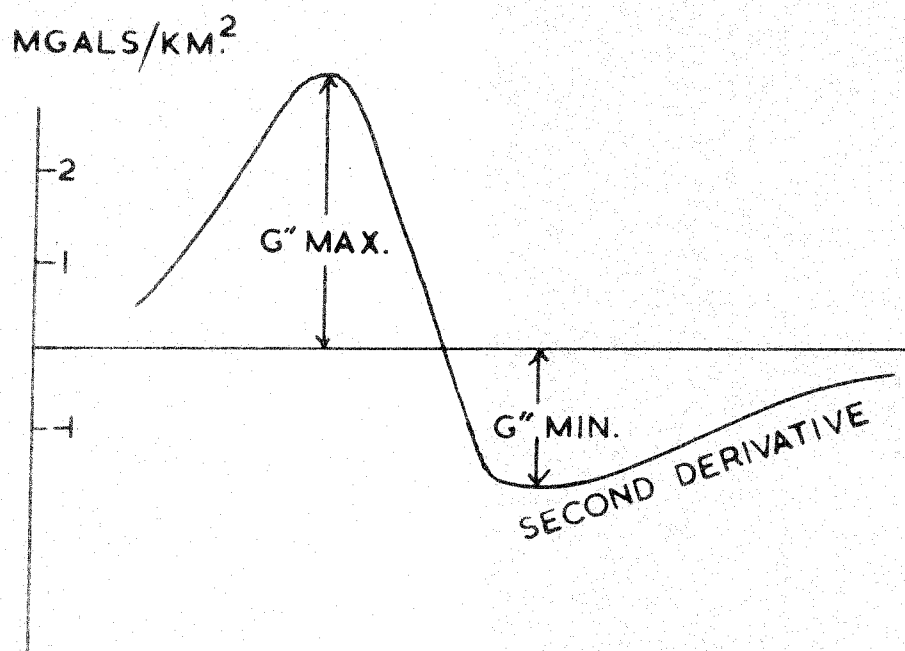
2. Methods of Interpretation.

2.1 The second derivative method.

The method is based on the fact that the second derivative of gravity across a profile above a two-dimensional semi-infinite, horizontal slab with a sloping edge has two turning values, the relative magnitudes of which depend upon the direction of slope. Since the boundary between sedimentary basins and the underlying denser basement rocks characteristically slopes inwards towards the basin, and the contacts of granite batholiths usually slope outwards, this criterion provides a means for distinguishing between buried granites and sedimentary basins from their gravity anomalies (Bott, 1962).

It was noted that granite batholiths and large sedimentary basins both give rise to negative gravity anomalies relative to the undisturbed surrounding regions, and that frequently the source of the anomaly is concealed by a later succession of sedimentary rocks or by the sea. The method permits a distinction.

FIGURE 1



to be made by a study of the gravity anomalies.

Referring to Figure 1, it was shown that with a negative density contrast, as x , the horizontal co-ordinate, increases, the value of the second derivative initially rises to a maximum, then falls to a minimum and finally rises again towards zero. The two turning points occur near the sloping edge, the maximum value always being further from the slab. The two turning points and the corresponding values of the second derivative, G'' , were computed for a range of values of i and z_1/z_2 . It was shown that the ratio of the magnitudes of the maximum second derivative and the minimum second derivative, $G''_{\text{max.}}/G''_{\text{min.}}$ was less than unity provided $0^\circ < i < 90^\circ$ and that $G''_{\text{max.}}/G''_{\text{min.}}$ was greater than unity provided $90^\circ < i < 180^\circ$.

Thus a comparison of the relative magnitudes of $G''_{\text{max.}}$ and $G''_{\text{min.}}$ gives the direction of slope and yields the required criterion. A difficulty in use of the technique to distinguish sedimentary basins was acknowledged in stating that it might be possible to construct a shape for which $G''_{\text{max.}}/G''_{\text{min.}}$ is less than unity although observations suggested that this was likely to be unusual. A further difficulty might arise from confusion with adjacent anomalies.

In conclusion it was stated that there were other characteristic distinctions between gravity anomalies caused by granites and sedimentary basins which were less suited to concise mathematical representation. An example was seen in the much more rapid recovery of the Bouguer Anomaly towards a background value beyond the position of $G''_{\text{max.}}$ for a sedimentary basin than for a granite.

2.2 Two-Dimensional Gravity Computer Programme.

This programme computes the gravity effect for any two-dimensional, polygonal shaped body

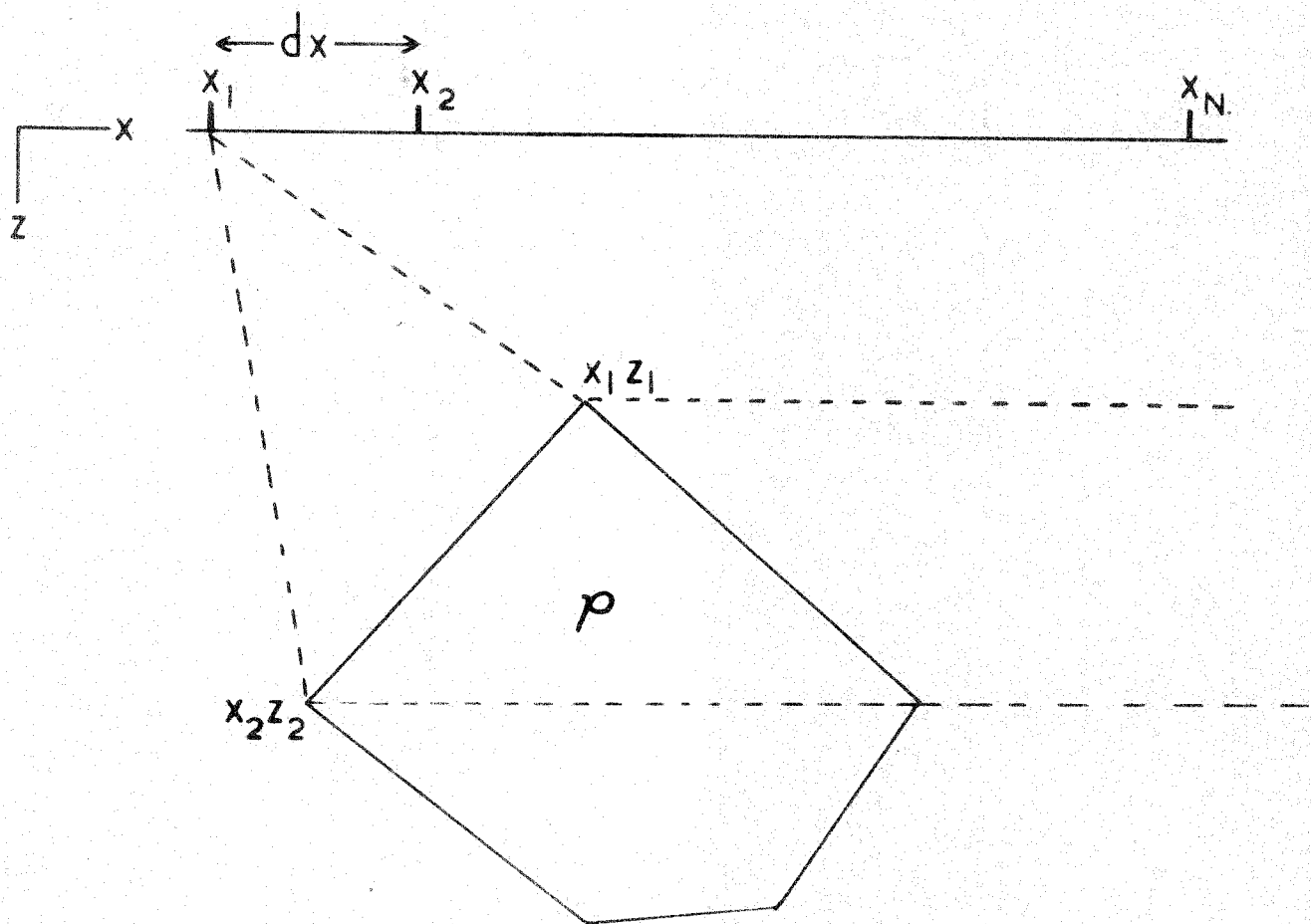


FIGURE 2

for any given density contrast ρ . (Stacey - Personal Communication). The programme is based on the method originally described by Talwani, Worzel and Landisman (1959). The gravity effect is computed for the required number of points ($x_1 \dots x_n$) at a specified horizontal interval dx , for a semi-infinite horizontal sheet which is defined in terms of the co-ordinates of one of the sloping faces of the polygonal body as shown in Figure 2.

The formula for the gravitational attraction of a semi-infinite sheet with a sloping end face is given by Heiland (1940). Algebraic summation of the effect of each sheet at all the positions taking into account that the effect of the sheets defined by the faces on the right hand side of the body must be subtracted to produce the required shape, then yields the magnitude of the gravitational effect at each point.

The programme has been used to compute the gravity profiles over theoretical granite bodies with vertical boundaries and differing thicknesses in order to establish the maximum gravity gradient that may be anticipated for a given anomaly amplitude over such a geological feature. The results are critically compared with the observed gradients in the interpretation section of this chapter.

2.3 Minimum Density Contrast Technique.

It has been shown, for the case of a mass distribution producing a negative anomaly, that if the contact between the anomalous body and the country rocks is taken as the density interface then a simple criterion exists to test the attitude of the boundary (Bott, Day and Masson-Smith, 1958). The steepest gradients theoretically lie within the boundary of the anomalous body if the

contact slopes inwards, and outside if the contact slopes outwards. In either case an abrupt change of gradient occurs at the exposed contact.

The magnitude of the change provides a measure of the angle of slope if the density contrast is known, or vice versa, by the approximate formula:

$$C = \pi G \rho \sin 2i.$$

where C is the difference between observed gradients at equidistant points on opposite sides of the contact, G the Gravitational constant, ρ the density contrast, and i the angle of dip. This relationship has been used during the interpretation of the 'Dublin Bay-Kish Bank Low' to establish a minimum limiting density contrast for the anomalous mass.

2.4 Sedimentary Basin Depth-Estimation Programme.

A computer programme in the ALGOL programming language for use with the Elliott 803 computer has been written by the author using a similar 'flow diagram' to that already existing for a programme prepared for the Ferranti Pegasus computer (Bott, 1960). The method assumes that the gravity anomaly is caused entirely by a sedimentary basin for which the density of the sediments in relation to the surrounding and underlying rocks is either known or assumed. It is then possible to calculate the shape of the floor of such a two-dimensional sedimentary basin from the regionally corrected gravity anomalies by a division of the total width of the sedimentary basin into a series of two-dimensional rectangular blocks. The regionally corrected gravity anomaly at the centre point of each block is obtained from the profile. The object of the programme is then to calculate the thickness of sediment beneath each block, which will account for all the observed anomalies. Facility is available for estimation of

the shape of a sedimentary basin in which one or both of the end blocks effectively extends to infinity. Such a situation exists when the margins of the basin are not terminated abruptly by faults, but where the floor slopes gently towards the upper surface.

An addition has been the introduction of a sub-routine to apply end-corrections (Holroyd - Personal Communication). Hence, the original two-dimensional basin is now modified to a basin of finite length perpendicular to the profile which causes a change in the calculated thickness and therefore the shape of the basin floor.

3. Interpretation.

3.1 Introduction.

i. Description of the Anomaly.

The 'Dublin Bay-Kish Bank Gravity Low' is located approximately ten miles to the east of Dublin and is elongate along a north-east to south-west or Caledonoid direction. The axis of the feature in this direction is about twenty miles in length and the width at right angles is approximately fifteen miles (Plate 1). The presence of the anomaly was not suspected from the evidence of gravity work on land and the cause of the anomaly is not obviously apparent from the coastal geology. The 'low' possesses an approximately rectangular outline with a single and elongate minimum region in which the minimum observed Bouguer Anomaly was -6.6 milligals. Inspection of the Bouguer Anomalies on land in conjunction with the measurements at sea suggests that the background anomaly is in the region of $+35$ milligals which would indicate an amplitude for the local anomaly of about 40 milligals.

BOUGUER ANOMALY

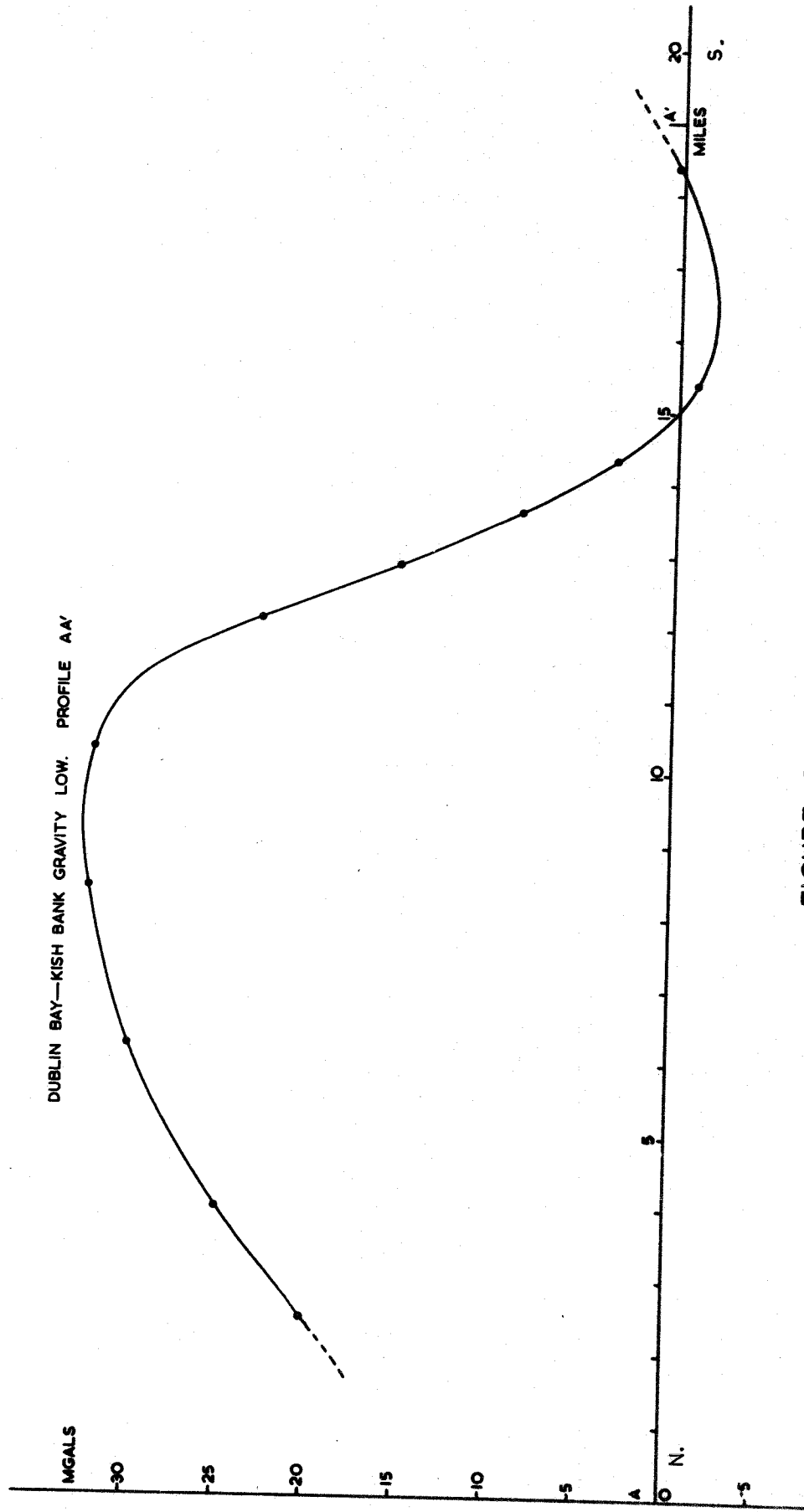


FIGURE 3

BOUGUER ANOMALY

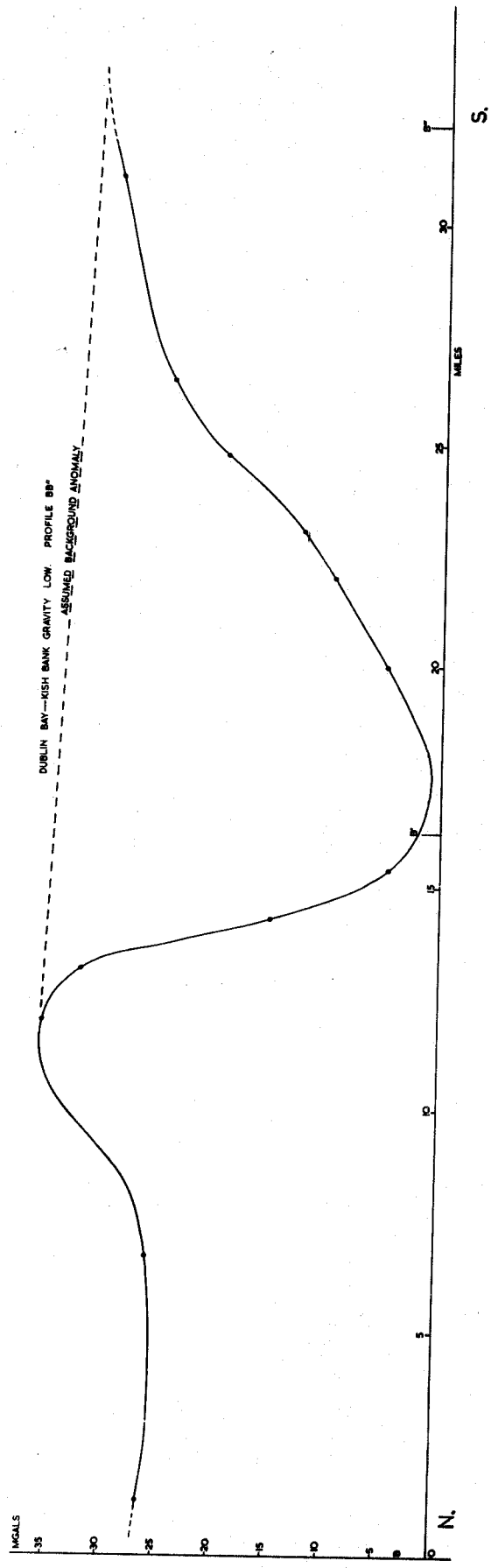


FIGURE 4

BOUGUER ANOMALY

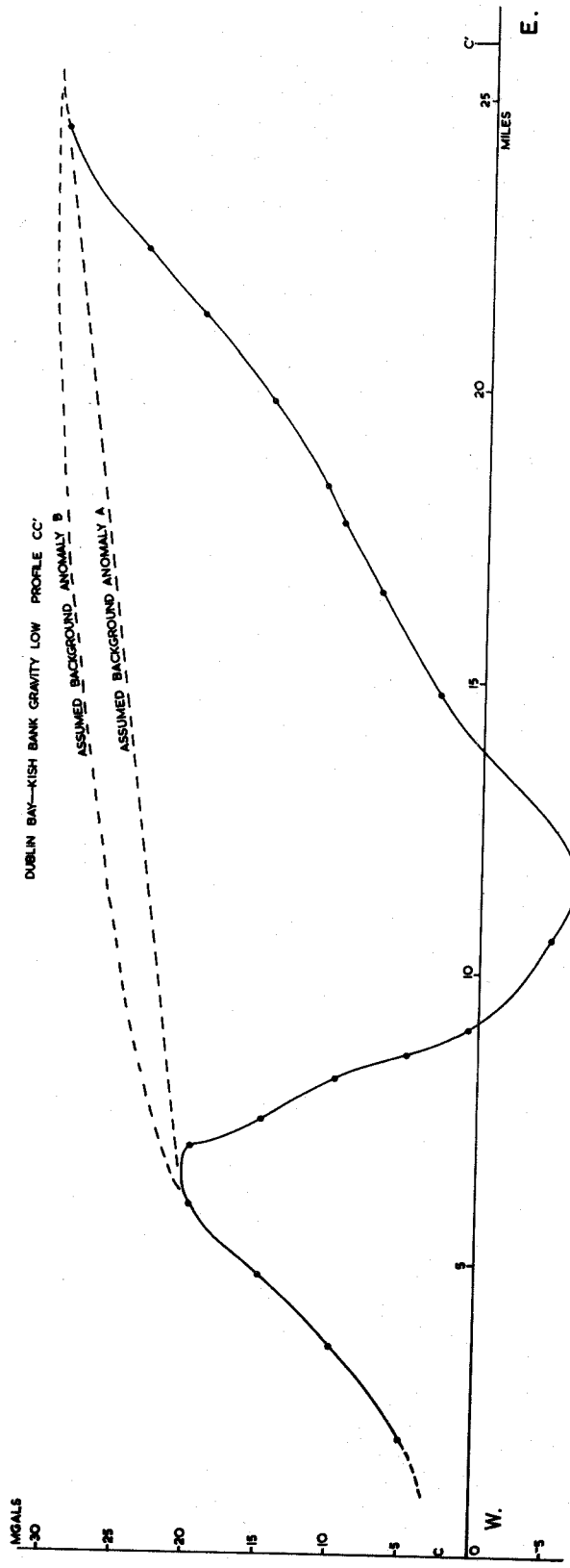


FIGURE 5

Steep gravity gradients were found to be present over the northern boundary of the feature and two detailed profiles in that area revealed maximum measured gradients of 11 mgals./mile along profile AA', (Plate 1), and more than 15 mgals./mile along profile BB'. The shape of the profiles are indicated in Figures 3 and 4. Steep gradients also exist along the south-western margin of the feature where the isogals on land show a steady rise towards the coast, as shown in Figure 5. The position of the negative anomaly only a few miles from the shore indicates that the land isogals, which trend north-east to south-west in this area, must change direction abruptly upon crossing the coastal margin to follow a north-west to south-east direction. To the east of the central minimum the data is more broadly distributed but it would appear that the gradients are more gentle over this margin, the Bouguer Anomalies rising to a measured maximum of +30.0 milligals.

ii. The Problem of Origin.

Large negative gravity anomalies of the type described above are caused by masses of material which possess significantly lower densities than the surrounding country rocks in which they are situated. The geological structures which are known to commonly produce negative anomalies of this magnitude fall into two main categories, namely, granite batholiths and large sedimentary basins. It has frequently been observed that post-tectonic granites are usually accompanied by negative gravity anomalies (Cook and Murphy, 1952; Bean, 1953; Bott, 1953, * Bott and Masson-Smith, 1960). Similarly, the common association of large negative anomalies with certain regions of New Red Sandstone rocks has been a significant result of the gravity data obtained in the British Isles (White, 1949; Cook and Thirlaway, 1956; Bott and Masson-Smith, 1960;

* Bott, M.H.P. and Masson-Smith, D. 1957.

* Bott, M.H.P., Day, A.A. and Masson-Smith, D. 1958.

Mansfield and Kennett, 1963; Bott, 1964). Much of the work of the above authors has been reviewed in the chapter concerned with previous geophysical investigations.

It is possible therefore that the 'Dublin Bay-Kish Bank' gravity anomaly could be caused by either a granite or a sedimentary basin. The geology of the coastal area does not provide conclusive evidence for either hypothesis. The extensive Leinster Granite, which forms the bulk of the Wicklow Mountains, is present on land but the gravity isogals over this structure and the anomaly at sea do not display obvious correlation. In addition it has been observed that basins containing light sediments occupying low lying areas frequently occur in close proximity to granite bodies which tend to occupy regions of elevated topography (Bott, 1964). It is apparent therefore that the critical evidence for the interpretation of the 'Dublin Bay-Kish Bank' anomaly must be sought in the character of the gravity profiles.

iii. The Background Anomaly.

Gravity work on land has shown that the Bouguer Anomaly rises rapidly when traced from the Leinster Granite to a position just north of Dublin where it attains a high value of +30 milligals (Murphy, 1952). The area of high anomaly was not found to be very extensive but confined to a district where only post-Silurian rocks outcrop (Plate 1). It was suggested by Murphy that the increase in anomaly was due to the presence under the Carboniferous of Ordovician strata, the density of which was increased from an adopted mean of 2.73 gm./cm^3 (Section 3.1 iv) as the result of local igneous activity. To the south of the Leinster Granite the Bouguer Anomaly rises steadily over the Lower Palaeozoics in a south-easterly direction attaining a value of +35 milligals just south of Bray (Thirlaway, 1951).

Of the marine stations, the two detailed profiles in the north indicate a background anomaly of between +32 and +36 milligals, while to the east the limited data available suggest a background value of at least +30 milligals. It would appear therefore that the undisturbed Bouguer Anomaly over the surrounding areas where Lower Palaeozoic strata either outcrop or are suspected to exist at no great depth, is of the order of ^{to} +30 to +36 milligals.

iv. The Densities of the Rocks of the Coastal Region.

In order to interpret the results of gravity observations in Ireland, density values were initially based upon measurements of the rocks of the West Midlands of England and Central Wales. In the following table of assumed densities of Irish rocks, only the value for the Leinster Granite was derived from laboratory measurements (Thirlaway, 1951).

Rock Type	Density (gm./cm ³)
Trias.	2.4
Carboniferous Lst.	2.7
Devonian.(O.R.S.)	2.6
Silurian.	2.8
Granite.	2.6

Consideration of the limited number of density measurements made available in Central Ireland by Jackson (1951) indicated that there was no large difference in density between rocks of widely different ages from the Cambrian up to the Carboniferous Limestone, the mean value being 2.70 gm./cm³. (Murphy, 1952). It was noted that the density of sandstones of every geological age was less than that of the more compact rocks. The Devonian and Carboniferous strata

were the only ones which contained great thickness of sandstone, and it was observed that even then the measurements indicated that the sandstone was not much lighter than 2.70 gm./cm^3 . From measurements of samples outside the area of Central Ireland the Pre-Palaeozoic rocks were found to have a density greater than 2.73 gm./cm^3 . A broad division of the densities of rocks in the central area was suggested by Murphy as follows:

Pre-Palaeozoics	2.75 gm./cm^3 .
Ordovician & Silurian	2.73 gm./cm^3 .
Devonian & Carboniferous	2.70 gm./cm^3 .

Although the Devonian was grouped with the Carboniferous it was acknowledged that the density would be less if thick deposits of sandstone were present, and a value of about 2.65 gm./cm^3 was suggested in this case.

More recently the absence of large density contrasts within the Palaeozoic rocks below the Carboniferous Limestone has been reiterated (Murphy, 1962). An almost uniform density of 2.70 gm./cm^3 for the Carboniferous Limestone, and an overall density of 2.73 gm./cm^3 for the underlying Lower Palaeozoics were also reaffirmed. The Old Red Sandstone deposits in Central Ireland of less than 200 metres (656 feet) thickness provided the main departure from previous estimates. While the dependence of the density on porosity was recognised, it was stated that the minimum density of these rocks was not less than 2.50 gm./cm^3 . Glacial gravels form a major component of the superficial deposits in parts of the central area, and for these a density of about 2.2 gm./cm^3 was considered appropriate by Murphy.

3.2 The Second Derivative Profiles.

The magnitude of the gravity gradients across the northern margin of the anomaly along profiles AA' and BB', together with the resulting values of the

Table 1.

Magnitude of the gradient between adjacent stations along Profile AA' from north to south. (mgals./mile.)

Value of Second Derivative. (mgals./mile/mile.)

0.21	.....	+1.38
2.00	.....	+5.65
7.09	.....	+4.34
11.0	.....	-3.67
8.25	.....	-0.91
7.57	.....	-3.97
4.00	.....	-3.76
-0.37	.....

Profile BB'

-0.30	.....	+2.32
2.67	.....	+11.36
15.73	.....	-5.29
9.91	.....	-3.51
-0.11	.....

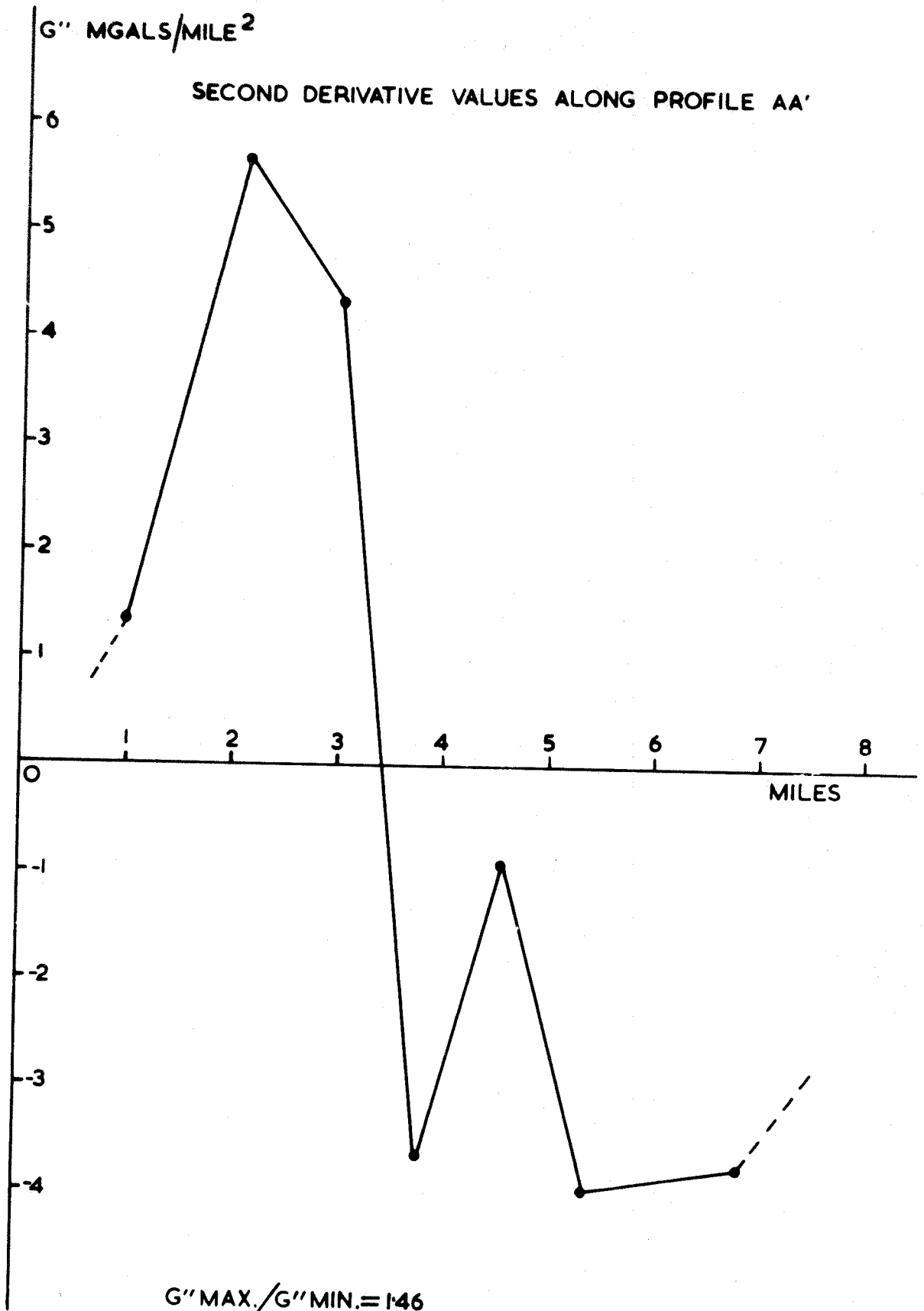
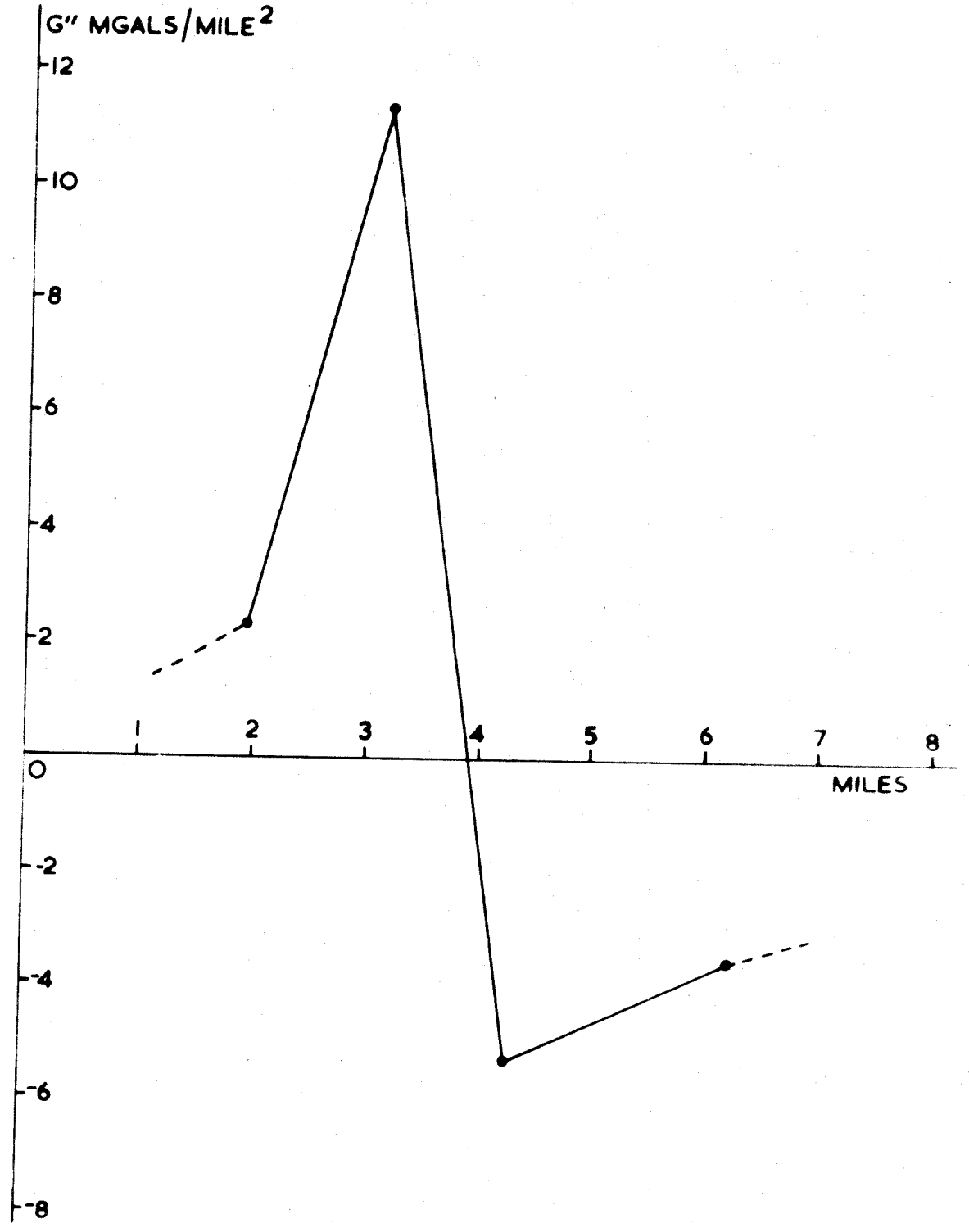


FIGURE 6

SECOND DERIVATIVE VALUES ALONG PROFILE BB'



$G'' \text{ MAX.} / G'' \text{ MIN.} = 2.16$

FIGURE 7

second derivative are recorded in Table 1. Figures 6 and 7 indicate in graphical form the distribution of the second derivative values.

The results obtained for $G'' \text{ max.}/G'' \text{ min.}$ as estimated from this data for profiles AA' and BB' were 1.46 and 2.16 respectively. This result indicates that the boundary of the anomalous mass slopes inwards towards the centre of the anomaly, and that if this is the case the presence of a sedimentary basin structure would seem more probable than a granite mass. (Section 2.1)

3.3 The Evidence of the Gravity Gradients.

Using the two-dimensional gravity computer programme, several profiles were obtained over the margins of theoretical granites with thicknesses of 5, 8, and 10 kilometres, and vertical end-faces for a negative density contrast of 0.15 gm./cm^3 . This value was considered to be the maximum possible from consideration of the density data (Section 3.1 iv). The values of gravity were computed at a horizontal interval of 1000 metres (3280 feet). Since the actual observed values of the detailed marine profiles were at a spacing of approximately 2000 metres (6560 feet), and the most extreme conditions were adopted for the computed models, it was anticipated that the maximum possible gravity gradients would be obtained from the theoretical profiles for the purpose of comparison with the observed gradients. A further profile was computed for a granite body with a margin sloping outwards at an angle of 45° . The results are shown in Table 2, and Figures 8 and 9.

These indicate that a granite with a vertical boundary and a thickness of 10 kilometres produces an anomaly of nearly 40 milligals which approximates to the amplitude of the observed anomaly. The maximum gradient for this model was found to be 11.5 mgals./mile . This is similar to the maximum observed gradient

Table 2.

Amplitude of the Anomaly and maximum gravity gradients produced by theoretical granites with vertical boundaries and different thicknesses for a density contrast of -0.15 gms/cm^3 .

Thickness of granite	Amplitude	Maximum gravity gradient.
10 kilometres	39.0 mgals.	11.5 mgals./mile.
8 "	34.0 "	10.8 " "
5 "	25.0 "	9.4 " "

Amplitude of the Anomaly and maximum gravity gradient produced by a theoretical granite with an outward sloping boundary at 45° for a thickness of 10 kilometres and a density contrast of -0.15 gms/cm^3 .

Thickness of granite	Amplitude	Maximum gravity gradient.
10 kilometres	42.0 mgals.	9.7 mgals./mile.

FIGURE 8

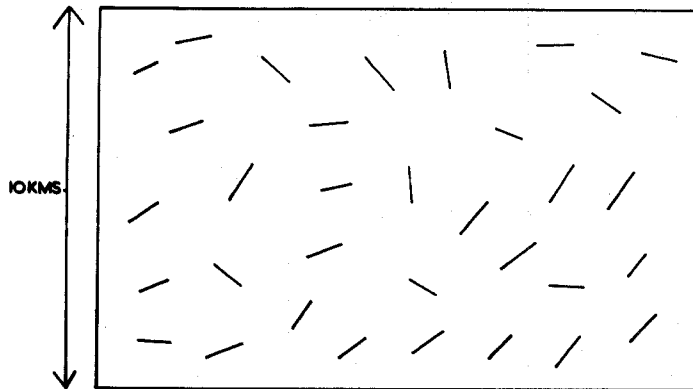
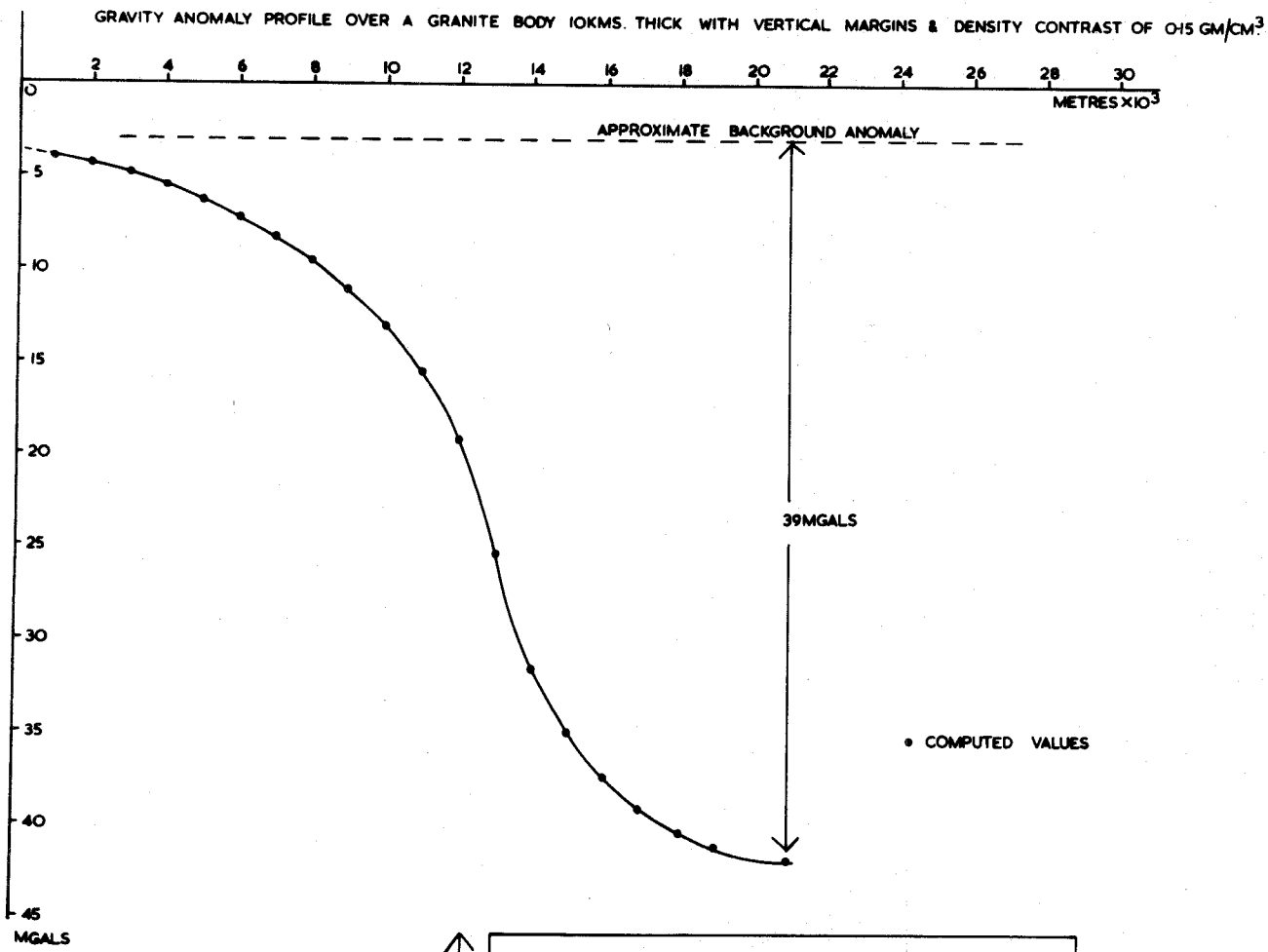
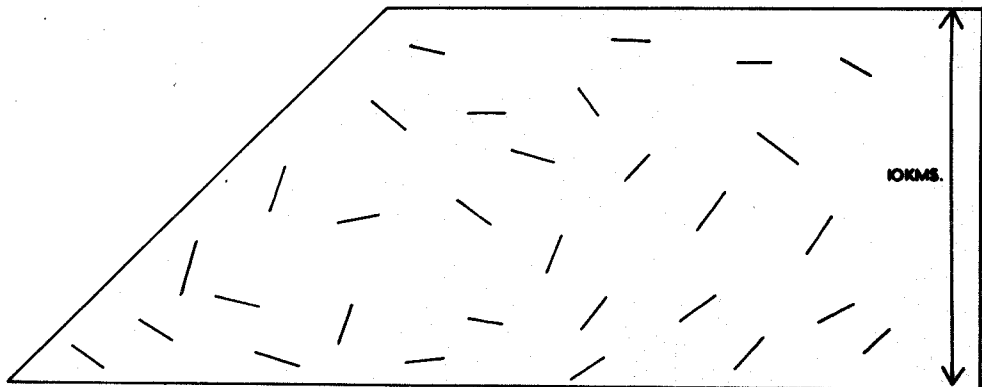
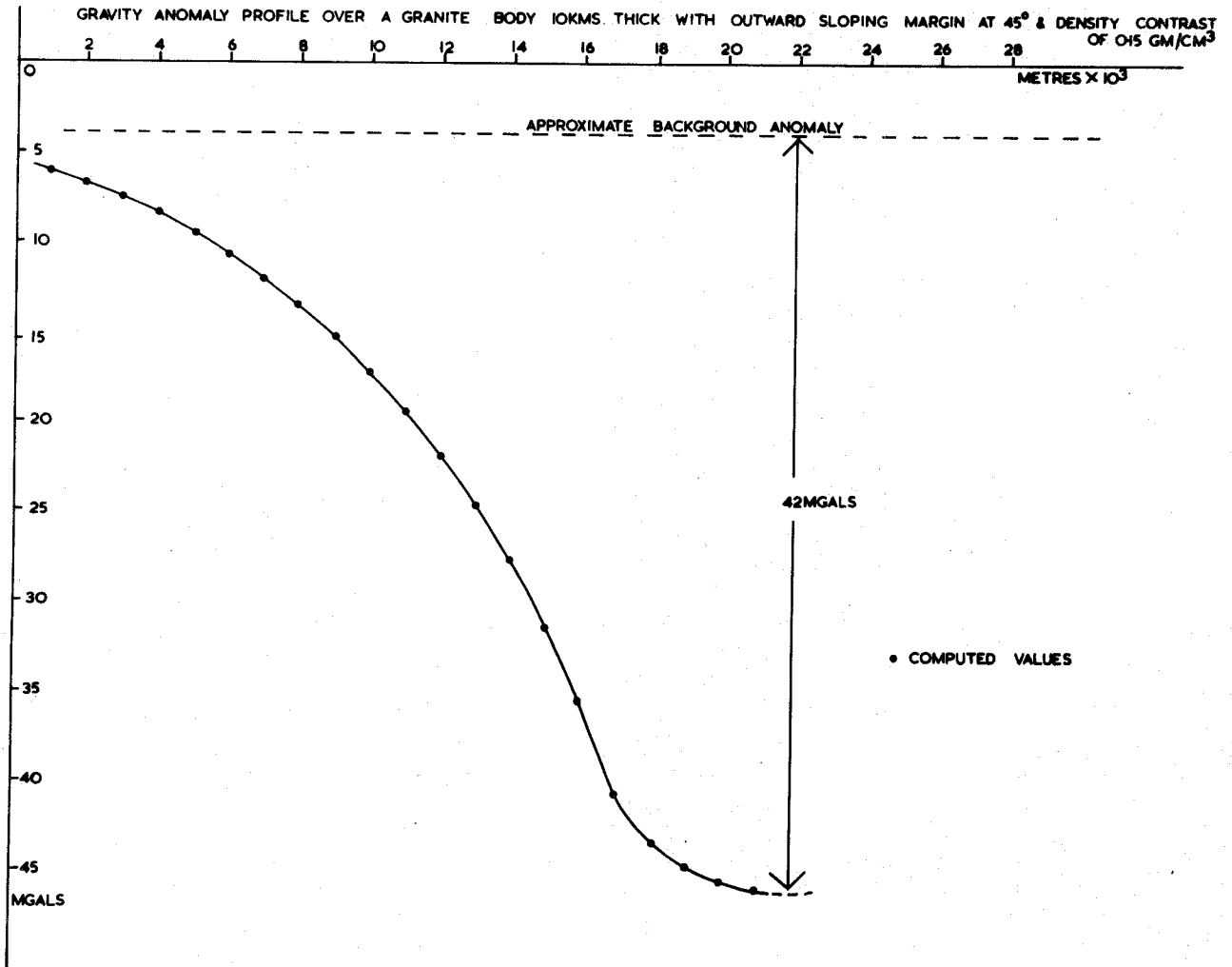


FIGURE 9



along Profile AA', but considerably less than the value of 15.7 mgals./mile recorded on Profile BB'.

Further evidence was obtained from the character of the complete profiles. It is apparent that the profiles for the computed models over granite bodies show a gradual return to the background level away from the centre of the anomaly. This is in clear distinction from the abrupt return to the background level that occurs in a distance of about one mile along the observed profiles. It was noted in the discussion of interpretation techniques that the observed effect is more characteristic of a sedimentary basin structure.

For a granite with an outward sloping boundary the divergence from the observed data is even more marked. The model for a granite with a thickness of 10 kilometres and a boundary sloping outwards at an angle of 45° produced an anomaly of approximately 42 milligals and a maximum gradient of 9.7 mgals./mile. The return to the background level was still more gradual. It is also apparent from the computed profile that the most rapid change of gradient occurs in a position near the central minimum of the calculated anomaly in comparison with the observed effect where this occurs along the section of the profile where the anomaly approaches the background level. This is an alternative method of stating that $G''_{\text{max.}}/G''_{\text{min.}}$ is less than unity for a relatively low density mass with an outward sloping margin.

(Section 2.1)

3.4 The implications of the minimum density results.

Using the relationship noted in section 2.3 above, an estimate was obtained for the lower limit of the density contrast required to produce the observed change in gradient along the detailed traverses AA' and BB' across

Table 3For Profile AA':

Using the relationship $C = \pi G \rho \sin 2i$. (Section 2.3).....1

Assuming $i = 45^\circ$, $\rho = \frac{C}{\pi G}$ 2

On one side of the estimated position of the contact the gradient was found to be 0.21 mgals./mile.

At an equal distance on the opposite side of the estimated contact the gradient was found to be 11.0 mgals./mile.

Therefore $C = 10.79$ mgals./mile.

Substituting in 2, $\rho = 0.28$ gm./cm.³

For Profile BB':

The gradients at equidistant points on opposite sides of the estimated contact were found to be 2.67 mgals./mile and 15.73 mgals./mile.

Therefore $C = 13.06$ mgals./mile.

$\rho = 0.34$ gm./cm.³.

the northern boundary of the anomaly. The necessary data from the observed profiles and the resultant densities are recorded in Table 3. An angle of 45° for the slope of the interface was assumed in order to provide the limiting conditions.

The resulting high density contrasts of 0.28 gm./cm.^3 and 0.34 gm./cm.^3 for profile AA' and BB' respectively, make an interpretation in terms of a granite very difficult to reconcile with evidence of the rock densities considered in section 3.1 iv. The values would seem to be more fitting for low density sediments of a type encountered in Mesozoic formations for which a density of about 2.4 gm./cm.^3 is widely accepted.

3.5 Summary of the evidence

Due to the lack of obvious geological correlation the interpretation of the 'Dublin Bay-Kish Bank' Anomaly has placed almost complete reliance on the evidence of the detailed gravity profiles which have been established across the northern boundary. However, the results of investigations of similar anomalies in the British Isles suggests that an anomaly of this magnitude is likely to be caused by a granite batholith or a deep sedimentary basin.

Consideration of the gravity profiles from three different aspects all presented difficulties for an interpretation involving the presence of a granite body, but provided positive evidence for a hypothesis based on the existence of a deep sedimentary basin. This proximity of a sedimentary basin and an area of high ground in which a granite mass forms the main bulk, in this case the Leinster granite of the Wicklow Mountains, has several precedents as already mentioned (Chapter 2). On the strength of this evidence, a detailed, quantitative

interpretation in terms of a sedimentary basin structure was conducted, the results of which form the content of the following section.

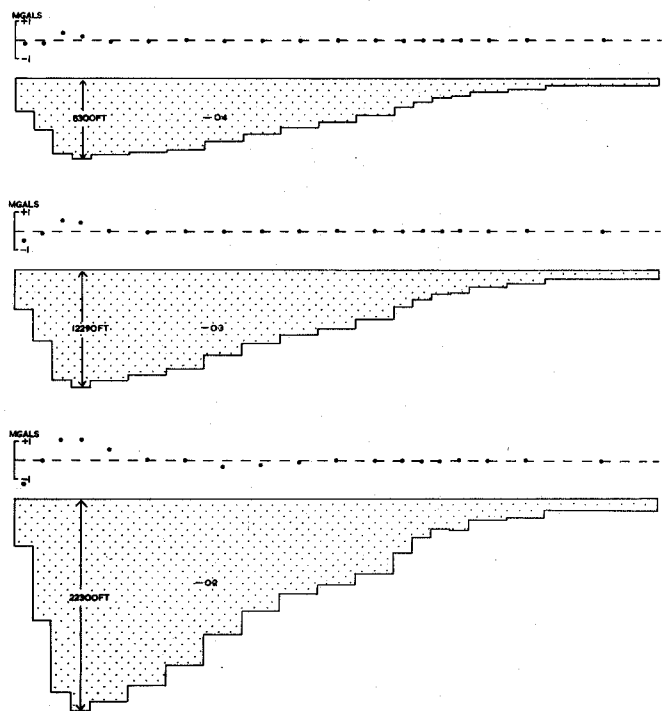
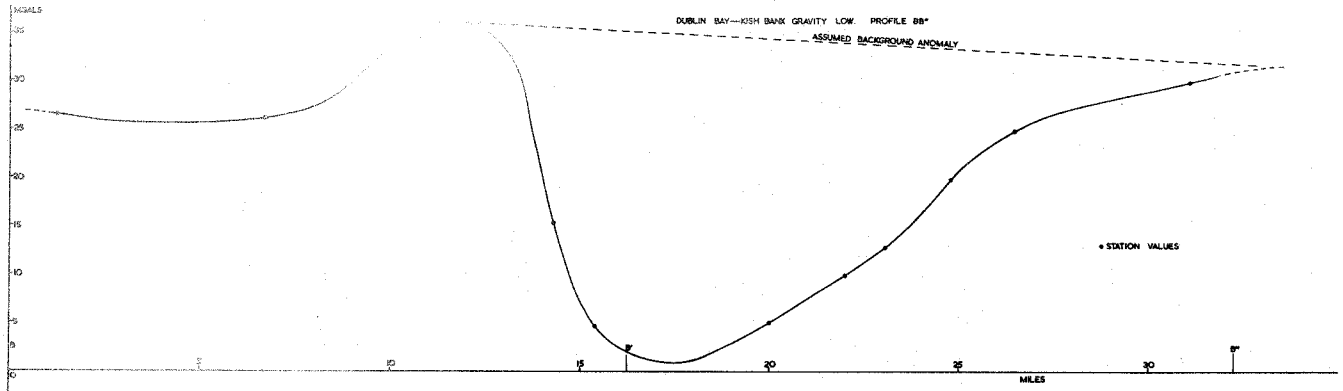
3.6 Detailed interpretation in terms of a Sedimentary Basin.

i. Depth Estimation.

The Sedimentary Basin depth-estimation programme (Section 2.4) was now employed, using data obtained from observed Profiles BB' and CC'. The method assumes that the anomaly is caused entirely by a sedimentary basin and that the background regional anomaly profiles are as shown in Figures 4 and 5. A uniform density contrast must be present throughout the anomalous mass, and the upper surface of the basin is assumed to reach the sea-bed.

End-corrections have been applied and the estimates of the maximum depth and overall shape are therefore applicable to a basin of finite length. Two positions of the regional background anomaly have been adopted in the case of Profile CC', in order to check the differences caused by uncertainty in the background level. Three values were assumed for the density contrast to the basement in the estimation of a model to explain observed profile BB'. These were -0.2, -0.3, and -0.4 gm./cm³. From a consideration of the density data, reviewed in section 3.1 iv, -0.4 gm./cm³ is believed to represent the maximum possible density contrast if low density Mesozoic sediments form the main 'fill' of the basin. If Carboniferous strata were to form a major component at depth, then the effective density contrast would be decreased and the maximum estimated thickness of the basin considerably increased. Alternatively, if Tertiary or Glacial deposits were present in large proportion, the maximum depth might be slightly less than that estimated. (Section 3.6 iii).

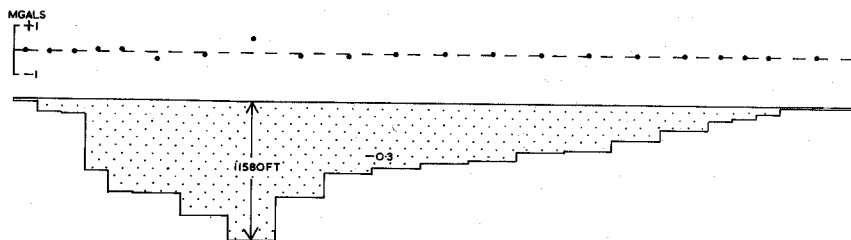
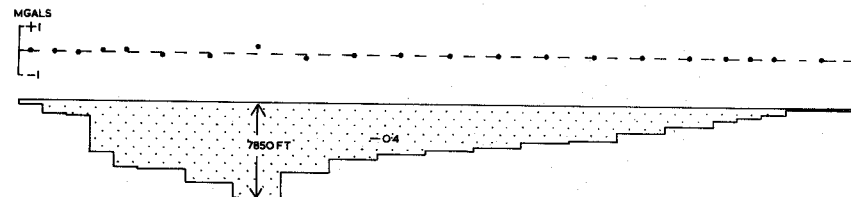
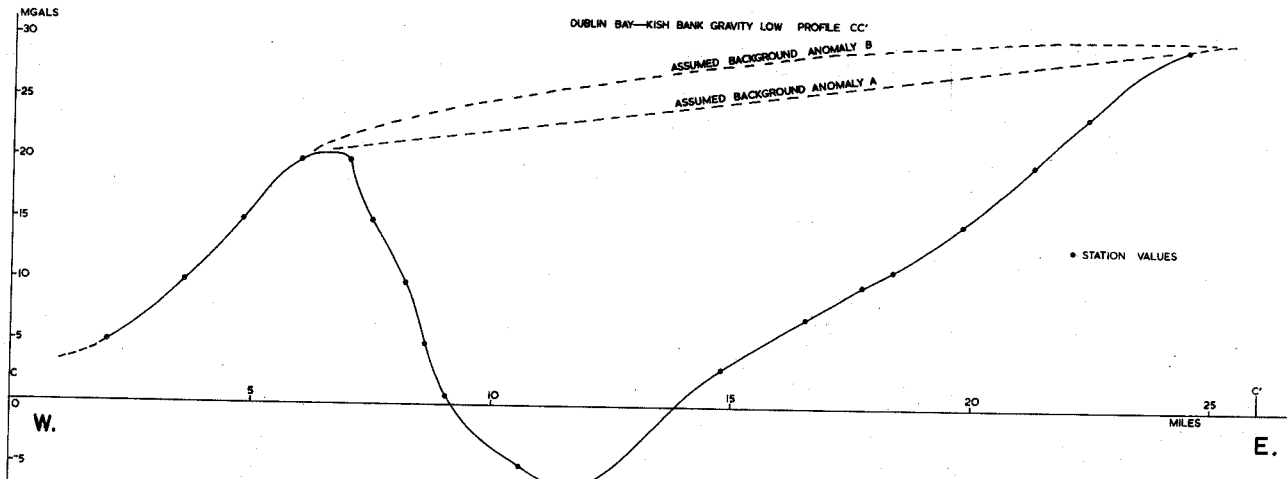
BOUGUER ANOMALY



INTERPRETATION OF THE BOUGUER ANOMALY PROFILE BB' ACROSS THE DUBLIN BAY-KISH BANK 'LOW' FOR DENSITY CONTRASTS AS INDICATED. THE RESIDUALS (OBSERVED MINUS CALCULATED ANOMALIES) ARE DISPLAYED ABOVE EACH MODEL.

FIGURE 10

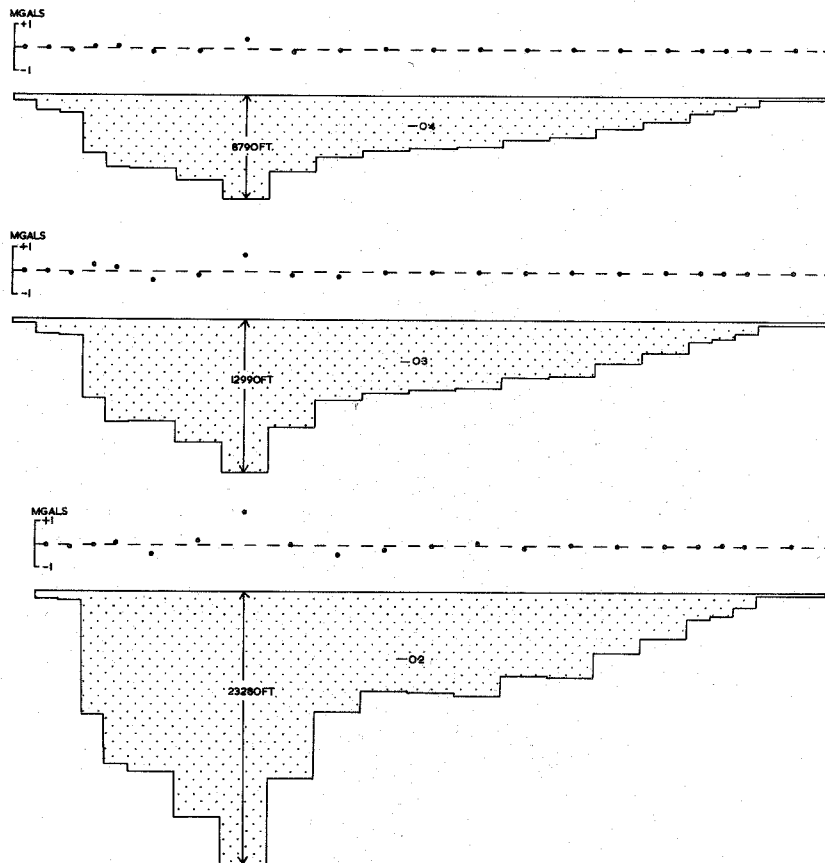
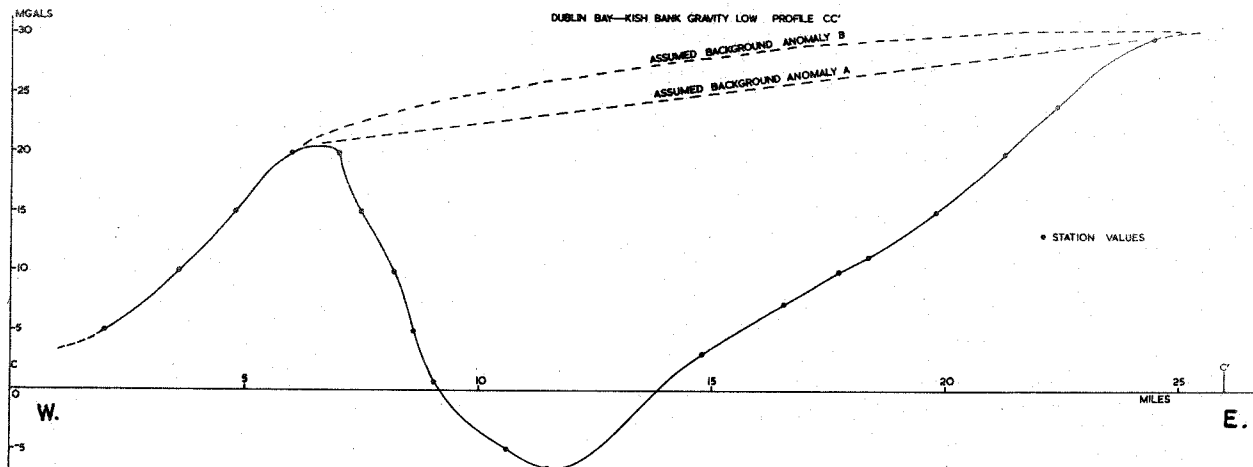
BOUGUER ANOMALY



INTERPRETATION OF THE BOUGUER ANOMALY PROFILE CC' ACROSS THE DUBLIN BAY—KISH BANK 'LOW' FOR DENSITY CONTRASTS AS INDICATED & THE ASSUMED BACKGROUND ANOMALY A. THE RESIDUALS (OBSERVED MINUS CALCULATED ANOMALIES) ARE DISPLAYED ABOVE EACH MODEL.

FIGURE 11

BOUGUER ANOMALY



INTERPRETATION OF THE BOUGUER ANOMALY PROFILE CC' ACROSS THE DUBLIN BAY—KISH BANK 'LOW' FOR DENSITY CONTRASTS AS INDICATED & THE ASSUMED BACKGROUND ANOMALY B. THE RESIDUALS (OBSERVED MINUS CALCULATED ANOMALIES) ARE DISPLAYED ABOVE EACH MODEL.

FIGURE 12

Assuming a density contrast of 0.4 gm./cm^3 , the model produced for Profile BB' indicated a maximum depth of 8,300 feet. If the density contrast was only 0.2 gm./cm^3 , then 22,300 feet of material in the deepest part of the basin would be necessary to account for the observed anomaly. The maximum depth, together with the overall shape of the basin are illustrated in Figure 10. Assuming the lower regional background anomaly A, and a density contrast of 0.4 gm./cm^3 , Profile CC' yielded a model with a maximum depth of 7,850 feet. For a density contrast of 0.3 gm./cm^3 , a maximum thickness of 11,580 feet of sediment was indicated. These figures and the attitude of the complete basin are shown in Figure 11.

ii. The effect of ambiguity in the position of the Regional Anomaly.

Figure 12 illustrates the maximum depth and overall shape of the basin along Profile CC', for the varying density contrasts and the higher, curved regional background B. This background level is higher than A by approximately five milligals over the central part of the anomaly, and results in an increase in the maximum estimated depth of 940 feet to 8,790 feet for a density contrast of -0.4 gm./cm^3 . The overall shape of the basin is not otherwise greatly altered as can be observed by a comparison of Figures 11 and 12.

Further use was made of the two-dimensional gravity computer programme to examine the effect of a downwarp in the crust, similar in amplitude and shape to the overlying basin. For the case of a density contrast of -0.4 gm./cm^3 , a crustal downwarp matching the shape of the basin was found to produce a gravity difference of 2.1 milligals between the edges and centre of the basin. This will result in a slight overestimate of the depth of the basin, in the case of a density contrast of -0.4 gm./cm^3 , of about 5%.

iii. The effect of a thick layer of Glacial Gravel.

In the Central Plain of Ireland Glacial Gravels form a significant component of the superficial deposits (Murphy, 1952) and it was considered desirable to obtain an estimate of the possible effect of several hundred feet of this material overlying the postulated basin. The available density data (Section 3.1 iv) suggest a value of 2.2 gm./cm.^3 for this material and a density contrast of -0.2 gm./cm.^3 with the postulated Mesozoic sediments of assumed density 2.4 gm./cm.^3 , which it may replace.

The two-dimensional gravity computer programme was used to calculate the effect of 100 metres (328 feet) of Glacial Gravel, and the observed profile along BB' ^{was} corrected accordingly. Re-estimation of the thickness of sediment revealed a decrease in the maximum depth to the floor of the basin by a similar amount.

iv. The character of the Northern Boundary.

Further use was made of the relationship described in section 2.3 by making assumptions for the density contrast and obtaining estimates for the angle of slope of the contact along the detailed profiles. The results are shown in Table 4. Of the two possible values of i , the angle of slope, only the higher values of 56° and 68° for density contrasts of 0.3 gm./cm.^3 and 0.4 gm./cm.^3 respectively along Profile AA' and 61° for a density contrast of 0.4 gm./cm.^3 along Profile BB' would explain the magnitude of the observed gravity gradients. These high contact angle estimates would be compatible with a faulted boundary for this northern margin. The shape of the computed models lends support to this idea. The faulting, if present, may have occurred along a pre-existing line of weakness possibly initiated in Caledonian times.

Table 4.

Using $C = \pi G \rho \sin 2i$ (Section 2.3)

For Profile AA':

$C = 10.79$ mgals./mile.

Density Contrast	$\sin 2i$	$2i$	i
0.4 gm./cm. ³	0.695	44° and 136°	22° and 68°
0.3 gm./cm. ³	0.930	68° and 112°	34° and 56°

For Profile BB':

$C = 13.06$ mgals./mile.

Density Contrast	$\sin 2i$	$2i$	i
0.4 gm./cm. ³	0.842	57° and 123°	28° and 61°

4. Conclusions.

The main conclusion to be drawn from the above analysis is that the Dublin Bay-Kish Bank 'Low' is caused by a sedimentary basin in which relatively low density Mesozoic sediments form the main 'fill'. It should be noted, however, in view of the close proximity of the Leinster Granite, that the possibility of a granite mass also contributing towards the gravity low cannot be completely ruled out. If it is assumed that the minimum region of the anomaly is caused entirely by the basin and further that Mesozoic sediments alone form the anomalous mass, then the depth to the floor of the deepest part of the basin is at least 8,000 feet.

Chapter 6

The 'East Irish Sea Low'

1. Introduction

The results of an earlier marine gravity survey conducted during 1961 proved the existence of a large gravity 'low' situated between the coasts of Furness and south-west Cumberland and the Isle of Man (Bott, 1964). The minimum observed Bouguer Anomaly was -3.1 milligals and the 'low' was named the 'Manx-Furness low', although the southern margin of the feature was not delineated by that survey. The anomaly was interpreted in terms of a sedimentary basin in which Permo-Triassic and Carboniferous rocks formed the main 'fill', and the maximum depth was estimated to be between 8,000 and 20,000 feet depending upon the assumed density contrast.

A possible alternative interpretation in terms of a granite body was also recognized and it was suggested that the problem might be resolved by critical gravity traverses and seismic lines. The surveys conducted by the author have shown that low Bouguer Anomalies are also present further south and cover much of the eastern part of the North Irish Sea.

It is suggested therefore, that this extensive area of low Bouguer Anomalies be renamed the 'East Irish Sea Low'. Detailed traverses across

the north-western boundary have provided evidence in support of the original interpretation in terms of a sedimentary basin. This chapter is concerned mainly with the evidence of these critical traverses.

2. Methods of Interpretation.

The techniques employed in the analysis of the detailed gravity profiles are similar to those used for the Dublin Bay-Kish Bank 'Low' and were described in the first section of Chapter 5. In addition, it has been possible in the present case to make use of geological evidence in certain areas where the gravity field over the marine area is continuous with structural features on land.

3. Interpretation

3.1 Introduction.

i. Description of the Anomaly.

The complete anomaly has been broadly described in Chapter 4 and only those features relevant to the detailed interpretation are reiterated in this section. The maximum observed gravity gradients occur over the northern margin of the anomaly where a value of 11.7 mgals./mile was recorded along Profile EE' (Plate 1). The maximum amplitude also occurs in this region and appears to have a magnitude of between 36 and 42 milligals depending on

the value of the background anomaly which is again subject to uncertainty.

The effect of this uncertainty is again considered in the detailed interpretation when models are constructed to explain the observed anomaly.

Steep gradients were also observed just off the coast of the Isle of Man where the gravity isogals show a tendency to run parallel to the existing coastline of the Island. A detailed Profile FF', to the south-east of Douglas, revealed a maximum gradient of 9.0 mgals./mile. Continuation of this profile in a south-easterly direction clearly indicates the secondary rise in the anomaly to a measured maximum value of +37.7 milligals. A further detailed traverse DD'', was established at right angles to FF', extending from near the south-western margin of the East Irish Sea 'Low' across the local 'high' to the south-east of Douglas and into the area of minimum observed Bouguer Anomalies to the north. The maximum observed gradient was 8 mgals./mile along the northern section of the profile where the values of gravity decrease towards the measured minimum of -3.6 milligals. The interpretation of the anomaly is considered in terms of the above profiles which are illustrated in Figures 13, 14, and 15.

ii. The Background Anomaly.

The position of the regional background anomaly over the western half of the feature can be estimated fairly accurately. A Bouguer Anomaly of

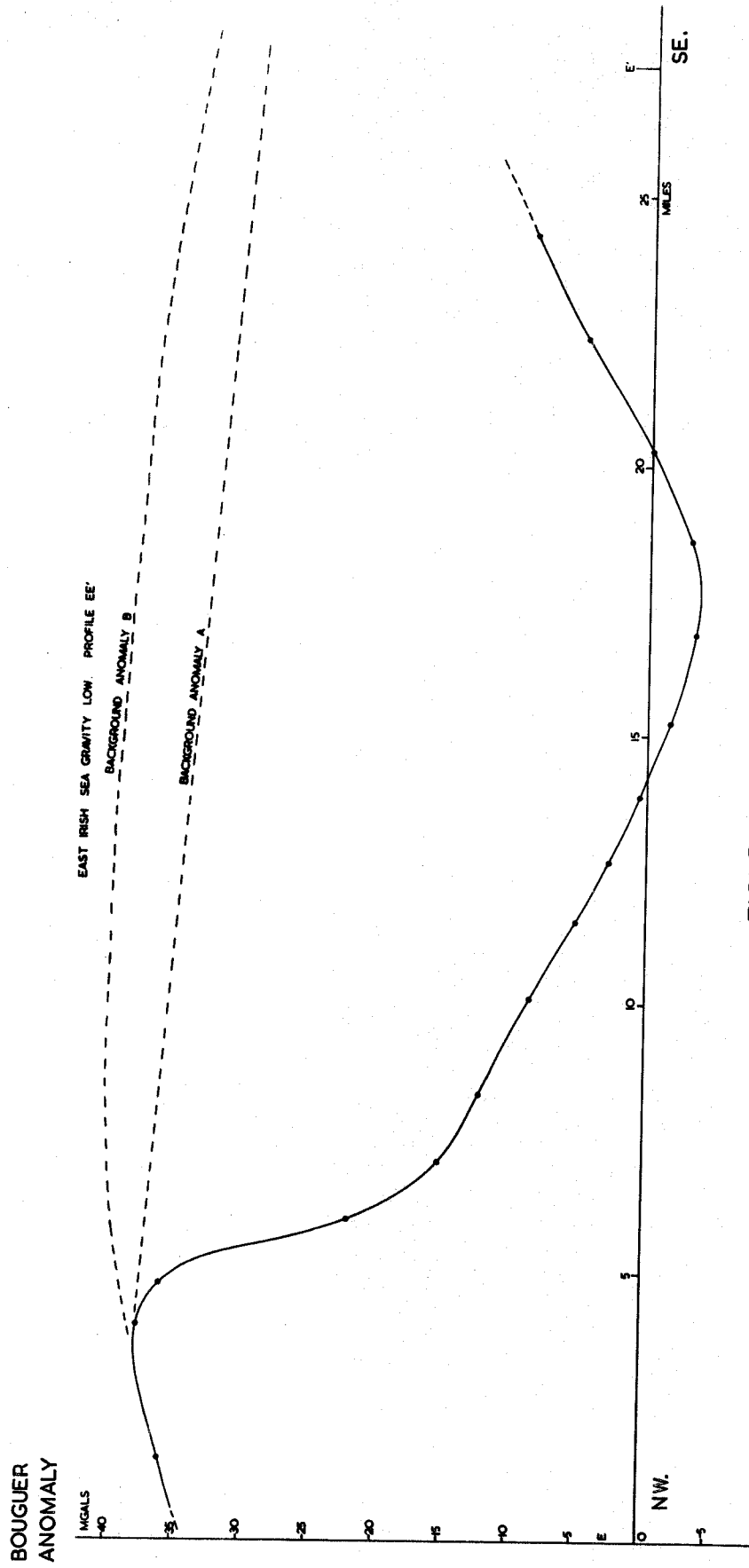


FIGURE 13

BOUGUER ANOMALY

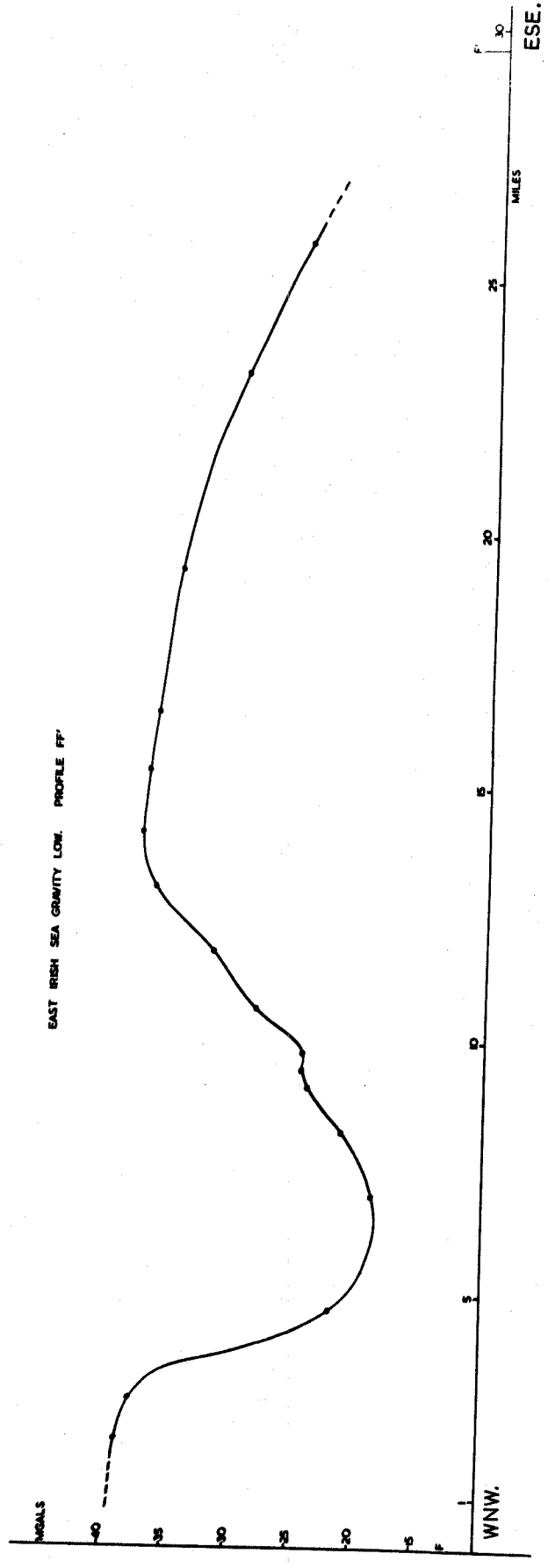


FIGURE 14

BOUGUER ANOMALY

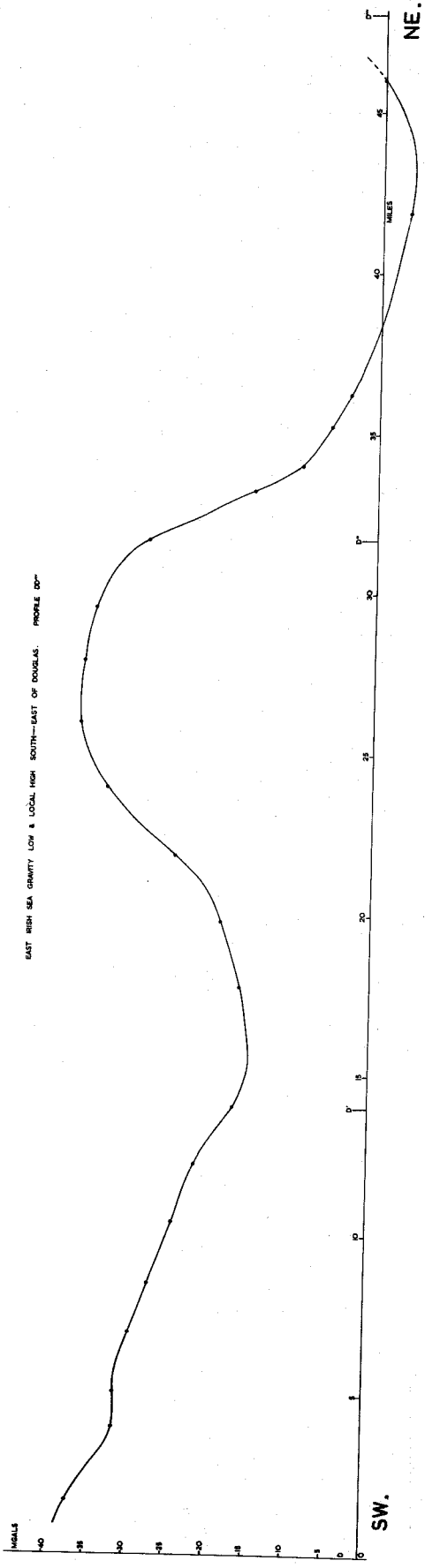


FIGURE 15

about +40 milligals is observed over the Lower Palaeozoics of the Isle of Man and in a large area at sea between the Island and Anglesey. The background anomaly at the western end of Profile EE' was taken to be approximately +38 milligals, the maximum Bouguer Anomaly recorded over the almost constant part of the profile in the vicinity of Ramsey Bay, being +37.7 milligals. The background value of Profile FF' near Douglas is also quite clear, since in that area the anomaly is caused by the Lower Palaeozoic Manx Slates and has a value close to +40 milligals. The southern end of Profile DD''' encroaches upon the region of high Bouguer Anomalies which has been referred to in Chapter 4 as the 'Central High'. The Bouguer Anomaly appears to have a steady value of approximately +40 milligals over a large area and the regional background anomaly has been drawn at this level over the southern part of the traverse. As already noted the anomaly shows a second rise as the profile continues northwards and a value in excess of +37 milligals is present at the centre of the local high. This suggests that the background level of at least +40 milligals is maintained over much of the marine area investigated by Profile DD'''.

Inspection of an earlier east-west profile, across the main northern minimum, from near Laxey on the Isle of Man to the Furness Coast, reveals that the assumed regional background anomaly was considered to decrease from

a value of approximately +42.0 milligals near Laxey to +25.0 milligals in Furness (Bott, 1964). The position of the background between the two areas is somewhat subjective but the value over the area of minimum Bouguer Anomaly was taken to lie between about +33 and +38 milligals. Similar values for the area have been adopted to determine the attitude of the background anomaly along Profile EE' for which two possibilities have been considered.

iii. The existing interpretation and the problem of the Eskdale Granite.

The interpretation for the area incorporating the main minimum of -3.6 milligals was developed following the interpretation of the marine survey of 1961 (Bott, 1964). The main conclusion, from the evidence of the abrupt gravity gradient off the east coast of the Isle of Man and the correlation of steep marginal gradients with the coastal strip of Permo-Triassic and Carboniferous rocks in Furness, was that the 'low' was caused by relatively low density sediments infilling a deep sedimentary basin. Permo-Triassic and Carboniferous rocks were considered to form the main 'fill' of the basin in the east.

The problem created by the proximity of the Eskdale Granite mass on land was emphasized, and it was observed that the central minimum at sea lay in direct continuation with the Eskdale negative gravity anomaly and might

therefore be partly or completely caused by the granite. The sedimentary basin hypothesis was considered more likely on theoretical grounds, and the quantitative interpretation was based on this assumption. The maximum depth in this case was shown to be in the range of 8,000-20,000 feet depending upon the assumed density contrast. This was considered to have a possible range of -0.2 to -0.4 gm./cm.³ if Carboniferous and Permo-Triassic sediments formed the main 'fill'. It was suggested that the ambiguity caused by the possible presence of a granite body could be resolved by critical gravity traverses and seismic lines.

iv. The Rock Densities.

Measurements of the mean densities of the various rock types on the Isle of Man have previously been made and the results are reproduced below (Cornwell, 1960). The most useful conclusion that may be drawn from the data, is that the density contrast produced by a granite mass is not likely to exceed -0.15 gm./cm.³. It would appear that only in extreme circumstances could a density contrast of -0.2 gm./cm.³ be exceeded (Bott, personal communication).

<u>Formation</u>	<u>Density.</u> (gm./cm. ³)
Foxdale Granite.	2.62
Dhoon Granite	2.71
Peel Sandstone	2.65

Carboniferous Lst.	2.70
Manx Slates	2.73
Drift. (Assumed)	2.00

3.2. The confirmatory evidence for the existing interpretation.

i. The Second-Derivative profiles.

The magnitude of the gravity gradients along Profiles EE' and FF' across the margin of the anomaly together with the resulting second-derivative values are shown in Table 5. Figures 16 and 17 illustrate graphically the distribution of the second-derivative values along the two profiles.

The value of $G'' \text{ max.}/G'' \text{ min.}$ for traverse EE', which extends from near Ramsey Bay towards the main problematical minimum, was found to be 2.15. This is indicative of a boundary sloping inwards towards the centre of the anomalous mass. A margin with this attitude is supporting evidence for the presence of a sedimentary basin structure in preference to a granite body. The value of $G'' \text{ max.}/G'' \text{ min.}$ as obtained from traverse FF' across the steep gradients to the east of Douglas was 1.62. This ratio again indicates a boundary inclined towards the area of low Bouguer Anomaly values, and therefore supports the hypothesis of a sedimentary basin situated close to the existing south-east coastline of the Isle of Man, the margin of which it may have actively controlled (Bott, 1964).

Table 5.

Magnitude of the gradient between adjacent stations along Profile EE' from north-west to south-east. (mgals./mile.)

Value of Second Derivative. (mgals./mile/mile.)

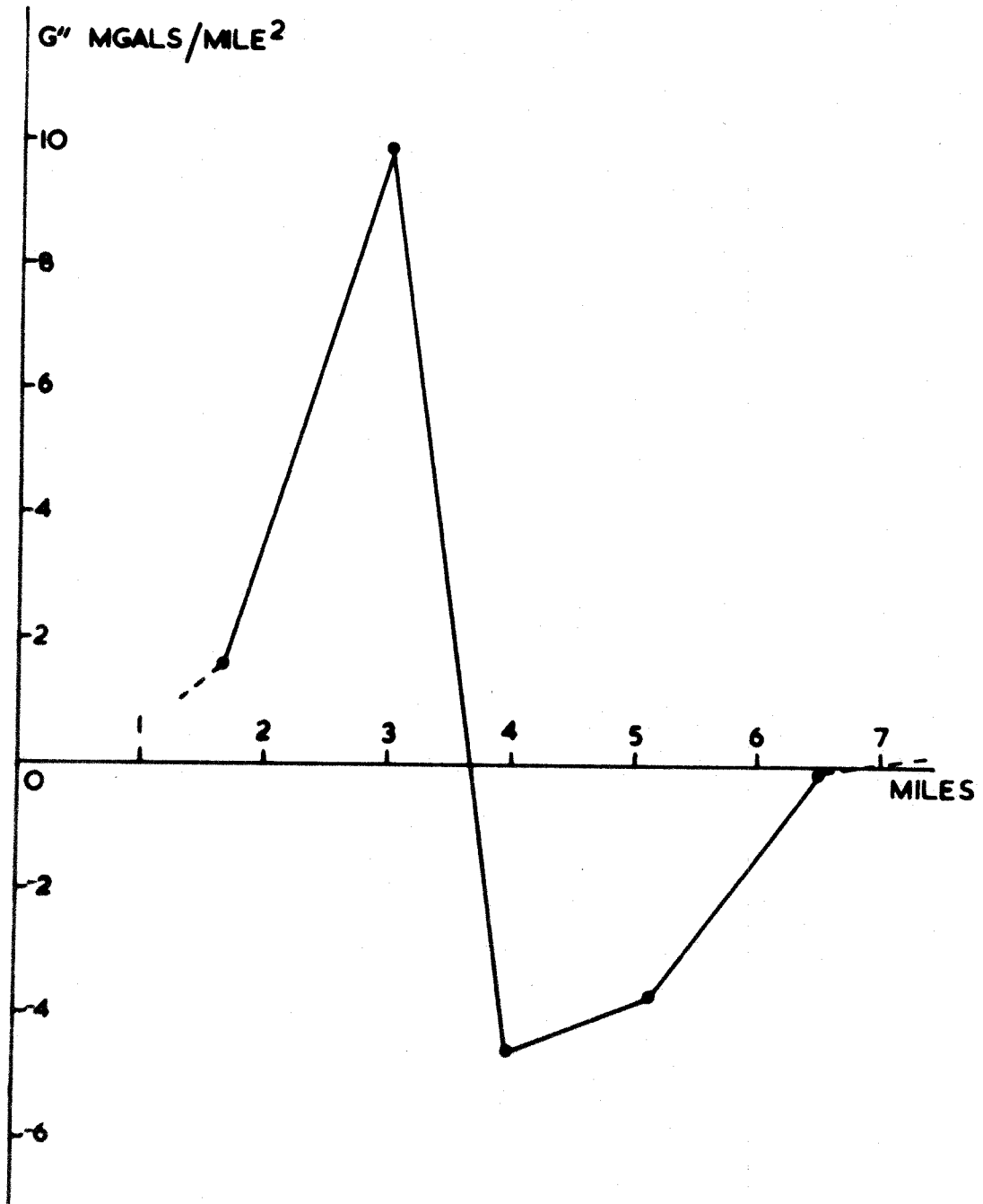
-0.73	.....	+1.59
1.87	.....	+9.88
11.75	.....	-4.62
6.57	.....	-3.68
2.23	.....	-0.08
2.11	.....	+0.10
2.27	.....	0.00
2.27	.....	-0.44
1.76	.....	-0.05
1.70	.....	-0.37
1.15	.....	-0.84
-0.28	.....	-0.94
-1.88	.....	-0.30
-2.44	.....

Profile FF' (west-east.)

1.12	.....	+6.27
9.08	.....	-3.83
1.30	.....	-1.86
-2.00	.....	-1.34
-3.41	.....

SECOND DERIVATIVE VALUES ALONG PROFILE EE'

FIGURE 16



$G'' \text{ MAX} / G'' \text{ MIN} = 2.15$

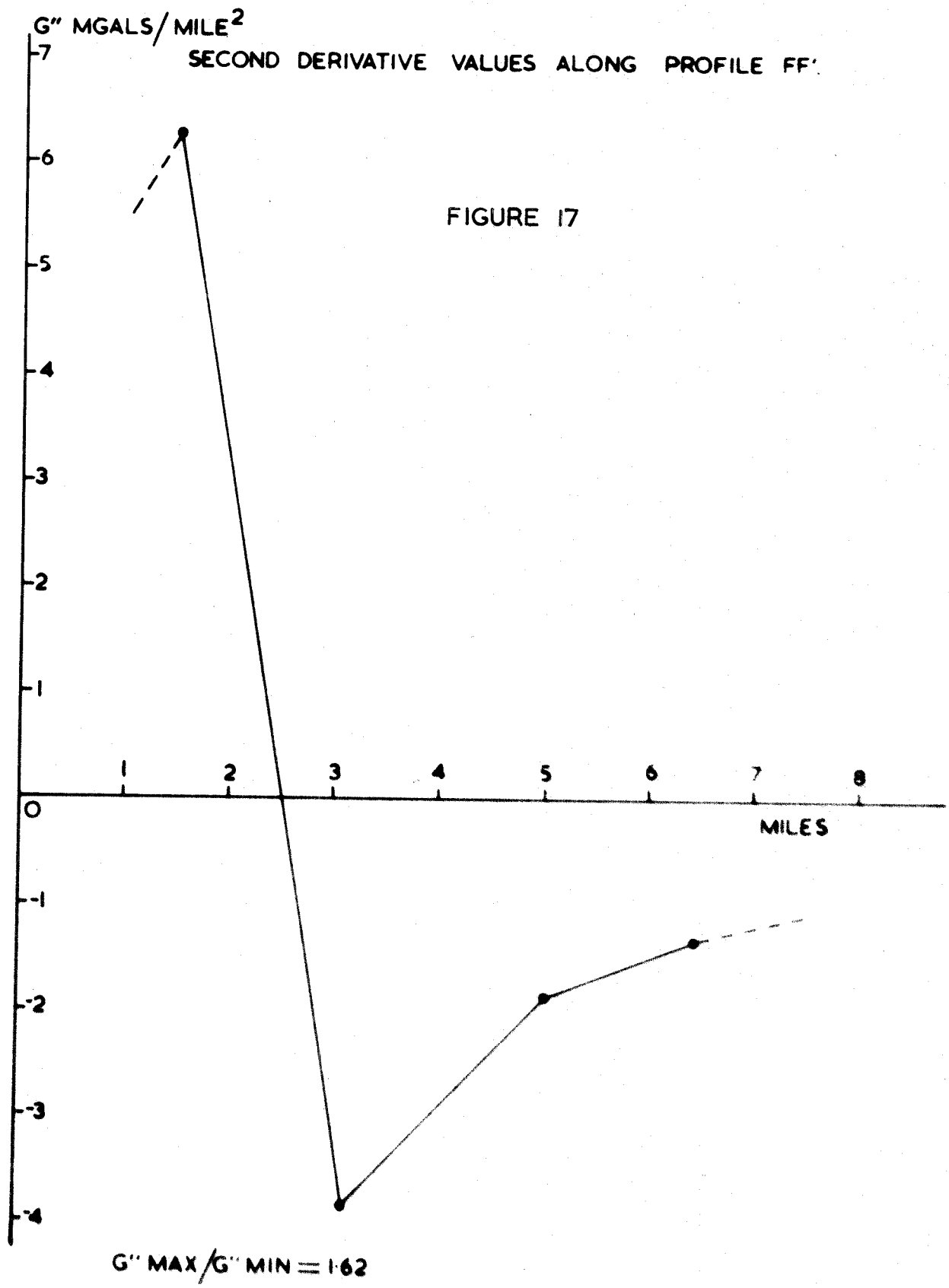


Table 6.For Profile EE':

Using the relationship $C = \pi G \rho \sin 2i$ (Chapter 5 Section 2.3)

Assuming $i = 45^\circ$, $\rho = \frac{C}{\pi G} \dots\dots\dots 1$

The difference in the gravity gradient (C), at equal distances on either side of the estimated contact along Profile EE' was found to be 10.10 mgals./mile.

Substituting in 1, $\rho = 0.26 \text{ gm/cm}^3$

For Profile FF':

The difference in gradient at equidistant joints on opposite sides of the estimated contact was found to be 8.16 mgals./mile.

Substituting in 1, $\rho = 0.21 \text{ gm/cm}^3$

ii. The Minimum Density results.

The relationship quoted in section 2.3 of Chapter 5 was again used to obtain an estimate of the minimum density contrast required to produce the observed change in gradient along the detailed Profiles EE' and FF'. The data from the observed profiles and the resulting minimum density contrasts are recorded in Table 6.

Although the values of 0.26 gm./cm^3 and 0.21 gm./cm^3 obtained from Profiles EE' and FF' respectively are not as great as those derived for the Dublin Bay-Kish Bank Anomaly, inspection of the rock density data included in section 3.1 iv again suggests that the results are incompatible with a hypothesis seeking to explain the anomaly in terms of a granite mass. An interpretation in terms of a basin structure containing low density sediments, of possibly Mesozoic age, could easily account for the above density contrasts and would seem to receive confirmation from this method.

iii. The Gravity Gradients.

Inspection of the Bouguer Anomaly profile from traverse EE' indicates an amplitude for the anomaly of between 37 and 42 milligals, depending upon the value of the assumed background, and a maximum observed gravity gradient of 11.7 mgals./mile . The amplitude and maximum gradient of the anomaly obtained from the computed profile for a theoretical granite model 10 kilometres

thick with vertical boundaries and density contrast of -0.15 gm./cm.^3 , were 39 milligals and 11.5 mgals./mile respectively as recorded in Table 2. The maximum gradients are therefore similar but differences are apparent in the position of the maximum gradients and the shape of the complete profiles. The characteristic gradual return of the anomaly to a background level away from a granite contact was emphasized in Chapter 5 and illustrated by Figures 8 and 9. This contrasts sharply with the observed Profiles EE' and FF', Figures 13 and 14 respectively, which display abrupt increases in gradient from the approximately constant background level towards the centre of the anomaly within a distance of only one mile. This is an alternative way of expressing the second-derivative observations which support the hypothesis of a sedimentary basin structure being the cause of the observed anomaly.

iv. Seismic Evidence.

The existing seismic work in the North Irish Sea was noted in Chapter 2. The results of a line of shots from near Holyhead towards the Solway Firth have been described by Agger and Carpenter (1964). These indicated that the depth to the crust-mantle boundary was about 3 kilometres less over this part of the Irish Sea than in adjacent areas on land, and also that a thick layer of sediments was present in the marine area covered by the shots. A single seismic traverse with a line of shots approximately parallel to the coast of

the Isle of Man, four miles south-east of Douglas indicated an absence of Lower Palaeozoic sediments down to a depth of 3,300 feet (Barnes, personal communication).

v. The Geological Correlations.

There are certain areas along the eastern margin of the 'East Irish Sea Low' where the gravity feature continues into the coastal region. This has been noted in south-west Cumberland and Furness where the steep marginal gradients of the 'low' away from the influence of the Eskdale Granite, correspond with the coastal strip of Permo-Triassic and Carboniferous rocks (Bott, 1964). It was noted in Chapter 1 that the sandstone of Permo-Triassic age in this region attains a thickness in excess of 3,000 feet. Such a thickness of strata with a density contrast of -0.4 gm./cm.^3 with the Lower Palaeozoic rocks would explain at least 10-15 milligals of the seaward drop in the Bouguer Anomalies. The proved thickness of Permo-Triassic rocks in the Seascale Bore (Chapter 1) was estimated to contribute at least 15 milligals and indicated that the negative contribution of the Eskdale Granite was falling off rapidly westwards (Bott 1964).

Low values of the Bouguer Anomaly continuous with the marine area are also present along the Lancashire coastal plain from Fleetwood in the north to Liverpool in the south. The values over a wide area in this region

lie between +10 and +15 milligals and again correspond with thick deposits of Triassic rocks. Boreholes have shown the Bunter Sandstone to have a thickness of 2,300 feet in the Southport and Formby district, and this is overlain by Keuper Sandstone which has a thickness of between 400 and 1,000 feet (Chapter 1). Strata of Permian age which have been entirely detected by boreholes, combine with the Triassic rocks to make up a total thickness of Permo-Triassic rocks in the area of approximately 7,000 feet.

The Triassic Plains of Lancashire and Cheshire have been noted as being geologically similar in that they may be considered to regionally overlie the western flank of the Carboniferous uplift of Northern England (White, 1949). The Trias of the Lancashire area occupies an incomplete basin open to the west with the eastern margin bounded by large scale faults downthrowing several thousand feet to the west. A linear zone of steep gravity gradients running south-south-west from slightly east of Preston corresponds with the known major fault separating the Lancashire Triassic area from the Wigan coalfield.

A zone of steep gradients with a similar Caledonian trend north of the Ribble Estuary was noted to 'line-up' exactly with the coastline between Southport and Formby, and by analogy was interpreted by White (1949) as a fault belt. It was concluded that in the Lancashire-Cheshire Trias-covered region the gravity data were in close correspondence with the known geology.

Between the western boundary of the Cheshire basin which is again marked by steep gravity gradients, and the Carboniferous outcrops to the east of the Vale of Clwyd, lies a platform which is structurally part of North-East Wales covered by about 1,000 feet of Trias (Powell, 1955). A borehole near Rhyl, at the northern end of the Vale of Clwyd, penetrated 500 feet of Bunter Sandstone before entering presumed Upper Carboniferous Barren Measures (Chapter 1). The position of the Trias is marked by a gravity low which transgresses the coastal margin, and the interpretation visualized a thickening of the Trias to 1,000 feet just off-shore from the evidence of the Lancashire coast, indicating a Triassic basin under the sea.

From the evidence of the erratics in Anglesey it has been suggested that the eastern part of the North Irish Sea has the form of a broad undulating plain over which Triassic sediments have the greatest areal distribution (Chapter 1). There is therefore, strong geological evidence to support a hypothesis which seeks to explain the observed Bouguer Anomalies over this part of the North Irish Sea in terms of thick deposits of low density Mesozoic sediments.

vi. Summary of the evidence.

Both the geological and geophysical evidence support the hypothesis of a thick succession of low density sediments being the source of the relatively low Bouguer Anomalies which have been shown to exist over much of the eastern

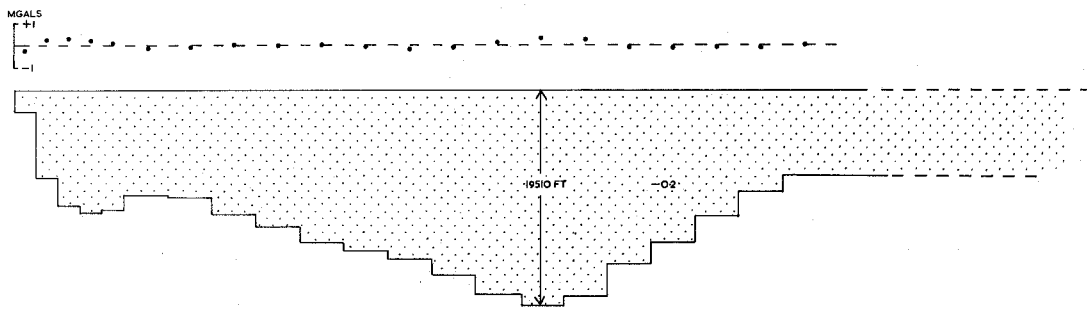
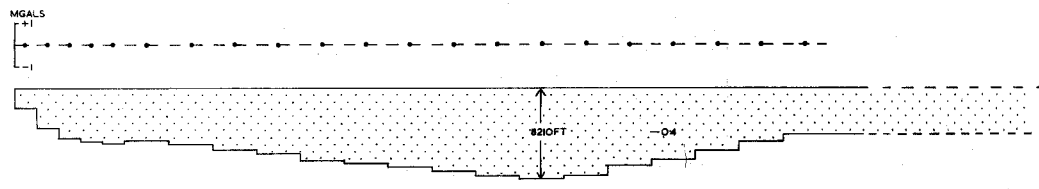
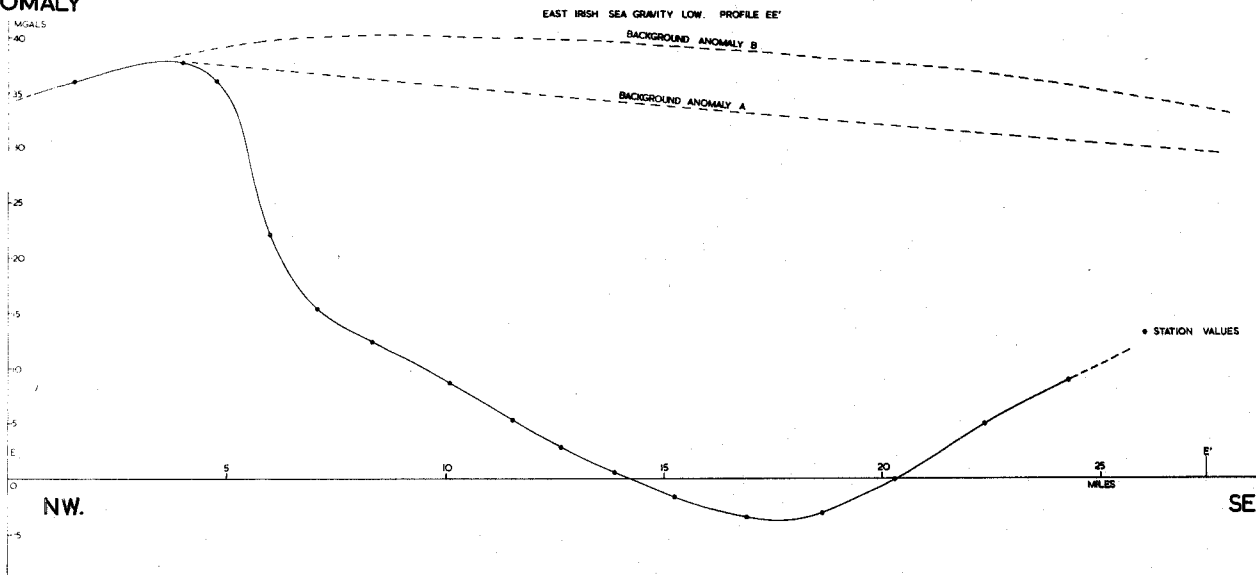
part of the North Irish Sea. The ambiguity created by the proximity of the Eskdale granite and its possible extension beneath the marine area to give the minimum observed Bouguer Anomalies in the north would seem to be resolved as a result of the detailed gravity work.

3.3 The Quantitative Interpretation.

i. Depth Estimation.

The sedimentary basin depth-estimation computer programme was again employed, the data being provided by Profile EE' situated across the northern boundary of the feature. Since this depth-estimation is a re-interpretation following the first survey of 1961 (Bott, 1964), only two density contrasts have been considered. From inspection of the available density data, -0.4 gm./cm.^3 is believed to provide an upper limiting density contrast if Mesozoic sediments predominate, while -0.2 gm./cm.^3 may be more appropriate if a considerable proportion of Carboniferous rocks are present. Two positions of the regional Bouguer Anomaly have again been adopted to examine the effect of uncertainty in the background level, and the shape and maximum depth for the lower regional anomaly is illustrated by Figure 18. It was estimated that the depth to the floor of the basin was 8,210 feet at its maximum development for an assumed density contrast of -0.4 gm./cm.^3 , while for a density contrast of -0.2 gm./cm.^3 , 19,510 feet of sediment were calculated to be necessary in the

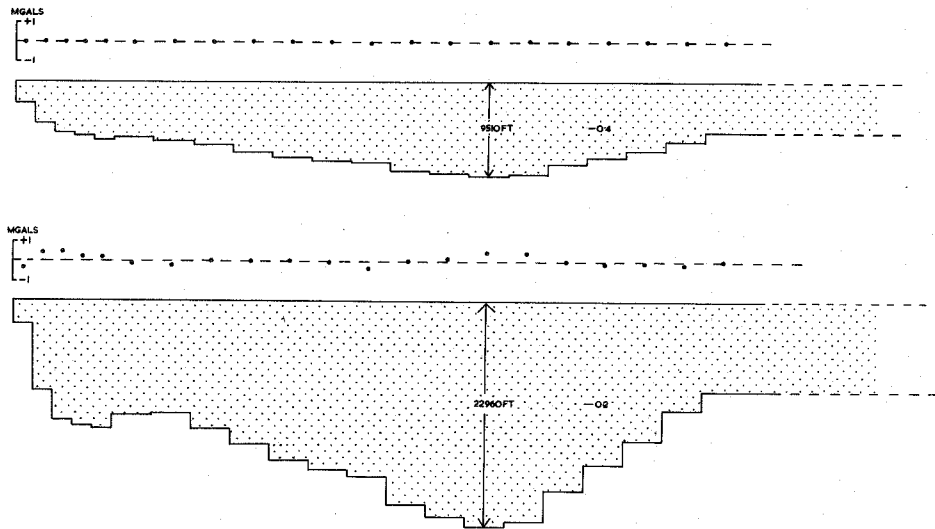
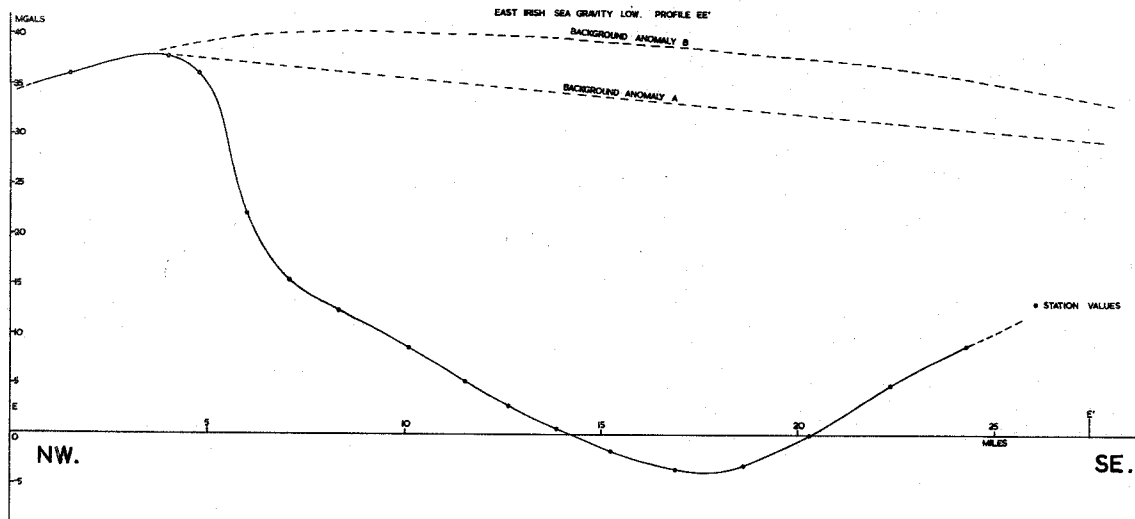
BOUGUER ANOMALY



INTERPRETATION OF THE BOUGUER ANOMALY PROFILE EE' ACROSS THE NORTHERN PART OF THE EAST IRISH SEA 'LOW' FOR DENSITY CONTRASTS AS INDICATED & THE ASSUMED BACKGROUND ANOMALY A. THE RESIDUALS OBSERVED MINUS CALCULATED ANOMALIES ARE DISPLAYED ABOVE EACH MODEL.

FIGURE 18

BOUGUER ANOMALY



INTERPRETATION OF THE BOUGUER ANOMALY PROFILE EE' ACROSS THE NORTHERN PART OF THE EAST IRISH SEA 'LOW' FOR DENSITY CONTRASTS AS INDICATED & THE ASSUMED BACKGROUND ANOMALY B. THE RESIDUALS (OBSERVED MINUS CALCULATED ANOMALIES) ARE DISPLAYED ABOVE EACH MODEL.

FIGURE 19

deepest part of the basin in order to explain the observed anomaly. In the absence of additional data the profile was discontinued in the south-east of the main minimum, and the programme facility to permit the final block to be treated as a semi-infinite sheet was utilized at this stage. The approximate position of the regional anomaly over the main minimum was interpreted from the original and complete profile, established in 1961, which extends from near Laxey on the Isle of Man to Furness.

ii. The effect of uncertainty in the position of the regional anomaly.

Figure 19 illustrates the maximum depth and general shape of the basin along Profile EE' for the two relevant density contrasts and the higher, curved regional background B. This causes a difference in amplitude of approximately 5 milligals at the centre of the anomaly, and results in an increase in the maximum depth of 1,300 feet to 9,510 feet for a density contrast of -0.4 gm./cm.^3 . The general shape of the basin is otherwise very similar as can be verified by a comparison of Figures 18 and 19. In the case of a density contrast of -0.2 gm./cm.^3 , the higher regional anomaly results in an increase in the maximum depth of 3,450 feet to 22,960 feet, but the conclusion with respect to the overall shape remains valid.

iii. The character of the boundary.

The relationship originally quoted in section 2.3 of Chapter 5 was again

Table 7.

Using $C = \pi G \rho \sin 2i$. (Chapter 5 Section 2.3)

For Profile EE':

$$C = 10.10 \text{ mgals./mile.}$$

Density Contrast	$\sin 2i$	$2i$	i
0.4 gm/cm ³ .	0.654	40° and 140°	20° and 70°
0.3 " "	0.870	60° and 120°	30° and 60°

For Profile FF':

$$C = 8.16 \text{ mgals./mile.}$$

Density Contrast	$\sin 2i$	$2i$	i
0.4 gm/cm ³	0.526	31° and 149°	15° and 74°
0.3 " "	0.700	44° and 136°	22° and 68°

employed to obtain estimates for the angle of slope of the contact of the anomalous mass along Profiles EE' and FF', for the assumed range of density contrasts. Of the two calculated values of i , the angle of slope, only the higher values of 60° and 70° for density contrasts of 0.3 gm./cm.^3 and 0.4 gm./cm.^3 respectively along profile EE', and 68° and 74° along Profile FF' would explain the magnitude of the gravity gradients. These estimates for the contact angle would be in agreement with a possible faulted margin along this north-western boundary. The results are recorded in Table 7.

iv. The significance of Profile DD'''.

Profile DD''', depicted as Figure 15, illustrates the nature of the Bouguer Anomaly values from near the south-western margin of the postulated basin, across the local 'high' to the south-east of Douglas, and into the main gravity minimum to the north. The local 'high', as described in Chapter 4, attains a measured maximum value of +37.7 milligals. The similarity of this reading with the Bouguer Anomaly values common over the Isle of Man suggest a qualitative interpretation in terms of a large upwarp of the basement rocks and a consequent diminution in the thickness of the overlying sediments.

Reference to the Aero-magnetic maps, (Geological Survey and Museum) of which a skeletal representation appears in Plate 3, reveals a marked lack of any disturbance in the isogams over the same area. It is suggested therefore,

that there is little or no contrast in the magnetic intensity between the basement rocks and the overlying sediments in this part of the North Irish Sea.

4. Conclusions.

The present surveys have indicated that the area of low Bouguer Anomaly values, originally detected in the area lying between the Isle of Man and Furness, extend over much of the eastern part of the North Irish Sea. Critical gravity traverses across the north-western and western boundaries have provided evidence to support the original interpretation in terms of a deep sedimentary basin, and make the possibility of a granite body being the cause of the main minimum increasingly unlikely. The geological evidence along the eastern coastal margin, together with the seismic information also indicate the presence of thick deposits of sediments over the region under investigation. The sedimentary basin depth-estimation programme was used to obtain models of the basin structure along the northern detailed traverse EE', and these show close agreement with the original estimates for the maximum depth.



Chapter 7

Major features of the Aero-magnetic Maps

1. Introduction.

The Aero-magnetic maps of Great Britain and Northern Ireland prepared by the Geological Survey cover most of the North Irish Sea. A comparison of this magnetic information with the Bouguer Anomaly map (Plate 1) provides additional evidence in connection with the interpretations advanced to explain the gravity data. Plate 3 is a skeletal representation of the Aero-magnetic maps covering the area from which the total field magnetic anomaly contours have been extracted at only 50 gamma intervals. This is considered adequate to illustrate the character and trend of the large scale magnetic anomalies. The inset included in Plate 3 shows the total magnetic field anomalies at 10 gamma intervals as measured using a sea-borne proton magnetometer off the coast of County Dublin (Stacey A.P., personal communication). The major magnetic features are now discussed in relation to the gravity interpretations.

2. The Magnetic Anomalies.

Over most of the eastern part of the North Irish Sea the magnetic gradients are relatively slight. The uniformity of the magnetic field is disturbed in the vicinity of Morecambe Bay by a narrow linear anomaly of more than 300 gamma. This feature is marked CC' in Plate 3 and forms the subject of a detailed interpretation in Chapter 8. The shallow magnetic gradients over the remaining area are in accord with the hypothesis advanced to explain the gravity field, of a sedimentary basin occupying most of the East Irish Sea.

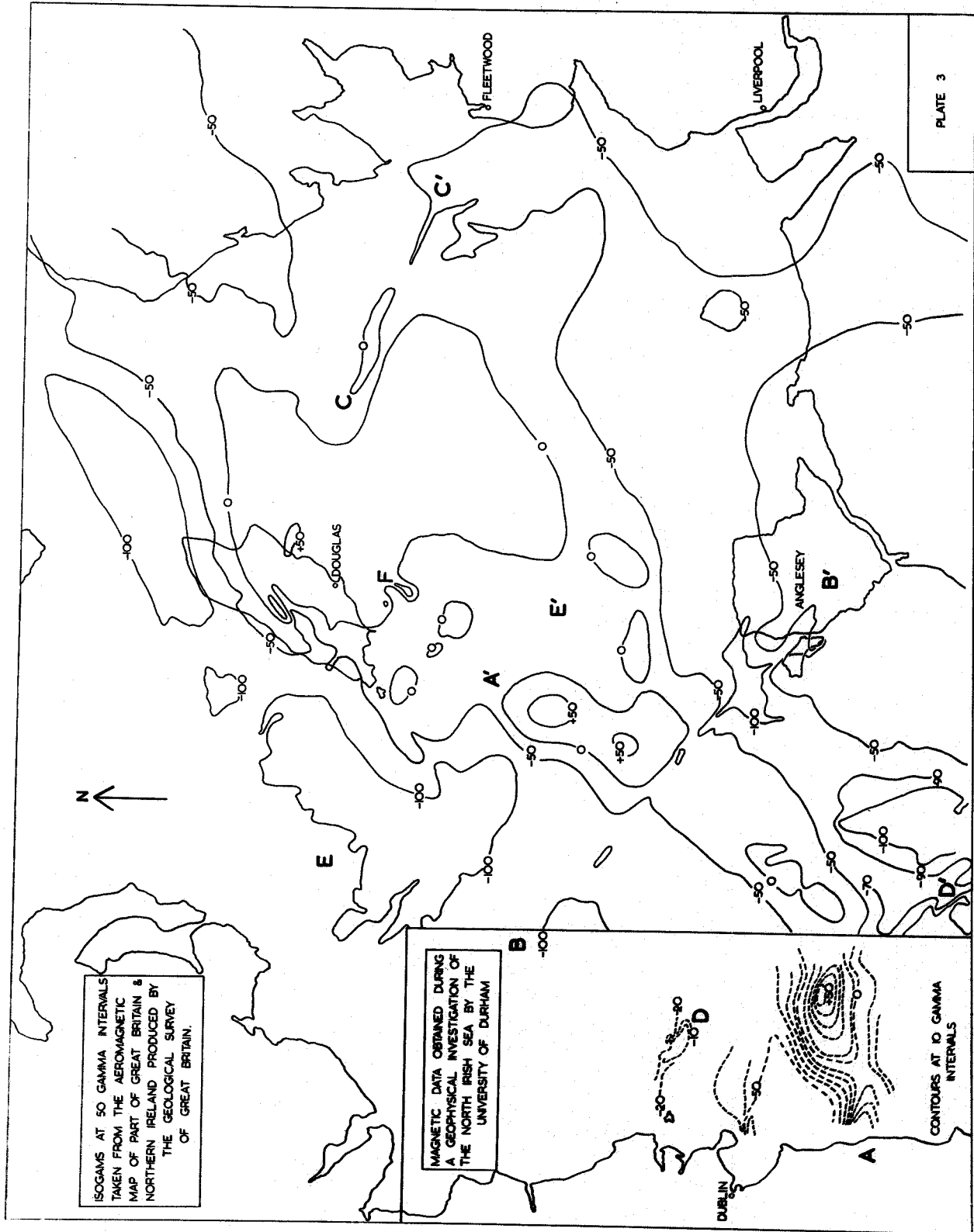
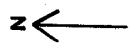


PLATE 3

ISOGAMS AT 50 GAMMA INTERVALS
 TAKEN FROM THE AEROMAGNETIC
 MAP OF PART OF GREAT BRITAIN &
 NORTHERN IRELAND PRODUCED BY
 THE GEOLOGICAL SURVEY
 OF GREAT BRITAIN.

MAGNETIC DATA OBTAINED DURING
 A GEOPHYSICAL INVESTIGATION OF
 THE NORTH IRISH SEA BY THE
 UNIVERSITY OF DURHAM

CONTOURS AT 10 GAMMA
 INTERVALS



FLEETWOOD

LIVERPOOL

DOUGLAS

ANGLESEY

DUBLIN

C

C'

B'

A'

E'

E

F

A

D

B

-50

-50

-50

-100

+50

-100

-100

-100

+50

+50

-50

-100

-50

-50

-50

-50

-70

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The existence of thick deposits of non-magnetic sediments overlying a magnetic basement at considerable depth could explain the observed magnetic field.

An arcuate, positive magnetic anomaly possessing a pre-dominantly Caledonoid trend is marked AA' on Plate 3. The feature is approximately 50 miles in length and between 7 and 10 miles wide. From a position about 20 miles south of the Isle of Man the anomaly extends in a south-westerly direction until near the Irish Coast where the proton magnetometer results indicate that it swings round to an approximately east-west direction. The southern end of this line of positive anomalies appears to correlate with the Cambrian outcrop on the Irish Coast near Bray Head. It has been suggested by Stacey that a structural high may exist between Bray Head and the Isle of Man. An anticlinal upwarp of the basement with a predominantly induced magnetisation in the direction of the present earth's field could explain the observed anomaly.

Comparison of the Aero-magnetic map with the gravity data indicates that the northern part of the magnetic anomaly AA' corresponds with the large area of high Bouguer Anomaly values which has been called the 'Central High' (Plate 1). The Bouguer Anomalies in this area exceed +40 milligals and are therefore similar in magnitude to the values over a wide area of the Lower Palaeozoic rocks on the Isle of Man. The Bouguer Anomalies comprising the 'Central High' are best explained in terms of a large uplift of relatively dense basement rocks flanked by younger and lower density sediments. Thus over the northern part of the magnetic anomaly AA' the magnetic and gravity

data appear to be in close agreement. Gravity data is absent to the south-west of the 'Central High' but it is anticipated that relatively high Bouguer Anomaly values would be encountered if measurements were continued into this area.

The south-western end of the magnetic feature AA' which has been delineated using a sea-borne proton magnetometer provides complementary evidence for the gravity data in the vicinity of Dublin Bay. Over most of the area occupied by the gravity anomaly which has been called the 'Dublin Bay-Kish Bank low' (Plate 1) the magnetic gradients are very slight. This is consistent with a hypothesis which seeks to explain the observed gravity anomaly in terms of a deep sedimentary basin. The existence of several thousand feet of non-magnetic sediments overlying a magnetic basement could account for the observed effect. Further, the sudden increase in the magnetic gradients associated with the anomaly AA' appear to coincide with the southern margin of the gravity feature. It is suggested therefore that the increase in the magnetic gradients is associated with a rise in the basement rocks which delineate the southern margin of the postulated sedimentary basin.

An extensive area of highly irregular magnetic anomalies with steep gradients occurs over the southern part of the postulated Peel-Ardglass basin. Close inspection reveals that a north-west to south-east trend affects this belt of anomalies and the character of the gradients suggests a near surface origin. The structural trend can be traced into the Tertiary Igneous province of North-East Ireland and it is suggested that the magnetic anomalies are caused mainly by Tertiary lavas overlying the southern part of the proposed

Mesozoic basin. Faulting and dyke intrusion may have also occurred and be responsible for the visible north-west to south-east trend of the anomalies.

Two linear magnetic features with a marked north-west to south-east trend are marked BB' and EE' on Plate 3. Magnetic feature BB' can be traced towards the Carlingford Tertiary igneous centre in North-East Ireland and appears to lie in continuity with the coastal embayment forming Carlingford Lough. The anomaly displaces feature AA', referred to earlier in this chapter, and probably represents a line of Tertiary Igneous activity with dyke intrusion accompanied by faulting. Magnetic feature EE' is associated with the belt of magnetic anomalies covering the southern part of the Peel-Ardglass gravity low and a similar interpretation is possibly valid.

Feature DD' is not fully defined but the structural line represented by the north-west to south-east trend of the magnetic contours in the south appears to coincide further north with a pronounced change in direction of feature AA' from a predominantly north-east to south-west or Caledonoid direction to an approximately east-west trend. DD' would therefore seem to be caused by a line of structural weakness along which movement may have displaced anomaly AA' which has been interpreted as an upwarp of Lower Palaeozoic rocks.

The magnetic feature marked F on Plate 3 is isolated and of small extent. The relatively steep gradients over the anomaly suggest a source at shallow depth and the anomaly is probably caused by a small stock of igneous material within the postulated basinal area. Detailed traverses are necessary before further estimates of the shape of the body and the age of the material can be made.

3. Conclusions

Over much of the North Irish Sea the magnetic data show close correspondence with the conclusions drawn from the gravity measurements. In the area occupied by the postulated East Irish Sea basin, the shallow magnetic gradients are consistent with the presence of a basement at considerable depth. The interpretation of the linear magnetic feature CC' is also compatible with the basin hypothesis as will be shown in Chapter 8.

A positive ridge of magnetic anomalies (AA') interpreted as an upwarp of Lower Palaeozoic basement rocks corresponds with an area of high Bouguer Anomalies, and the magnetic anomalies in the Dublin Bay area are consistent with the hypothesis of a sedimentary basin being the cause of the observed gravity anomaly.

Chapter 8

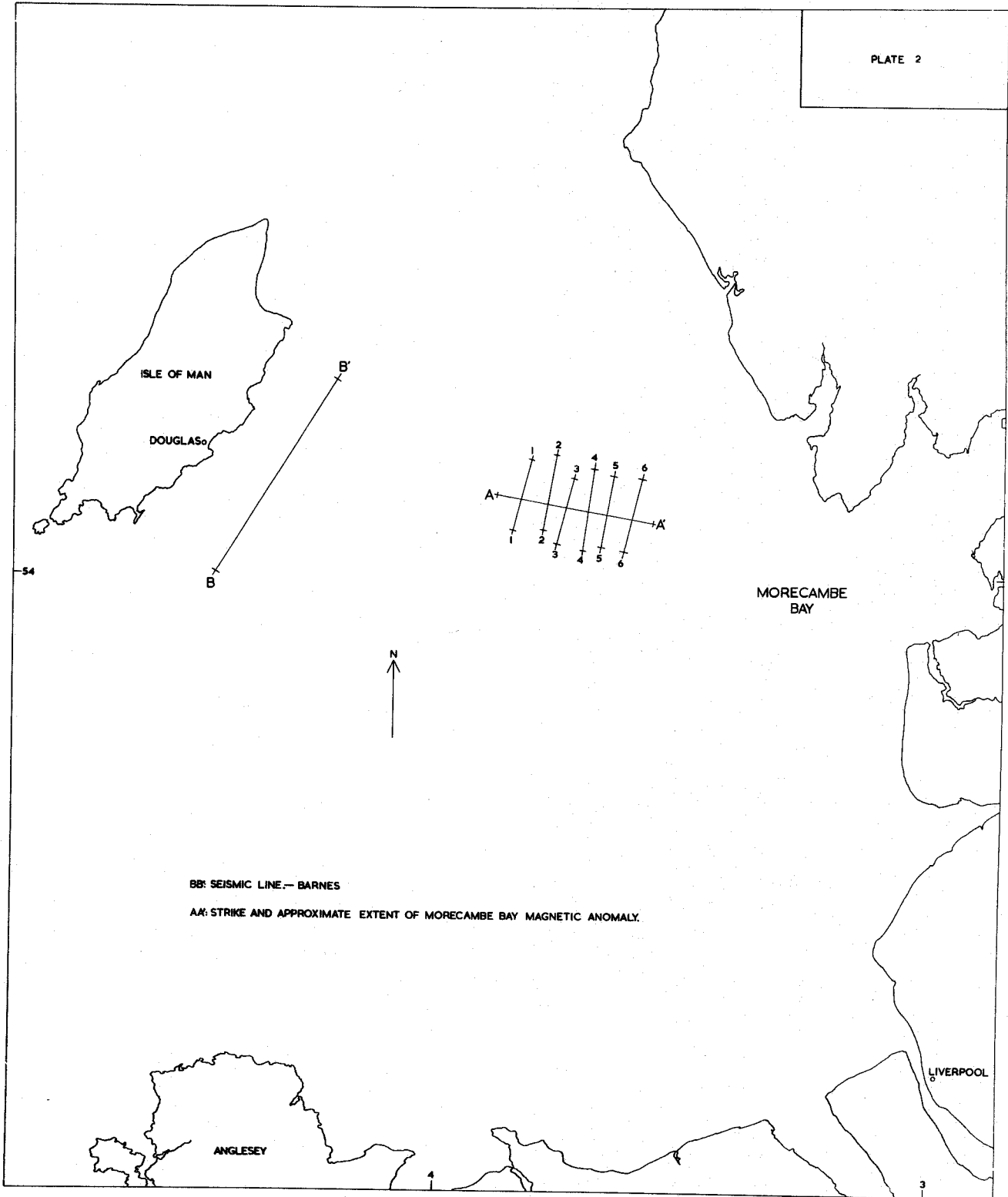
The Morecambe Bay Magnetic Anomaly.

1. Introduction

The Morecambe Bay Magnetic Anomaly is situated within the area occupied by the East Irish Sea gravity 'low' and is marked CC' on Plate 3 which is contained in Chapter 7. The feature appears on the Aero-magnetic maps as a narrow linear anomaly approximately 20 miles long and 3-4 miles wide. The long axis is aligned in a west-north-west direction and the very steep gradients over the anomaly indicate a source at relatively shallow depth. It was considered that a series of traverses with a sea-borne magnetometer would provide the data necessary for detailed interpretation. Six traverses were run across the anomaly on the 27th August 1964 using the sea-borne proton magnetometer and the practical details are described in the following section.

2. The Survey.

The position of the anomaly was fixed on the Marine Decca Charts by means of a 10 kilometre square grid overlay reduced to the same scale as the Marine Charts. A single traverse had been run obliquely across the anomaly in 1961 and the recorded Decca co-ordinates helped to locate the anomaly. The six traverses were run in a $N 10^{\circ} E$ true direction to cross the anomaly at right angles to its strike which was approximately 109° magnetic. Traverses were spaced at approximately one and a half mile intervals. The total length of each traverse was about six miles in order to permit a reliable estimate of the background to be obtained. Plate 2 shows the



BB' SEISMIC LINE.— BARNES

AA' STRIKE AND APPROXIMATE EXTENT OF MORECAMBE BAY MAGNETIC ANOMALY.

position of the six traverses.

The instrument used was a Gray proton magnetometer Mk. IV, the 'fish' streaming at approximately two ships' length astern. Readings were taken automatically at about 15 second intervals and recorded by an observer. Decca Navigator and magnetometer observers synchronised watches using a radio time signal to ensure accurate positioning. Accurate time records were also needed for the daily variation correction. Because of the narrow width of the anomaly the ships' speed was reduced to about eight knots giving readings at about 200 feet intervals.

3. Reduction of Observations.

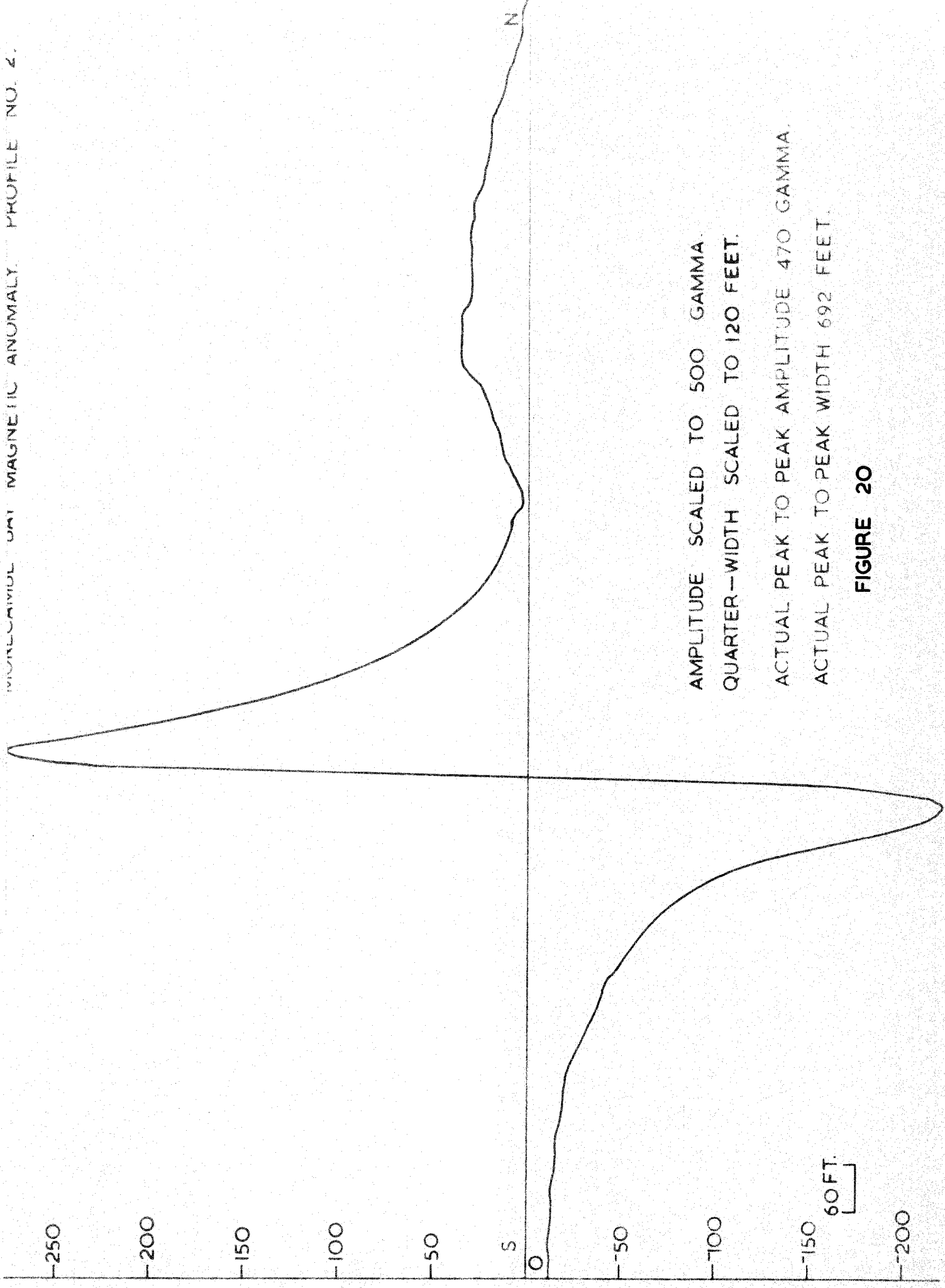
The instrument readings were corrected and reduced to values of total magnetic intensity measured in gamma using a computer programme available in the department (Johnson, personal communication). The corrections effected by this programme are as follows:

3.1 Regional Correction.

This correction takes into account the regional magnetic gradients over the earth's surface. The values adopted for the components of the regional gradients are the same as those used in the preparation of the Aero-magnetic maps (Geological Survey and Museum, 1964). Thus the regional gradients were assumed to be 238.42 gamma/degree north and 28.42 gamma/degree east relative to a chosen origin at 54° N. and 4° E. An arbitrary value of 46,600 gamma was assumed for the total magnetic field at this point.

3.2 Daily Variation Correction.

Data for the Daily Variation Correction was obtained from a Magnetogram supplied by the Eskdalemuir Observatory. The variation in millimetres



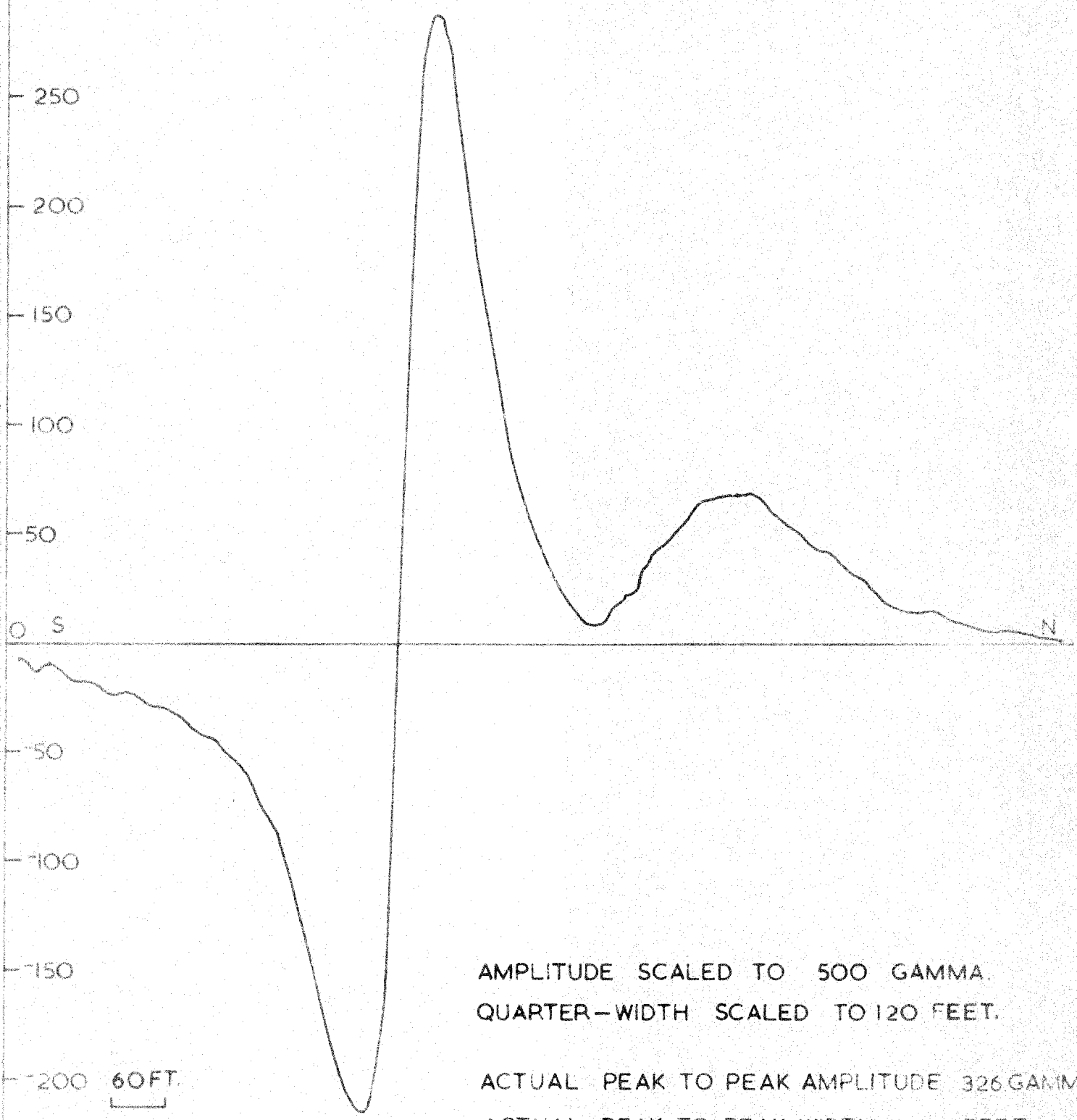
AMPLITUDE SCALED TO 500 GAMMA.
QUARTER-WIDTH SCALED TO 120 FEET.

ACTUAL PEAK TO PEAK AMPLITUDE 470 GAMMA.
ACTUAL PEAK TO PEAK WIDTH 692 FEET.

FIGURE 20

GAMMA

MORECAMBE BAY MAGNETIC ANOMALY. PROFILE NO.3



AMPLITUDE SCALED TO 500 GAMMA.
QUARTER-WIDTH SCALED TO 120 FEET.

ACTUAL PEAK TO PEAK AMPLITUDE 326 GAMMA
ACTUAL PEAK TO PEAK WIDTH 1252 FEET.

FIGURE 21

recorded on the Magnetogram relative to a given background for both the horizontal and vertical fields is converted to gamma by the programme using the scale factor given on the Magnetogram.

4. Errors

A magnetic survey off the coast of Co. Dublin during the 1965 season provided several intersecting traverses. This technique suggested that the value obtained for the magnetic field is accurate to within approximately 5 gamma (Stacey, personal communication).

5. Description of the Anomaly.

The anomaly on the Aero-magnetic maps is nearly 20 miles long and between 3 and 4 miles wide. The long axis is aligned in a west-north-west direction. All the detailed profiles show similar characteristics and two have been selected for the interpretation. These are the profiles numbered 2 and 3 on Plate 2. The anomaly profiles along these traverses are the least complicated and are therefore considered to be most suitable for an interpretation in terms of a simple model.

A distinctive feature that emerges from the detailed profiles is the approximately equal amplitude of the positive and negative peaks. This is illustrated by observed profiles 2 and 3 which are presented in scaled form as Figures 20 and 21. The negative part of the anomaly occurs to the south suggesting that the direction of magnetisation within the anomalous body is probably different from the direction of the magnetic field at the present day. The average peak to peak amplitude of the anomaly as obtained from the six profiles was found to be 380 gamma. The peak to peak widths of profiles 2 and 3 are 692 feet and 1,252 respectively. The maximum gradients associated with the anomaly occur over the northern flank. Along profile 2 a maximum

gradient of approximately 983 gamma/mile was recorded over a horizontal distance of about 1/5 mile. A value of 508 gamma/mile was recorded over a similar distance along profile 3.

Some of the profiles show a second maximum to the north. A further important aspect is the rapid return of the anomaly to a background value in each direction, a characteristic which proved to be one of the critical factors in interpretation.

6. Methods of Interpretation.

The methods of interpretation used for this particular anomaly are described in the following sections.

6.1 The Pseudo-gravity method.

Use of this method permits an estimation of the possible range of magnetisation direction to be obtained from the observed magnetic data in the case of a non-infinite two-dimensional body. The theoretical basis for the pseudo-gravity technique is Poisson's theorem relating gravity and magnetic potentials as follows:

The gravity potential U , at a point P due to an element of volume δr is given by the expression,

$$U_{(P)} = \frac{G \rho \delta r}{r} \quad \text{-----} \quad 1$$

where G is the Gravitational constant, ρ the density of the body, and r the distance of the body from the point of reference. The magnetic potential V , at the same point is given by,

$$V_{(P)} = \underline{J} \cdot \nabla' \left(\frac{1}{r} \right) \delta r \quad \text{-----} \quad 2$$

where \underline{J} is the magnetisation, and the operator ∇' refers to differentiation with respect to the co-ordinates of the elementary body. These two equations

can be combined thus,

$$V = \frac{J}{G^p} \cdot \nabla' (u)$$

This is Poisson's formula and it is valid for a finite body provided the direction of magnetisation and the ratio of intensity of magnetisation to the density remain constant.

A pseudo-gravity transformation originally developed by Baranov (1957) uses the upward continuation theorem in connection with Poisson's theorem to deduce a pseudo-gravity equivalent from the magnetic anomaly on the assumption that the density at every point of the body is given by,

$$\rho = \frac{J}{G}$$

If it is assumed that the intensity of magnetisation has the same sign throughout the body it follows from an expression developed for the pseudo-gravity field at a point (Bott, Smith, and Stacey, 1966 unpublished) that the computed pseudo-gravity must also always have this sign. Bott, Smith and Stacey have shown that this condition can only be satisfied by a limited range of magnetisation directions for any given total field magnetic anomaly.

The method has been programmed for use with a computer to calculate a range of values for the direction of total magnetisation that yield acceptable pseudo-gravity fields (Stacey, personal communication).

6.2 The Bruckshaw and Kunaratnam Method.

Bruckshaw and Kunaratnam have developed a method for the interpretation of magnetic anomalies over uniformly magnetised dykes which is dependent upon simple scaling laws and is applicable to any observed component of the field. (Bruckshaw and Kunaratnam, 1963). It is also valid for any resultant direction

of magnetisation and for any strike direction. The theory is developed by consideration of the basic equation for an anomaly caused by a dyke with a flat top of horizontal width t , at a depth z below the plane of observation:

$$F = 2 J \sin \theta \left[\sin(\phi + I - \theta)(\alpha_1 - \alpha_2) + \cos(\phi + I - \theta) \log_e \frac{r_2}{r_1} \right].$$

when J represents the resultant transverse intensity of magnetisation making an angle ϕ with the horizontal, I the direction lying in the vertical plane containing the Magnetic Meridian in which the anomaly is measured, θ the geological dip of the dyke, and (r_1, α_1) , (r_2, α_2) the polar co-ordinates of the edges of the dyke with respect to the point of observation. This formula only applies to a dyke with a strike perpendicular to the magnetic meridian but it was shown by Bruckshaw and Kunaratnam that with little modification it could be used for a structure of any strike. The above equation modifies to the form:

$$F/2J \sin \theta = (\alpha_1 - \alpha_2) \sin i + \cos i \log_e \frac{r_2}{r_1}.$$

$$\text{where } i = (\phi + I - \theta).$$

in which the right hand side is dependent only on the ratio of dimensions. From the standard curves contained in Bruckshaw and Kunaratnam's paper it is possible to obtain an initial estimate of i and t/z , the depth-width ratio, and subsequently a series of estimates of the depth. The width follows automatically, and if the dip of the dyke is assumed estimates of the direction and intensity of magnetisation can be made.

6.3 2-D MAGN Computer Programme. (Stacey)

The following two sections contain a brief account of the principles involved in the computer programmes, 2-D MAGN. and 2-D MAGSCALE. (Stacey, personal communication). The methods recognize that the essential data

required from the observed profiles is the shape, intensity and direction of total magnetisation of the body causing the anomaly, and that this can be achieved by comparison of the observed profiles with those derived for theoretical models. Any two-dimensional body may be defined ^{approximately} in terms of an n-sided polygon. The anomaly at a given point produced by the semi-infinite horizontal slabs as defined by each face of the polygon can be calculated from formulae for the horizontal and vertical disturbance at a point due to a semi-infinite slab with a sloping end face (Talwani, Worzel, and Landisman, 1959; Morgan and Grant, 1963). The effect of the complete body at the point is obtained by algebraic summation of the disturbances due to all the slabs taking into account the fact that the effect of some of the slabs must be subtracted to obtain the required shape. This is the basis for the first programme which permits the calculation of the horizontal, vertical or total field components of the anomaly as required, for any two-dimensional body of polygonal outline.

6.4 2-D MAGSCALE Computer Programme.

Consider a simple dyke of rectangular cross-section and uniform magnetisation.*
 Allowing for the fact that the depth to the bottom of the body has a negligible effect on the anomaly if it is more than ten times the width, five variables still remain; the depth to the top of the dyke, its width, α' the strike of the body measured clockwise from the horizontal projection of the total magnetisation J, the inclination of the total magnetisation J within the body, of which α' is indeterminate since the polarisation in the plane of the traverse alone is applicable.

* Stacey, 1961.

A large number of theoretical curves would be necessary during interpretation of a field profile without further simplification. However this is possible since the character of magnetic anomalies permit J to be effectively eliminated by scaling the observed and theoretical profiles to the same amplitude. In addition, the analysis of magnetic formulae indicates that the anomaly at any point is dependent upon the shape of the disturbing body, but independent of the scale of the structure. Consequently reduction of the observed and calculated anomalies to a constant width eliminates a dimensional factor.

The second programme, 2-D MAGSCALE, computes the anomaly over the disturbing body in basically the same way as the 2-D MAGN programme, but also scales the amplitude and width to specified values. The normal interpretation procedure involved the preparation of a library of curves for a range of depth-width ratios and magnetisation directions, possessing fixed amplitude and half or quarter-width dimensions. The field profiles are similarly scaled and compared to find a satisfactory 'match'. In the case of a vertical dyke the answer is unique.

When a theoretical curve bearing a satisfactorily close resemblance to the observed profile is obtained, J of the anomalous body is given by:

$$|J| = |J|_{\text{model}} \cdot \left(\frac{\text{amplitude scale factor for theoretical curve.}}{\text{field}} \right)$$

where J is in c.g.s. units (Stacey - personal communication). Similarly, the true depth and width of the top of the body are given by the expressions:

$$\text{depth} = \frac{(\text{depth to top of model}) \cdot (\text{scale factor for model})}{\text{horizontal scale factor for field curve}}$$

width = $\frac{\text{width of top of model}}{\text{horizontal scale factor for field curve}} \cdot (\text{scale factor for model})$

horizontal scale factor for field curve

7. Interpretation.

7.1 Introduction.

The linear character of the Morecambe ^{Bay} magnetic anomaly and the very steep marginal gradients indicate a source at shallow depth and it is therefore unlikely that the anomaly is caused by anomalous features within the basement. The position of the anomaly within the area of the postulated sedimentary basin containing thick Mesozoic and Carboniferous sediments also suggests that a basement origin is improbable.

The anomaly can be best explained in terms of an intrusive igneous body at shallow depth within the sedimentary deposits. The detailed interpretation has attempted to explain the observed anomaly in terms of a simple sheet structure involving either a vertical dyke or a horizontal sill.

i. Direction of Magnetisation.

The distribution of the positive and negative features of the anomaly suggest that the direction of magnetisation within the anomalous body is different from the direction of magnetisation of the present earth's field (Section 5). In the interpretation it is necessary to know the direction of magnetisation, and a range of possible directions has been obtained using the pseudo-gravity technique. It was observed both from the aero-magnetic maps and the detailed profiles that a difference in background level of approximately 30 gamma is present from north to south across the anomaly, and this was removed by applying a progressive incremental correction along the profiles. The modified data was now used to obtain an estimation of the direction of magnetisation by means of

Table 8.

Profile No.	1	2	3	4	5
Range of estimated direction of magnetisation allowing for the effect of the earths' field, measured downwards from the northern horizontal.	175°-225°	160°-226°	139°-219°	125°-195°	128°-199°
Median Value.	200°	193°	179°	160°	163°
Overall range of direction from results of all profiles.			125°-226°		
Range of median values.			160°-200°		

the pseudo-gravity method. The range of values so obtained is given in Table 8. From this Table it can be seen that the spread of the values from the central part of the range obtained for each profile is from 160° to 200° measured downwards from the northern horizontal. Thus, assuming a non-infinite and effectively two-dimensional structure, the pseudo-gravity results confirm the initial impression that the direction of magnetisation within the anomalous body is distinctly different from the direction of magnetisation of the earth's field at the present day, and suggest a direction aligned towards the south.

ii. The 2-D MAGSCALE Computer Method.

The observed profiles 2 and 3 were now scaled to a total peak to peak amplitude of 500 gamma, and quarter-width of 120 feet. The quarter-width is taken as the horizontal distance between the two points on the curve where a value equal to a quarter of the total amplitude measured from the negative peak was attained. The adjusted profiles could now be directly compared with those computed for chosen theoretical models scaled in the same manner.

Figures 20 and 21 illustrate the shape of the scaled anomaly for profiles 2 and 3. A series of curves for a dyke model was now computed, using the 2-D MAGSCALE programme, for depth-width ratios of 5:1, 2:1, 1:1, 1:2, and 1:5, and directions of magnetisation of 155° , 185° , and 215° . In all the models the depth to the bottom of the theoretical dyke was maintained at a minimum of ten times the width, and a value of .001 was arbitrarily adopted for the value of the intensity of magnetisation. From the evidence of the first method it was anticipated that the above range of magnetisation directions, in conjunction with the widely differing depth-width ratios would produce a library of curves indicating the combination of these relevant variables capable of yielding the most satisfactory 'fit' with the observed profiles. It was further required that the

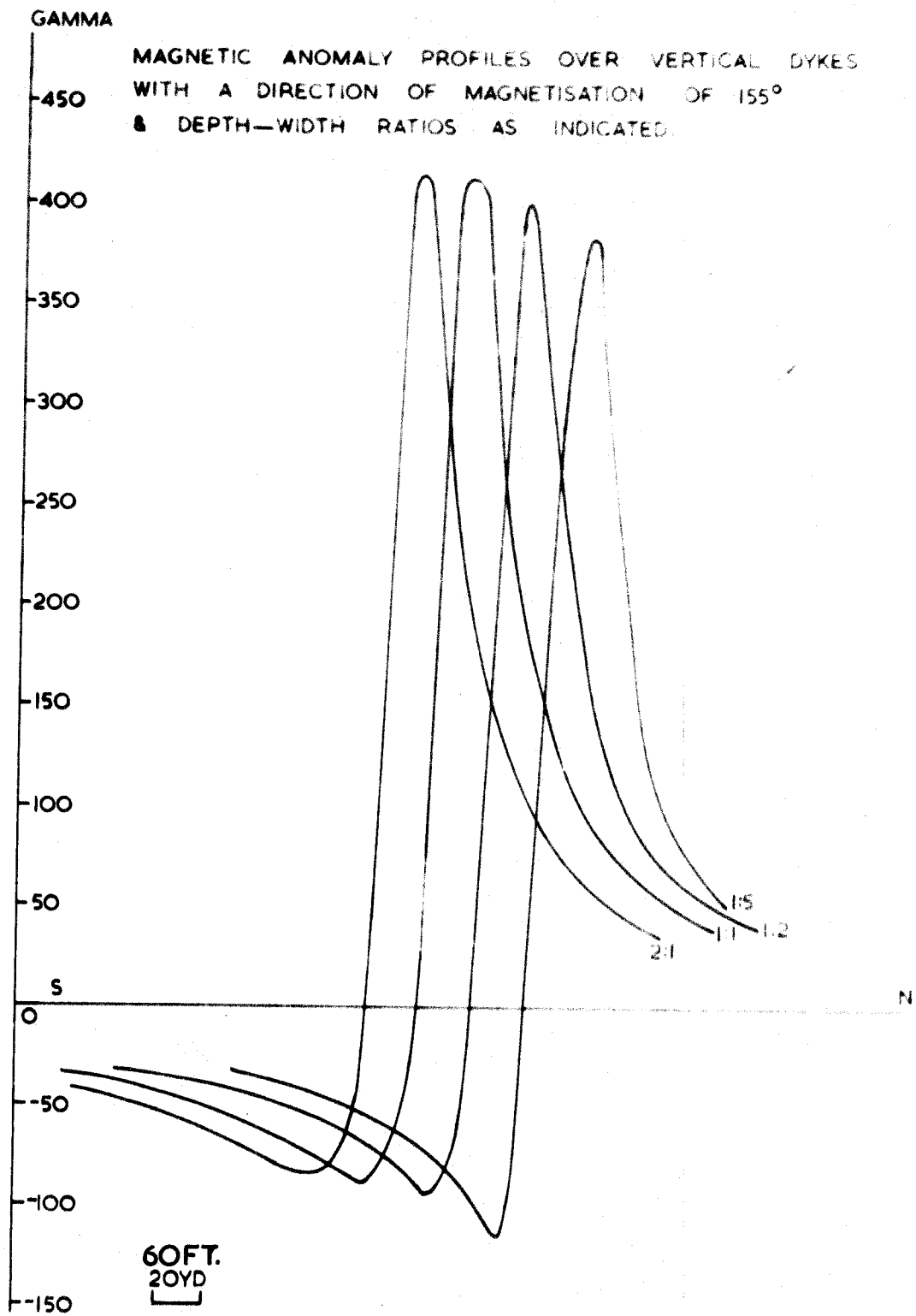


FIGURE 22

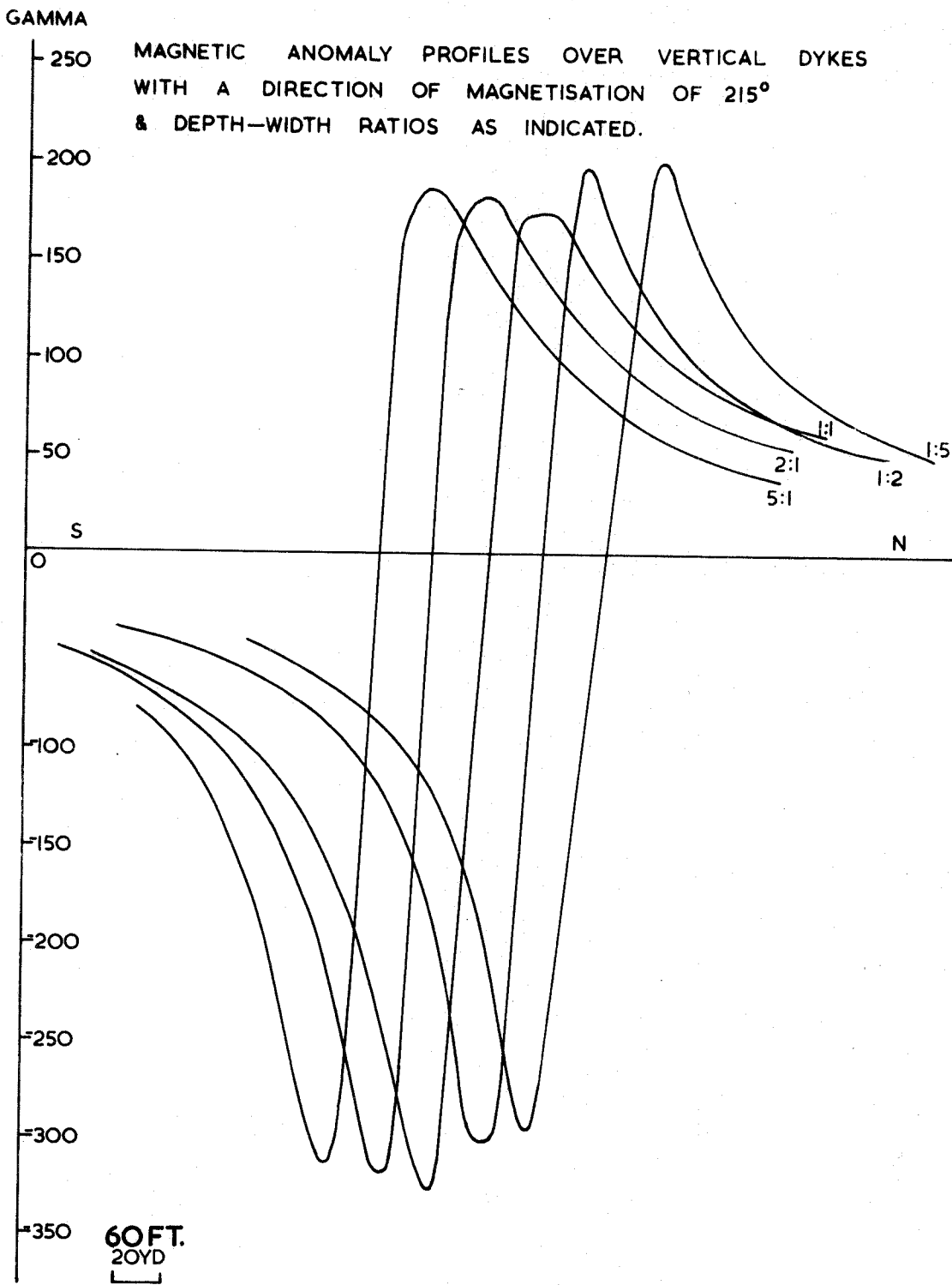
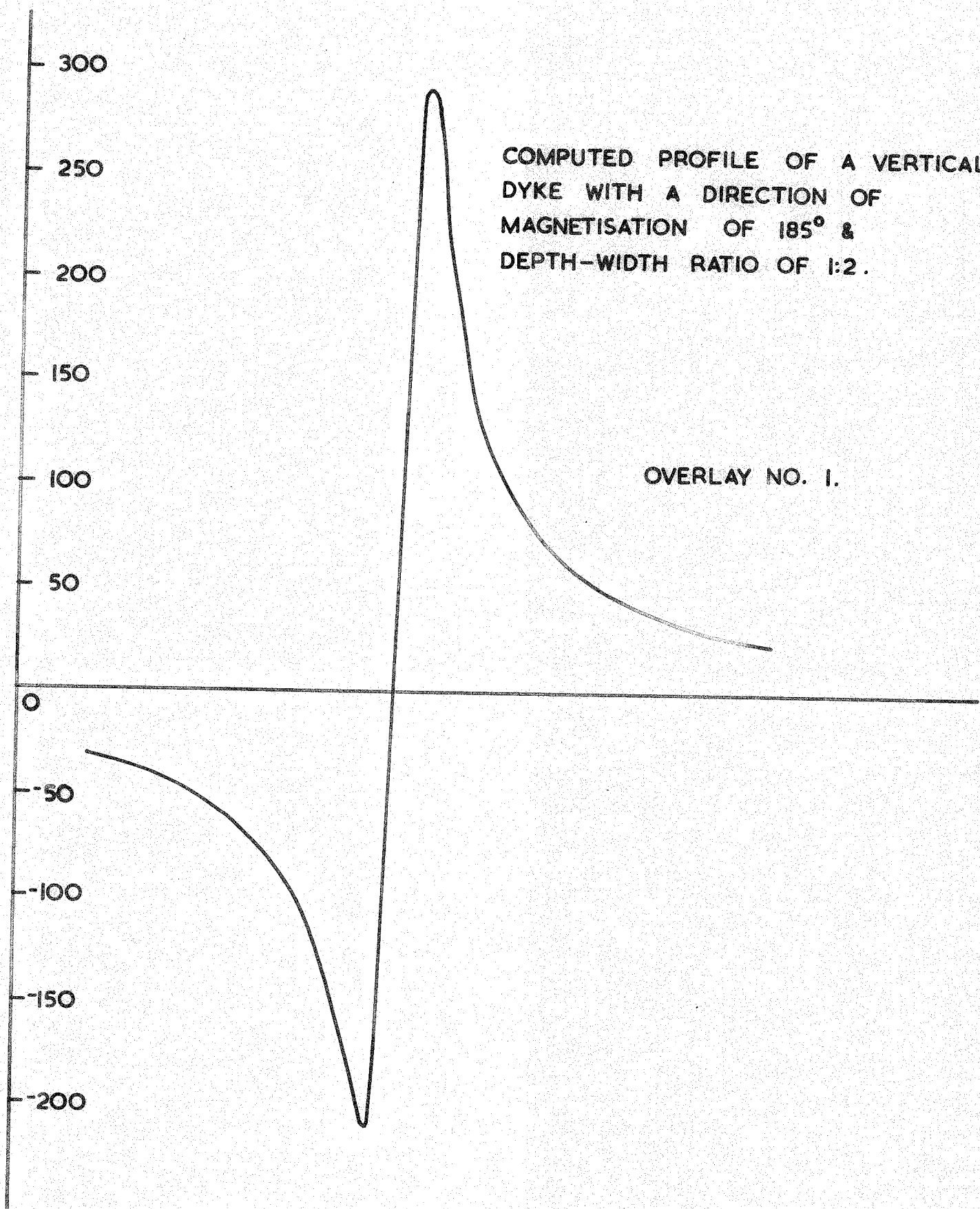
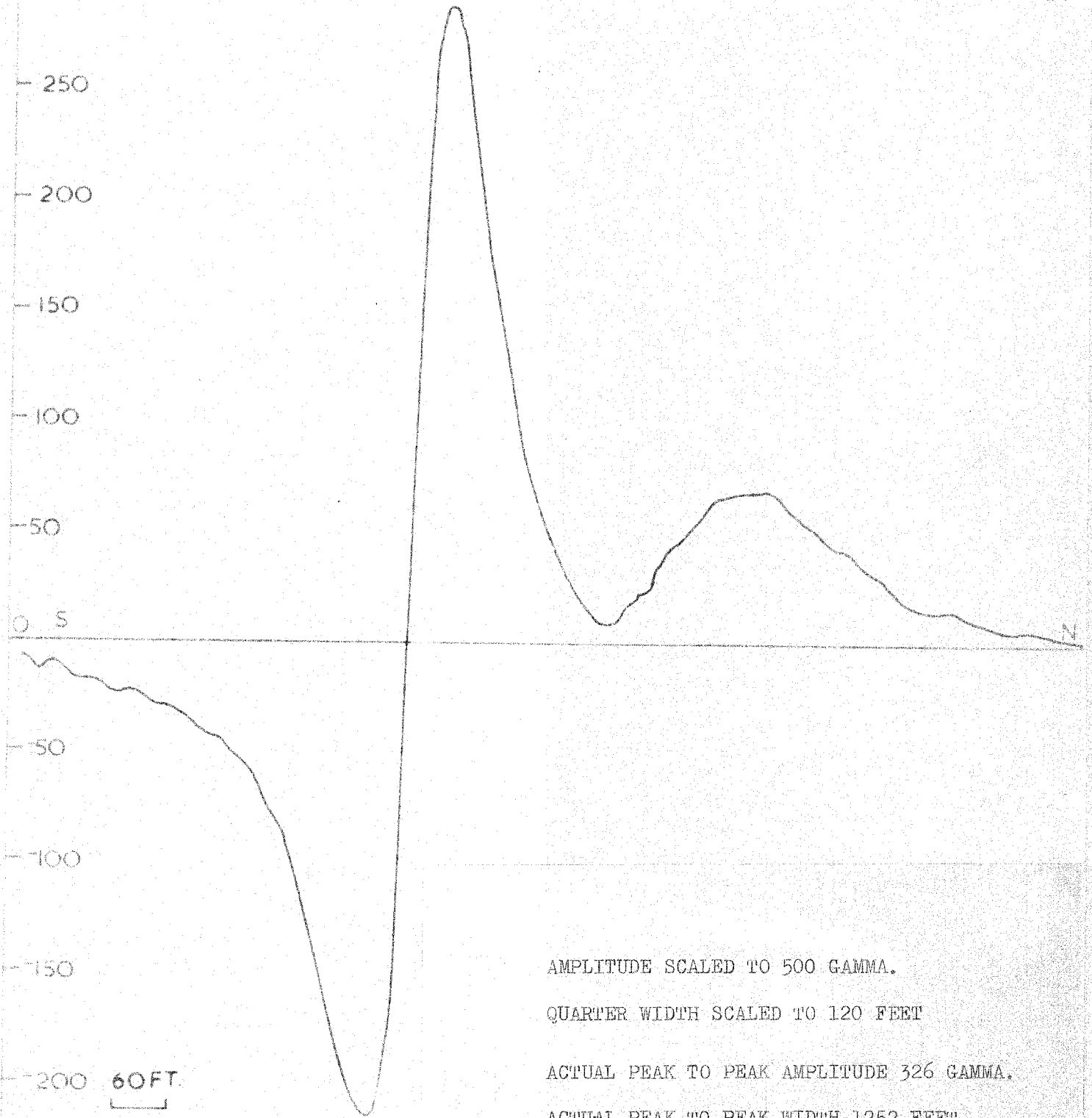


FIGURE 24



GAMMA

MORECAMBE BAY MAGNETIC ANOMALY. PROFILE NO 3.



set of curves should indicate a divergence from this similarity for all other combinations. The computed profiles for the theoretical models are presented in Figures 22, 23, and 24. If these are compared with the observed profiles of Figures 20 and 21, it is apparent that for all the depth-width ratios the family of curves for the models with directions of magnetisation of less than 155° and greater than 215° show a wide divergence from the similarly scaled observed anomaly. A direction of magnetisation of 185° produced a series of curves bearing a close similarity in both distribution of positive and negative peaks and shape of the overall anomaly to the observed profile. Closer inspection suggests that the most satisfactory 'fit' is provided by a dyke having a depth-width ratio of 1:2. The closeness of the 'fit' with observed profile 3 is indicated by Overlay No.1, and the dimensions of the model on unscaling are contained in Tables 9 and 10.

The computed curve for a vertical dyke having these characteristics displays a broad similarity with the observed anomaly. The relative magnitude of the positive and negative parts of the profiles show close correspondence, but disagreement exists on the flanks of the profiles particularly towards the north. This is seen as a more gradual decline of the computed profile to a background level compared with the observed anomaly. The only method by which an equally rapid return to background could be secured was by reducing the thickness of the dyke to such an extent that the correspondence of observed and computed profiles was lost over the central part of the profile.

The northern flank of the observed profile is also complicated by a secondary rise in the anomaly which is broader and of considerably less amplitude than the dominant feature of the profile as can be seen in Figures 20 and

Table 9.Profile 2.

Amplitude scale factor for the field curve is 1.061.

" " " " " theoretical curve is 1.5171.

Horizontal scale factor for the field curve is 0.1002.

" " " " " theoretical curve is 0.3609.

Therefore, using the relationships noted in section 6.4:

Depth to top of dyke is $\frac{60 \times 0.3609}{0.1002}$ feet.

= 216 feet.

Since the depth-width ratio was 1:2, the width becomes,

432 feet.

$$|J| = \frac{.001 \times 1.5171}{1.061}$$

= .00143

Table 10.Profile 3.

Amplitude scale factor for the field curve is 1.535.

" " " " " theoretical curve is 1.5171.

Horizontal scale factor for the field curve is 0.0618.

" " " " " theoretical curve is 0.3609.

Therefore the depth to the top of the dyke is:

$$\frac{60 \times 0.3609 \text{ feet.}}{0.0618}$$

$$= \underline{351 \text{ feet.}}$$

Since the depth-width ratio was 1:2, the width becomes,

$$\underline{702 \text{ feet.}}$$

$$|J| = \frac{.001 \times 1.5171.}{1.535}$$

$$= \underline{.00099}$$

21. It is possible that this may be caused by another dyke structure at increased depth. In spite of the apparent discrepancies it is not possible to eliminate a dyke structure as a result of these computed profiles. The depth, width, and intensity of magnetisation presented in Tables 9 and 10 show fairly good agreement with the values obtained from the Bruckshaw-Kunaratnam method which is discussed in the following section.

iii. The Bruckshaw-Kunaratnam Method.

The Bruckshaw-Kunaratnam method as described in section 6.2 was used to obtain further estimates of the depth, width, direction of magnetisation and intensity of magnetisation assuming a dyke form for the anomalous body. The various parameters as obtained from field profiles 2 and 3, together with the required ratios are presented in Tables Nos. 11 and 12 respectively.

The values of i and t/z as obtained from the standard curves supplied with the original paper are listed in Tables 13 and 14, together with the factors obtained and the resulting estimates of the value of z , the depth to the top surface of the dyke. Knowledge of t/z , the width-depth ratio then permits an estimate for the width to be directly obtained.

The intensity of magnetisation is usually indeterminate since it involves the relation:

$$F/2J\sin\theta = Mm.$$

where θ is the angle of dip of the dyke, Mm is the value of the dominant feature on the model, and F is the magnitude of the corresponding feature of the field curve. If it is assumed that the dyke is vertical then $\sin\theta$ becomes unity, and the expression reduces to:

$$F/2J = Mm.$$

The value of J obtained by this method is a minimum limiting value for the special

Table II

<u>Parameter</u>	<u>Value (feet)</u>
$x_2^3 - x_4^1$	123
$x_2^1 - x_2^1$	861
$x_2^3 - x_4^1$	922
$xM - x_2^1$	615
$xM - xm$	692
$x_4^3 - x_4^1$	461
$x_4^3 - x_2^1$	338
$(x_4^3 - x_4^1) / (x_2^1 - x_2^1) = 0.142$	$(x_4^3 - x_4^1) / (x_2^1 - x_2^1) = 1.071$
$(xM - x_2^1) / (xM - xm) = 0.889$	$(xM - x_2^1) / (x_2^1 - x_2^1) = 0.714$
	$m/M = 0.798$

Table 12

Parameter	Value (feet)
$x_2^3 - x_4^1$	209
$x_2^1 - x_2^1$	1544
$x_4^3 - x_4^1$	918
$xM - x_2^1$	1002
$xM - xM$	1252
$x_4^3 - x_4^1$	1002
$x_4^3 - x_2^1$	417

$(x_4^3 - x_4^1) / (x_2^1 - x_2^1) = 0.135$	$(x_2^3 - x_4^1) / (x_2^1 - x_2^1) = 0.595$	$m/M = 0.749$
$(xM - x_2^1) / (xM - xM) = 0.800$	$(xM - x_4^1) / (x_2^1 - x_2^1) = 0.649$	

Table 13.Profile 2:

From curves in figure 3 of original paper (Bruckshaw and Kunaratnam):

$$\underline{i=8 \text{ and } t/z=2.3.}$$

Depth and width.

Figure no. of set of curves in original paper.	Factor.	Depth (z). (feet)
4	3.1	223
5	3.8	227
6	1.95	236
7	5.75	160
8	0.6	205
9	1.5	225
10	2.75	224

The average depth to the top surface of the dyke is therefore,

214 feet.

The value of t/z is 2.3, giving an estimate for the width of:

492 feet.

$$\underline{J' = .00119 \text{ e.m.u. } \phi = 191^\circ}$$

Table 14.Profile 3:

From curves in figure 3 of original paper:

$$\underline{i=10 \text{ and } t/z=2.8.}$$

Depth and width.

Figure no. of set of curves in original paper.	Factor.	Depth (z). (feet)
4	3.5	358
5	3.95	391
6	2.05	488
7	5.8	158
8	0.75	277
9	1.54	271
10	2.75	364

The average depth to the top surface of the dyke is therefore,

330 feet.

The value of t/z is 2.8, giving an estimate for the width of:

924 feet.

$$\underline{J' = .00072 \text{ e.m.u. } \phi = 189^\circ}$$

case of a vertical dyke with a strike direction which is magnetic east-west. Certain corrections must be made in calculating the intensity and direction of magnetisation when the strike is not east-west. In this case it is equivalent to measuring the anomaly in a direction I' in the vertical plane perpendicular to the strike of the feature for a modified intensity J' . For a vertical dyke with a strike direction making an angle of β with magnetic east-west the following equations permit the calculation of J' , and the direction of magnetisation ϕ .

$$I' = \tan^{-1} \left(\frac{\tan I}{\cos \beta} \right).$$

$$i = \phi + I' - \theta$$

$$J' = J (\cos^2 I \cos^2 \beta + \sin^2 I)^{\frac{1}{2}}$$

The calculated values for profiles 2 and 3 are presented in Tables 13 and 14 respectively. The results from the Bruckshaw-Kunaratnam method were compared with the estimates obtained from the 2-D MAGSCALE programme. A good agreement exists between the estimates for the depth to the top of the anomalous body and the direction of magnetisation assuming a dyke structure. The estimates for the direction of magnetisation obtained from both methods fall within the range suggested by the pseudo-gravity technique. However, the estimates for the depth and width along the two profiles are very variable as can be seen by comparing Tables 13 and 14, and the values obtained for the intensity of magnetisation are low for a dyke. These results suggest that the complete anomaly is unlikely to be caused by a simple dyke.

7.2 A Horizontal Sill.

i. The 2-D MAGN. Computer Method.

Attention is next directed to the possibility that a sill or belt of lavas might cause the anomaly. To establish a general estimate of the

Table 15.

Direction of magnetisation → 75° 105° 135°

Ratio of positive to negative parts of the Anomaly.

<u>Depth-thickness ratio</u>		75°	105°	135°
2:1		3.44	1.18	0.41
4:1		3.42	1.18	0.41
10:1		3.40	1.18	0.41

Ratio of positive to negative features of the observed anomaly was
approximately 1.2.

direction of magnetisation use was made of the 2-D MAGN. computer programme. Profiles were computed for a horizontal tabular body extending to the north with a vertical southern boundary, and directions of magnetisation centrally positioned within each quadrant of 45° , 135° , 225° , and 315° , and a depth-thickness ratio of 1:1.

From these it was found that a direction of magnetisation of 135° produced a curve of approximately the required shape. Data for a series of sills with a range of magnetisation directions at intervals of 30° comprising 135° , 105° , and 75° , and depth-thickness ratios of 2:1, 4:1, and 10:1 were now computed. The 2-D MAGSCALE programme was unable to handle shapes in which only two co-ordinates were specified as in the case of a horizontal sill, and scaling was accomplished by means of a hand calculator. Because of this difficulty, only the calculated anomalies which showed a suitable distribution of positive and negative features were modified in this way. The data were also presented in table form showing the ratio of the positive and negative parts of the anomaly for all combinations of direction of magnetisation and depth-thickness ratio, thus indicating the divergence from the observed value (Table 15).

Inspection of this table shows that a direction of magnetisation of 105° yields an acceptable maximum to minimum ratio, and that variation of the depth-thickness ratio has no noticeable effect upon this aspect of the anomaly profile. Directions of magnetisation of 75° and 135° produced maximum to minimum ratios which differed from the observed value by nearly 200%, and increase of the depth-thickness ratio to 10:1, which is effectively equivalent to raising the lower surface of the sill produced only a very small improvement.

MAGNETIC ANOMALY PROFILES OVER HORIZONTAL SILLS
WITH A DIRECTION OF MAGNETISATION OF 105°
& DEPTH — THICKNESS RATIOS AS INDICATED.

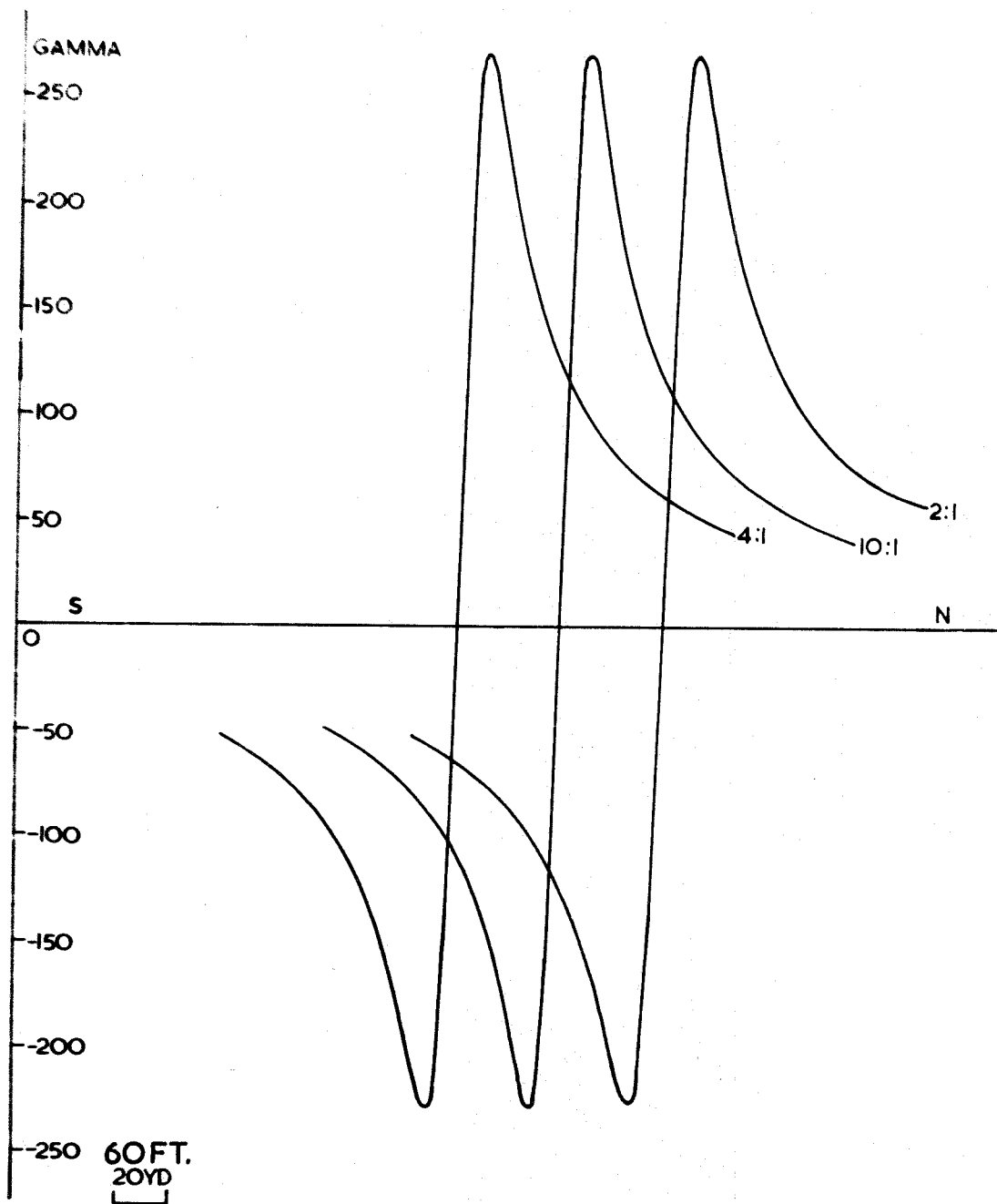
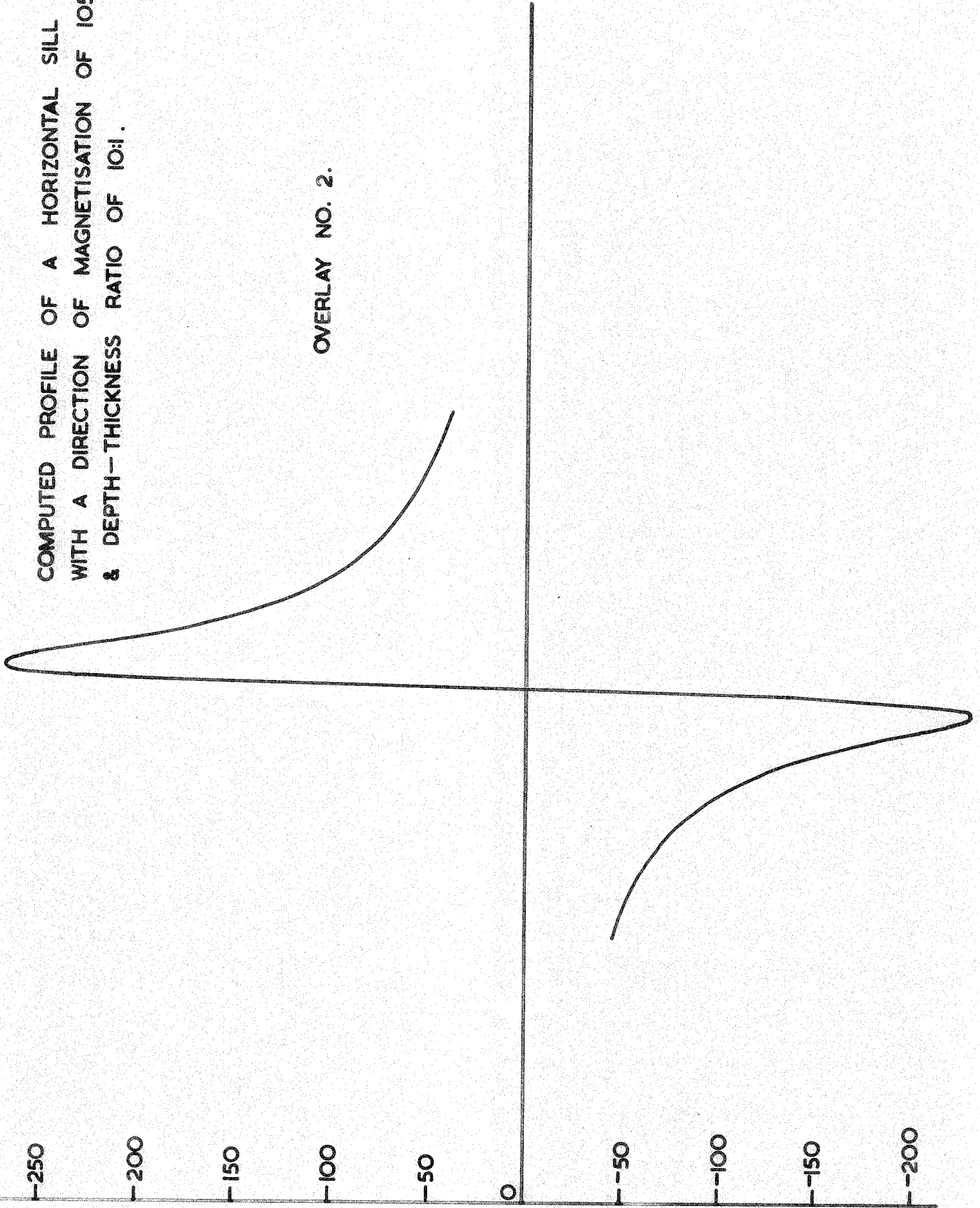
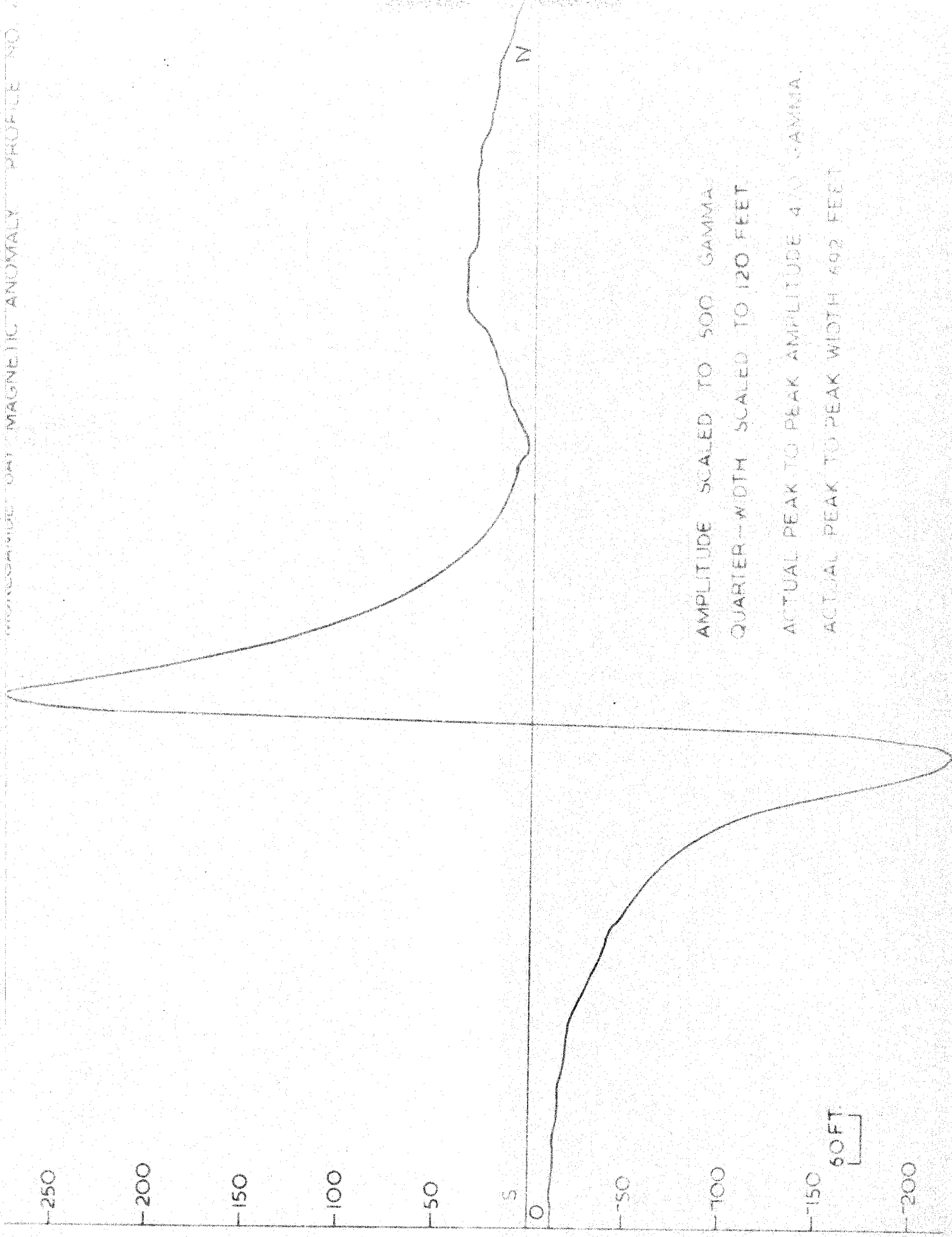


FIGURE 25

COMPUTED PROFILE OF A HORIZONTAL SILL
WITH A DIRECTION OF MAGNETISATION OF 105°
& DEPTH-THICKNESS RATIO OF 10:1.

OVERLAY NO. 2.





AMPLITUDE SCALED TO 500 GAMMA
QUARTER-WIDTH SCALED TO 120 FEET

ACTUAL PEAK TO PEAK AMPLITUDE 470 GAMMA
ACTUAL PEAK TO PEAK WIDTH 692 FEET

The scaled data for a sill with a direction of magnetisation of 105° and different depth-thickness ratios are presented in the form of profiles in Figure 25. The best 'fit' with the observed anomaly was considered to be a sill having a depth-thickness ratio of 10:1, and this is shown in Overlay No.2. When a comparison is made with the best 'fit' obtained for a dyke model, a slight improvement is apparent. The relative magnitude of the positive and negative features again show good correspondence as also does the southern flank of the profile. To the north, the gradients of the theoretical profile again decrease more rapidly than is the case for the observed anomaly.

There are difficulties therefore in attempting to fit theoretical computed profiles for both simple sill or dyke models to the observed anomaly, although a sill structure appears to give a better overall correspondence. The secondary rise of the anomaly to the north might then be caused by an irregularity on the top surface of the body.

8. Conclusions.

If the anomaly is caused by a vertical dyke, the depth to the top surface, from the evidence of the two detailed profiles investigated, lies between 214 feet and 351 feet, and the width between 432 feet and 924 feet. A direction of magnetisation of about 185° - 190° is indicated by the 2-D MAGSCALE and Bruckshaw-Kunaratnam methods which is within the estimated range of 160° - 200° as calculated using the pseudo-gravity technique. The shallow depth estimate is consistent with the magnitude of the magnetic gradients but the large difference in the estimates for the width of the structure along adjacent profiles and the low values of the intensity of magnetisation are features that make an interpretation

in terms of a simple dyke model seem improbable. The divergence of the computed anomaly for a vertical dyke from the observed anomaly is greater than that for a horizontal sill or belt of lavas extending to the north. The secondary maximum is also more easily explained if the anomalous structure is continuous in a northerly direction.

The direction of magnetisation of 105° required to explain the observed anomaly in the case of a horizontal sill or belt of lavas is not within the range specified by the pseudo-gravity technique. This is to be expected since a semi-infinite structure of this type violates the basic assumption of the pseudo-gravity theory. In either case, however, it would appear that the direction of permanent magnetisation within the anomalous body is different from the direction of the magnetic field at the present day. This suggests that the dyke is not of Tertiary age since the earth's magnetic field is believed to have remained stable from Tertiary to Recent time (Cox and Doell, 1960). The pre-Tertiary rocks do not usually have magnetisations parallel to the present field. The Carboniferous and especially the Permian magnetic fields were relatively very 'steady' and were vastly different from the present configuration of the field. Palaeomagnetic investigations on the Whin Sill of Permo-Carboniferous age has indicated that the direction of remanent magnetisation is towards the south (Creer, Irving and Nairn, 1959). The pseudo-gravity calculations indicate a similar direction of magnetisation for the Morecambe Bay anomaly which may be of similar age.

Of the simple models considered, it is suggested that the Morecambe Bay magnetic anomaly is explained better by a horizontal sill or belt of lavas which is extensive in a northerly direction with a faulted southern

boundary. The direction of total magnetisation in this case is approximately 105° . The magnetic gradients indicate that the anomalous structure is at shallow depth and a Permo-Carboniferous age is suggested by analogy with other intrusive igneous rocks of this age. The intrusion of a sill of this age within the area occupied by the East Irish Sea gravity 'low' would be consistent with the suggested gravity interpretation in terms of a sedimentary basin in which Permo-Triassic and Carboniferous rocks form the main 'fill'.

General Conclusions.

A high regional background gravity anomaly of approximately +35 to +40 milligals is believed to exist over much of the North Irish Sea. Large negative anomalies of up to 40 milligals amplitude have been discovered superimposed upon this high regional anomaly. These have been named the East Irish Sea 'low' which occupies most of the eastern part of the North Irish Sea, and the Dublin Bay - Kish Bank 'low' which is located in the approaches to Dublin. The shape and magnitude of these anomalies suggested interpretations in terms of either large granite batholiths or deep sedimentary basins. Critical gravity traverses across the margins of the features have led to a conclusion in favour of the latter interpretation in both areas. The presence of several thousand feet of low density sediments of possibly Mesozoic age were shown to be necessary in this case. The Dublin Bay - Kish Bank anomaly was interpreted on the evidence of the critical gravity traverses alone. The problem created by the proximity of the Leinster granite on land and the possibility that part of the anomaly might be caused by the presence of a low density granite body beneath the sea could probably be resolved by detailed seismic investigation.

Geological evidence has been used during the interpretation of the East Irish Sea 'low' in addition to the detailed gravity traverses. The possible seaward extension of the Eskdale granite to give the minimum Bouguer Anomalies in the north would seem to be invalidated by the evidence of the critical traverses. The presence of at least 8,000 feet of low density sediments is necessary to explain the observed anomaly. From the evidence of the coastal geology in south-west Cumberland, the Lancashire coastal plain, and North Wales it would seem that Permo-Triassic rocks are likely to form the main

'fill' of the basin. The very steep gravity gradients encountered over the margins of the anomalous features adjacent to the land in certain areas may be associated with faulted boundaries, and suggest a tectonic control of the coastline in those areas.

The data provided by the Aero-magnetic maps have been shown to be consistent with the gravity interpretation in the North Irish Sea. Further geophysical work in the area could take the form of surface ship gravity measurements over the deep which runs in a north-south direction down the western half of the Irish Sea and into the North Channel. Detailed seismic work in the Dublin Bay area could resolve the uncertainty caused by the nearness of the Leinster granite.

Acknowledgements

I wish to thank Professor K.C. Dunham for the privilege of working in the department and Dr. M.H.P. Bott for his supervision and guidance. I would like to record my gratitude to Professor T. Murphy of the Dublin Institute for Advanced Studies for establishing the gravity base stations in Dun Laoghaire and for other assistance during the surveys, and to Dr. R.F. King and Dr. D. J. Blundell of the Department of Geology, University of Birmingham for measuring the value of gravity at the Holyhead base. My thanks are also due to Dr. F. Gray, Mr. G. Wilson and Mr. M.S. Maconochie, together with many research students who provided support and assistance throughout the marine surveys. Finally, I am indebted to D.S.I.R. for a maintenance grant during the period of this research.

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APPENDIX 1.

Explanation of the Table.

1. Base connections refer to the base station(s) observed at the beginning and end of a run of gravity stations. The abbreviations used for the different base station names are as follows:

D.L. 1	-	Dun Laoghaire No. 1.
D.L. 2	-	Dun Laoghaire No. 2.
D.	-	Douglas
H.	-	Holyhead.
L.	-	Liverpool.
F.	-	Fleetwood.

2. Depths have been corrected to mean sea level.

3. The value of observed gravity is corrected for drifts. It is otherwise unreduced and is related to the assumed value of 'g' at Pendulum House which is 981.2650 cms./sec.²

4. The Free Air and Bouguer anomalies have been calculated assuming the density of sea-water to be 1.03 gms./cm.³, and that of the rocks underlying the sea-bed to be 2.50 gms./cm.³

Station No.	Date & Time G.M.T.	Base Con- nection.	Latitude (N)	Longitude (W)	Depth in ft. (rel. to M.S.L.)	Gravity on sea- bed (rel. to Pen. Ho.)	Free Air Anomaly mgals.	Bouguer Anomaly mgals.
IS129	2.6.63	H.	53 37.0'	4 30.5'	195	437.3	28.0	31.7
	1505							
IS130	9.6.63	D.	54.9.0'	4 27.0'	83	484.6	37.1	38.7
	1132							
IS131	1202	"	54 8.0'	4 26.3'	113	483.7	35.6	37.8
IS132	1242	"	54 7.4'	4 23.7'	111	466.8	19.8	21.9
IS133	1326	"	54 5.9'	4 20.6'	124	462.4	16.6	18.9
IS134	11.6.63	D.	54 5.0'	4 17.0'	129	466.7	21.9	24.3
	1500							
IS135	1540	"	54 4.5'	4 16.3'	133	466.4	22.1	24.6
IS136	12.6.63	D.-H.	54 2.6'	4 29.6'	125	476.3	34.8	37.1
	0802							
IS137	0915	"	54 0.3'	4 34.3'	133	470.8	32.2	34.7
IS138	2.7.63	H.-L.	53 22.3'	4 40.1'	129	407.3	23.6	26.1
	0731							
IS139	1330	"	53 26.0'	4 10.5'	134	426.3	37.0	39.5
IS140	1450	"	53 25.9'	4 1.9'	117	412.1	24.0	26.2
IS141	1555	"	53 25.9'	3 54.5'	105	411.1	23.9	25.8
IS142	1705	"	53 25.8'	3 47.3'	89	405.0	19.0	20.7
IS143	1815	"	53 26.0'	3 38.5'	70	403.3	18.4	19.7
IS144	1915	"	53 25.9'	3 31.1'	50	402.1	18.8	19.7
IS145	2015	"	53 25.8'	3 24.1'	49	404.4	21.2	22.1
IS146	2215	"	53 20.1'	3 30.7'	23	394.2	21.0	21.4

IS147	3.7.63	L.	53 31.7'	3 26.3'	86	409.6	15.4	17.0
	1244							
IS148	1344	"	53 31.8'	3 35.0'	107	412.0	16.2	18.2
IS149	6.7.63	L.-H.	53 31.8'	3 43.8'	134	414.3	16.7	19.2
	1500							
IS150	1615	"	53 31.8'	3 52.1'	151	415.5	16.7	19.5
IS151	1743	"	53 31.6'	4 1.7'	136	418.0	20.4	23.0
IS152	10.7.63	D.	54 5.4'	4 18.5'	123	464.4	19.1	21.4
	0723					466.9		
IS153	0756	"	54 4.9'	4 16.6'	123	469.9	22.3	24.7
IS154	0833	"	54 4.2'	4 14.8'	127	472.7	26.0	28.4
IS155	0905	"	54 3.6'	4 13.2'	133	477.4	29.4	31.9
IS156	0945	"	54 3.2'	4 11.3'	142		34.1	36.8
IS157	20.7.63	D.-F.	54 1.0'	4 6.5'	132	473.5	34.2	36.6
	0835							
IS158	0953	"	53 59.2'	3 58.9'	143	466.9	29.5	32.2
IS159	1054	"	53 57.8'	3 52.7'	134	457.0	22.2	24.7
IS160	1218	"	53 56.5'	3 43.9'	110	444.0	12.7	14.7
IS161	1353	"	53 54.9'	3 35.2'	95	439.1	11.0	12.8
IS162	1513	"	53 54.5'	3 26.4'	71	436.9	10.9	12.2
IS163	1633	"	53 53.9'	3 17.4'	51	433.4	9.5	10.5
IS164	1741	"	53 54.2'	3 9.3'	30	434.0	11.2	11.7
IS165	28.7.63	D.	53 55.6'	4 22.6'	147	447.2	14.5	17.2
	0746							
IS166	0855	"	53 52.3'	4 22.2'	181	444.1	13.7	17.1

IS167	1007	D.	53 52.9'	4 15.3'	174	446.7	16.0	19.3
IS168	1148	"	53 47.8'	4 12.8'	162	446.6	24.0	27.1
IS169	1416	"	53 48.4'	3 57.2'	139	444.6	22.8	25.4
IS170	1512	"	53 48.1'	3 49.3'	130	442.3	21.6	24.0
IS171	1620	"	53 47.7'	3 41.0'	117	440.0	20.7	22.9
IS172	1727	"	53 47.5'	3 32.8'	104	433.4	15.4	17.3
IS173	30.7.63	D.-H.	53 58.4'	4 29.7'	151	463.0	25.9	28.8
	1143							
IS174	1314	"	53 52.4'	4 29.8'	197	451.5	20.0	23.7
IS175	1453	"	53 47.7'	4 21.2'	181	446.0	22.3	25.7
IS176	1633	"	53 42.3'	4 20.6'	185	440.4	24.2	27.6
IS177	1742	"	53 42.7'	4 13.1'	145	430.7	16.6	19.3
IS178	1915	"	53 42.3'	4 1.3'	145	432.3	18.8	21.5
IS179	31.7.63	H.	53 37.4'	4 6.5'	145	426.3	20.0	22.7
	0829							
IS180	1230	"	53 26.6'	4 38.4'	127	415.5	25.8	28.2
IS181	17.6.64	D.	53 58.2'	4 38.0'	164	463.2	25.6	28.7
	1400							
IS182	4.8.64	D.-D.L.1	53 48.9'	4 48.7'	219	461.6	33.8	37.9
	1100							
IS183	1245	"	53 48.0'	5 3.8'	266	465.5	35.6	40.6
IS184	1409	"	53 48.8'	5 16.6'	232	461.2	32.5	36.8
IS185	1640	"	53 45.6'	5 47.5'	209	448.5	25.9	29.8
IS186	5.8.64	D.L.1-H.	53 20.6'	5 54.0'	122	374.3	-6.3	-4.0
	1040							

IS187	1150	D.L.1-H.	53	21.6'	5	46.5'	199	385.9	-1.4	2.3
IS188	7.8.64	H.-D.	54	2.0'	4	21.0'	158	462.5	20.0	23.0
	1000									
IS189	1140	"	54	3.1'	4	24.0'	129	462.0	20.0	22.4
IS190	1224	"	54	4.3'	4	26.4'	123	472.2	28.8	31.1
IS191	1256	"	54	5.2'	4	28.5'	124	479.1	34.4	36.7
IS192	8.8.64	D.-H.	53	45.1'	4	39.3'	212	455.4	33.5	37.5
	1100									
IS193	1220	"	53	39.8'	4	45.8'	144	445.4	35.7	38.4
IS194	11.8.64	H.-D.	53	33.6'	4	58.0'	180	438.3	35.0	38.4
	1317									
IS195	1423	"	54	37.3'	4	53.3'	167	446.4	38.7	41.8
IS196	1600	"	53	39.4'	5	4.3'	200	450.5	37.4	41.2
IS197	21.8.64	D.	53	54.9'	4	17.5'	154	445.7	13.7	16.6
	1220									
IS198	1305	"	53	56.6'	4	15.5'	154	450.7	16.1	19.0
IS199	1504	"	53	58.2'	4	13.0'	140	458.2	22.3	24.9
IS200	1600	"	53	59.9'	4	11.0'	136	469.4	31.2	33.7
IS201	1640	"	54	1.3'	4	8.5'	135	474.9	34.7	37.2
IS202	1722	"	54	2.7'	4	6.2'	134	476.3	34.2	36.7
IS203	1801	"	54	4.0'	4	4.2'	129	476.9	33.2	35.6
IS204	1843	"	54	5.6'	4	2.0'	114	471.6	26.7	30.8
IS205	30.8.64	D.-D.L.1	53	54.7'	4	45.5'	211	464.4	28.6	32.5
	1000									
IS206	1125	"	53	53.1'	4	58.5'	208	462.6	29.3	33.2

IS207	1248	"	53 54.1'	5 10.6'	223	466.4	30.7	34.9
IS208	1520	"	53 51.4'	5 44.7'	215	461.8	30.4	34.5
IS209	1645	"	53 49.7'	5 56.5'	135	449.1	25.7	28.2
IS210	1810	"	53 43.7'	6 2.5'	99	438.9	26.5	28.3
IS211	31.8.64	D.L.1	53 20.8'	5 50.4'	144	379.4	-3.1	-0.4
	1008							
IS212	1105	"	53 22.6'	5 42.9'	210	388.3	-1.3	2.6
IS213	1215	"	53 21.5'	5 38.7'	202	388.7	1.3	5.1
IS214	1315	"	53 24.7'	5 36.5'	217	397.9	4.8	8.9
IS215	1402	"	53 25.7'	5 39.2'	214	403.9	9.6	13.6
IS216	1520	"	53 26.7'	5 52.0'	142	405.3	14.3	17.0
IS217	12.5.65	D.L.2	53 23.2'	5 55.0'	89	383.8	1.7	3.3
	1020							
IS218	13.5.65	D.L.2	53 20.8'	6 0.2'	89	393.2	14.5	16.2
	0932							
IS219	1025	"	53 25.4'	5 59.0'	68	412.9	29.0	30.3
IS220	14.5.65	D.L.2	53 16.7'	6 2.2'	93	376.2	3.2	4.9
IS221	1350	"	53 16.3'	5 58.5'	93	367.1	-5.5	-3.7
IS222	1420	"	53 13.2'	5 58.0'	89	359.6	-8.2	-6.6
IS223	15.5.65	"	53 29.4'	5 45.7'	212	431.2	31.8	35.8
	1020							
IS224	1101	"	53 33.2'	5 47.5'	228	427.8	21.9	26.1
IS225	1153	D.L.2	53 38.6'	5 49.0'	209	434.9	22.4	26.3
IS226	1346	"	53 38.7'	6 2.8'	72	423.2	19.9	21.3
IS227	1432	"	53 35.9'	5 54.2'	168	426.1	20.3	23.5

IS228	1510	"	53	31.1'	5	54.5'	137	419.8	23.0	25.6
IS229	17.5.65	"	53	22.2'	5	54.0'	142	380.7	-3.7	-1.1
	0950									
IS230	1015	"	53	23.6'	5	56.0'	87	389.6	7.0	8.6
IS231	1035	"	53	23.9'	5	57.2'	65	395.6	14.0	15.2
IS232	1052	"	53	24.4'	5	58.0'	70	404.2	21.6	22.9
IS233	1132	"	53	25.8'	6	0.0'	75	415.7	30.7	32.1
IS234	1155	"	53	27.5'	6	1.5'	57	417.6	31.4	32.5
IS235	1232	"	53	29.1'	5	55.0'	144	424.5	30.1	32.8
IS236	1352	"	53	28.1'	5	45.0'	210	429.3	31.9	35.9
IS237	1415	"	53	27.0'	5	45.3'	234	425.7	28.3	32.7
IS238	1435	"	53	25.8'	5	45.5'	242	407.0	10.9	15.4
IS239	1457	"	53	24.7'	5	45.1'	244	394.7	-0.1	4.5
IS240	1602	"	53	19.1'	5	40.8'	203	389.6	5.7	9.5
IS241	19.5.65	"	53	13.8'	5	49.3'	79	373.9	5.8	7.3
	0944									
IS242	1025	"	53	14.2'	5	45.8'	151	381.8	8.4	11.2
IS243	1052	"	53	14.1'	5	43.0'	176			
IS244	1132	"	53	13.4'	5	40.0'	206	396.1	20.2	24.0
IS245	1210	"	53	13.4'	5	36.5'	169	399.8	26.4	29.6
IS246	1237	"	53	13.3'	5	32.8'	218	398.1	21.5	25.5
IS247	1334	"	53	8.7'	5	25.8'	259	397.4	24.7	29.5
IS248	20.5.65	D.L.2	53	12.6'	6	3.7'	98	379.9	12.3	14.1
	0815									
IS249	0939	"	53	13.2'	6	2.0'	91	366.9	-1.1	0.6

IS250	1150	D.L.2	53 12.9'	5 59.0'	88	360.1	-7.2	-5.6
IS251	24.5.65	"	53 10.1'	5 59.0'	139	374.5	7.7	10.3
	1050							
IS252	1130	"	53 7.3'	5 57.8'	66	387.4	29.7	30.9
IS253	1210	"	53 5.4'	5 53.0'	113	374.6	16.4	18.5
IS254	1245	"	53 5.0'	5 48.2'	59	363.9	10.0	11.1
IS255	25.5.65	"	53 16.6'	5 52.7'	147	375.0	-1.6	1.2
	0910							
IS256	0945	"	53 17.3'	5 46.0'	97	380.4	6.2	8.0
IS257	1017	"	53 17.5'	5 40.5'	171	389.1	9.6	12.8
IS258	1140	"	53 9.7'	5 35.7'	197	396.4	26.4	30.0
IS259	26.5.65	"	53 8.4'	5 42.7'	144	378.3	13.6	16.3
	0635							
IS260	0705	"	53 9.7'	5 47.0'	105	376.0	12.2	14.1
IS261	0735	"	53 10.7'	5 52.0'	105	369.8	4.6	6.6
IS262	0810	"	53 13.4'	5 52.5'	136	371.9	0.6	3.2
IS263	2.6.65	D.	53 59.5'	4 58.2'	191	467.9	26.4	30.0
	0901							
IS264	0956	"	54 0.3'	5 8.7'	213	471.1	27.1	31.1
IS265	1049	"	54 0.8'	5 19.3'	269	462.8	14.3	19.4
IS266	1103	"	54 0.0'	5 36.5'	259	464.3	17.8	22.6
IS267	1252	"	53 59.8'	5 48.5'	135	466.3	28.5	31.1
IS268	1402	"	54 6.6'	5 43.2'	86	471.8	27.6	29.2
IS269	1454	"	54 7.0'	5 32.2'	180	478.0	26.8	30.2
IS270	1539	"	54 6.7'	5 22.7'	208	465.6	12.9	16.8
IS271	1700	"	54 5.5'	5 2.2'	213	473.0	21.6	25.6

IS272	3.6.65	D.	54 6.5'	3 59.7'	106	459.2	13.6	15.6
	0959							
IS273	4.6.65	"	54 6.1'	4 0.5'	111	463.9	18.5	20.6
	1033							
IS274	1055	"	54 6.9'	3 58.7'	94	453.3	7.9	9.6
IS275	1130	"	54 7.6'	3 57.0'	90	450.3	4.3	6.0
IS276	1259	"	54 8.6'	4 56.0'	88	449.1	1.9	3.6
IS277	1414	"	54 14.5'	3 54.2'	53	455.2	1.8	2.8
IS278	1445	"	54 16.1'	3 57.7'	62	463.8	7.4	8.6
IS279	5.6.65	"	54 20.5'	4 10.1'	48	496.8	35.0	35.9
	0929							
IS280	1000	"	54 19.4'	4 6.5'	73	498.2	36.3	37.7
IS281	1018	"	54 19.0'	4 5.5'	67	495.8	34.9	36.2
IS282	1035	"	54 18.2'	4 3.7'	59	480.3	21.0	22.1
IS283	1050	"	54 17.6'	4 2.2'	58	472.4	14.1	15.2
IS284	1108	"	54 16.9'	4 0.5'	64	468.8	11.1	12.3
IS285	1152	"	54 15.2'	3 55.8'	55	458.8	4.3	5.3
IS286	1225	"	54 13.7'	3 52.7'	73	452.9	-0.7	0.6
IS287	1243	"	54 13.0'	3 50.7'	76	449.6	-3.1	-1.7
IS288	1304	"	54 12.1'	3 48.5'	80	446.7	-5.1	-3.6
IS289	6.6.65	"	53 51.1'	4 24.2'	191	447.8	18.4	22.0
	1030							
IS290	1056	"	53 50.0'	4 27.0'	216	449.9	20.5	24.5
IS291	1129	"	53 49.0'	4 30.0'	206	450.8	23.5	27.3

IS292	1153	D.	53 48.4'	4 32.3'	199	451.9	26.0	29.7
IS293	1220	"	53 47.2'	4 34.7'	184	451.4	28.1	31.6
IS294	1300	"	53 46.7'	4 36.5'	200	451.3	27.7	31.4
IS295	7.6.65	"	54 10.9'	4 57.5'	272	483.9	20.7	25.8
	1137							
IS296	1200	"	54 10.2'	4 55.7'	261	483.7	22.2	27.1
IS297	1221	"	54 9.7'	4 54.5'	228	481.7	23.1	27.4
IS298	1241	"	54 9.4'	4 53.0'	178	479.9	25.2	28.6
IS299	1303	"	54 8.5'	4 51.5'	128	475.1	25.2	27.6
IS300	1323	"	54 7.9'	4 50.2'	120	472.8	24.2	26.4
IS301	1341	"	54 7.3'	4 49.2'	119	474.8	27.1	29.3
IS302	1403	"	54 6.6'	4 47.5'	116	472.3	26.0	28.1
IS303	10.6.65	"	54 45.5'	3 22.0'	74	435.0	21.8	23.2
	1215							
IS304	1304	"	53 44.4'	3 12.2'	49	425.5	15.6	16.5
IS305	1345	"	53 38.8'	3 13.0'	49	415.3	13.3	14.2
IS306	1425	"	53 38.6'	3 23.0'	82	422.6	18.6	20.1
IS307	1508	"	53 38.0'	3 33.5'	102	421.4	17.0	18.9
IS308	1549	"	53 37.3'	3 42.5'	116	424.8	20.4	22.6
IS309	1643	"	53 36.7'	3 54.2'	143	418.9	13.4	16.1
IS310	13.6.65	D.-H.	53 36.6'	4 30.8'	202	433.4	24.3	28.1
	1306							

APPENDIX 2.

The following pages contain drawings, not to scale, of the Base Positions in the different harbours. The values of gravity are expressed as a difference in milligals relative to Pendulum House Cambridge.

DUN LAOGHAIRE NO. 1

YACHT CLUB

YACHT BASIN

STEPS

ST. MICHAEL'S QUAY

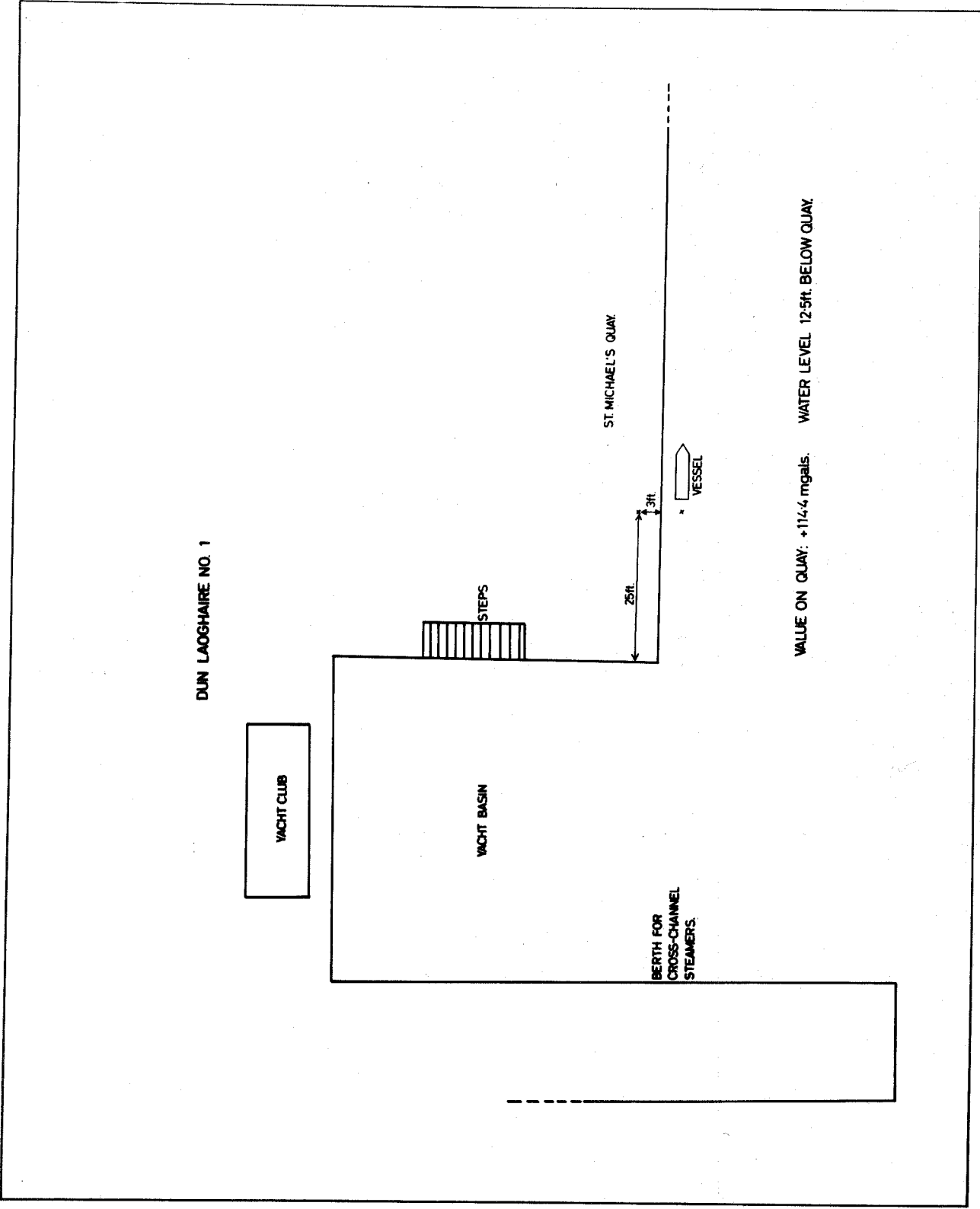
25ft.

3ft.

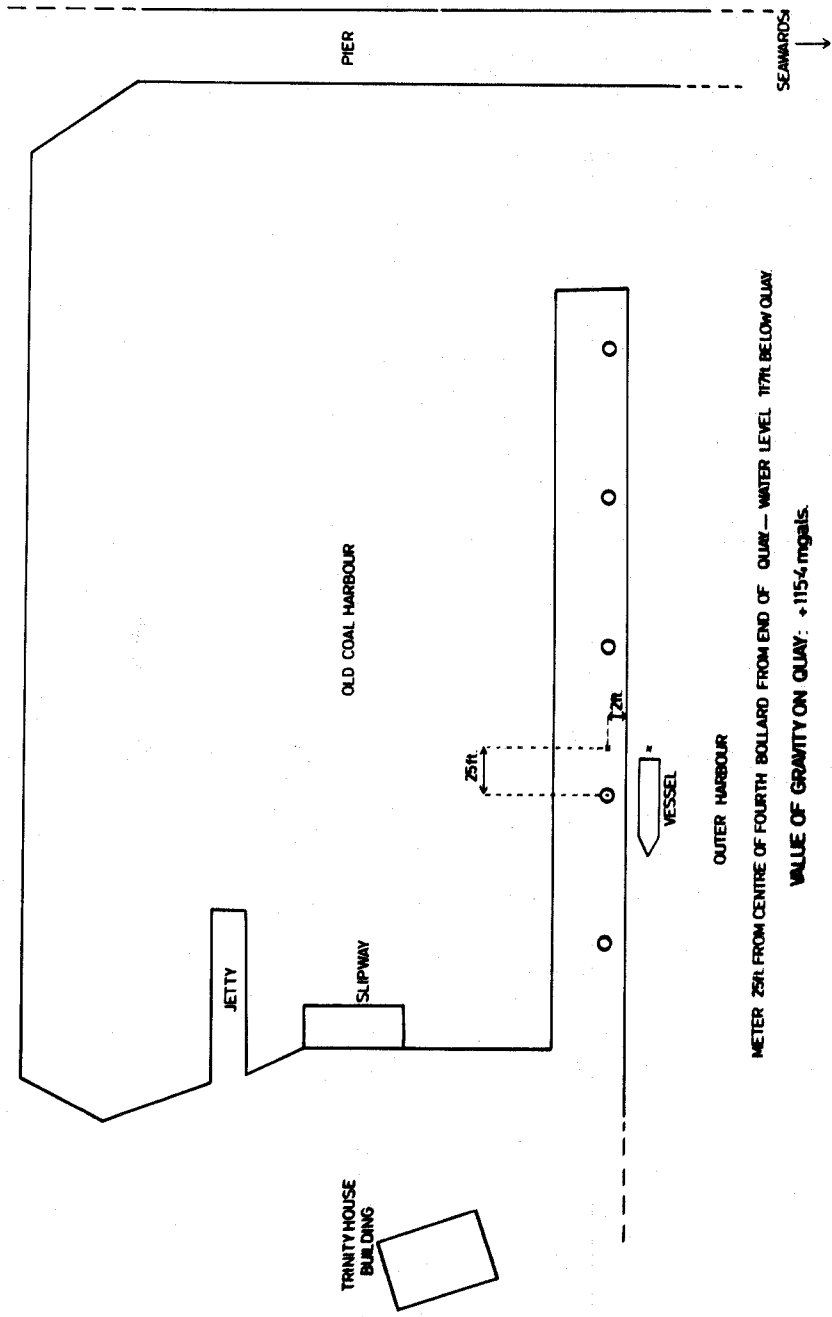
VESSEL

BERTH FOR
CROSS-CHANNEL
STEAMERS.

VALUE ON QUAY: +114/4 mgals. WATER LEVEL 12.5ft. BELOW QUAY.



DUN LAOGHAIRE NO. 2



TRINITY HOUSE BUILDING

JETTY

SLIPWAY

OLD COAL HARBOUR

PIER

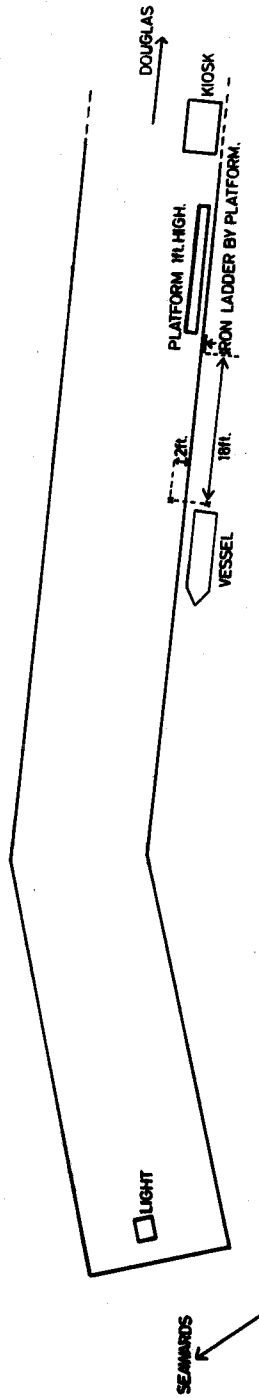
SEAWARDS

VESSEL

OUTER HARBOUR

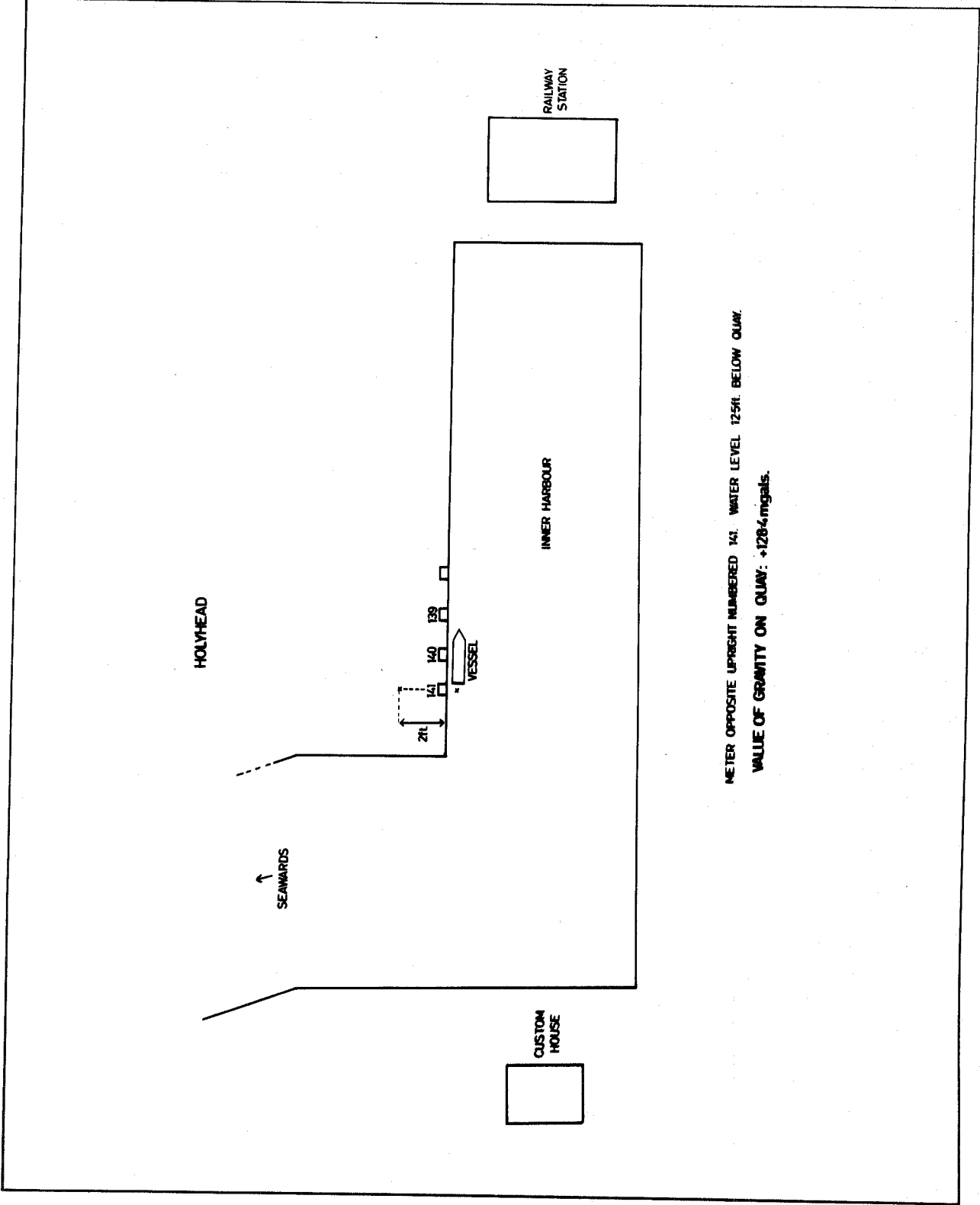
METER 25M FROM CENTRE OF FOURTH BOLLARD FROM END OF QUAY - WATER LEVEL 177M BELOW QUAY.
VALUE OF GRAVITY ON QUAY: +115.4 mgals.

DOUGLAS, ISLE OF MAN



MOORED TO BREAKWATER ON SOUTH SIDE OF HARBOUR.

VALUE ON QUAY: +213.6 mgals. WATER LEVEL 10.5ft. BELOW QUAY.



METER OPPOSITE UPRIGHT NUMBERED 141. WATER LEVEL 125ft. BELOW QUAY.
VALUE OF GRAVITY ON QUAY: +128.4 mgals.

APPENDIX 3.

Plates 5 and 6 illustrate the internal arrangement of the gravimeter. The outer coil of the beam displacement transducer referred to on page 39 can be seen in the middle foreground of Plate 5.

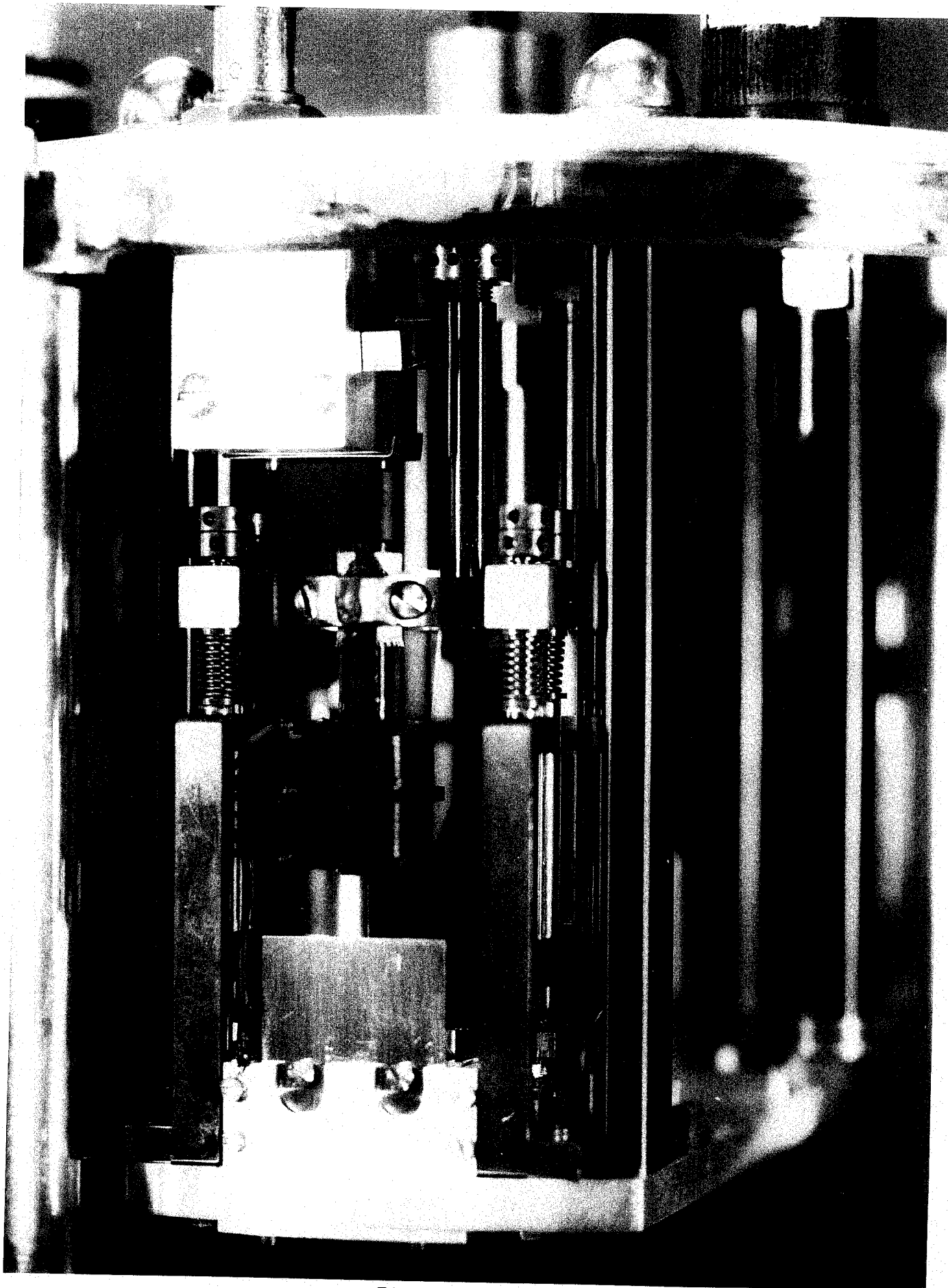


PLATE 5

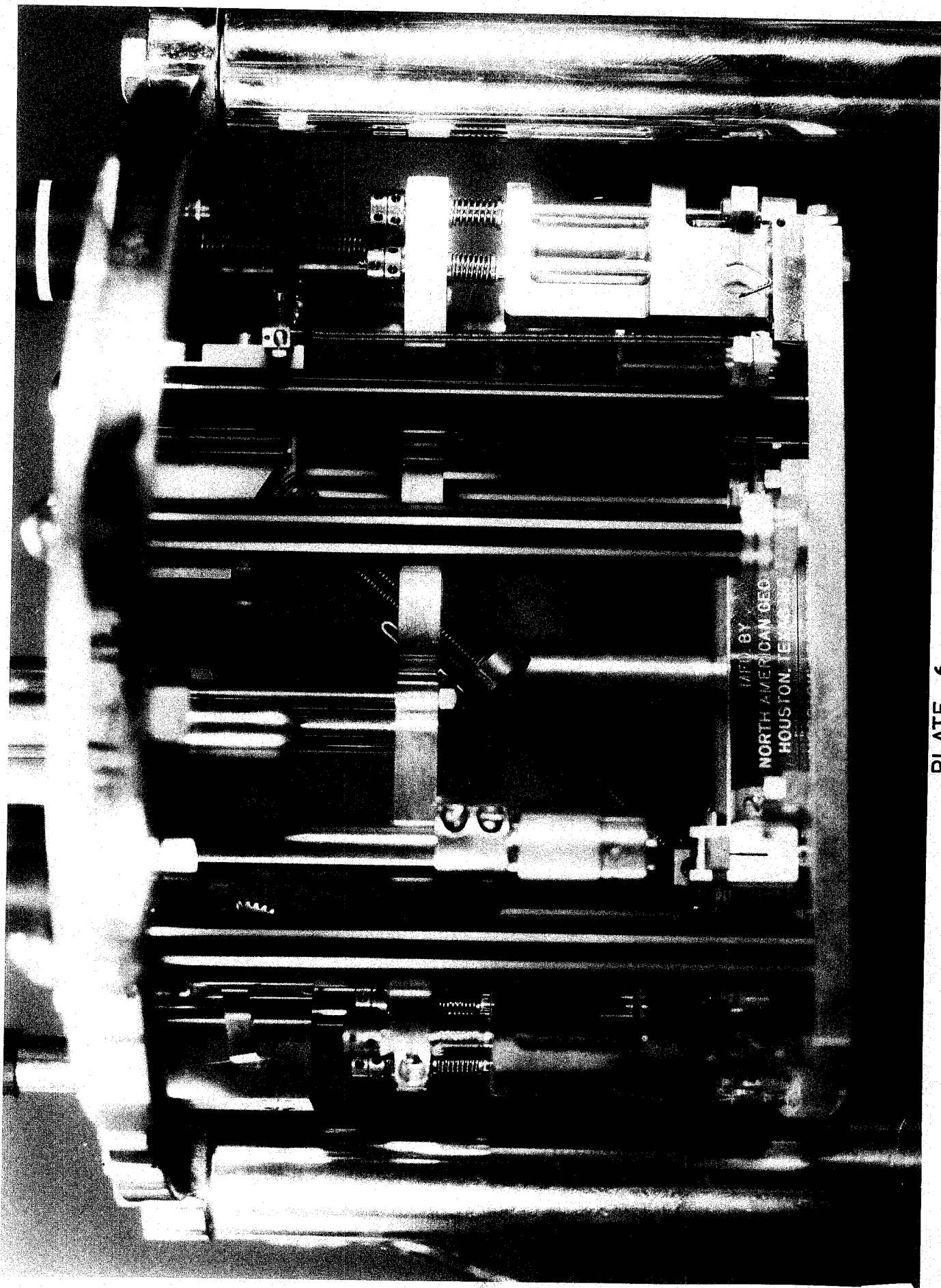
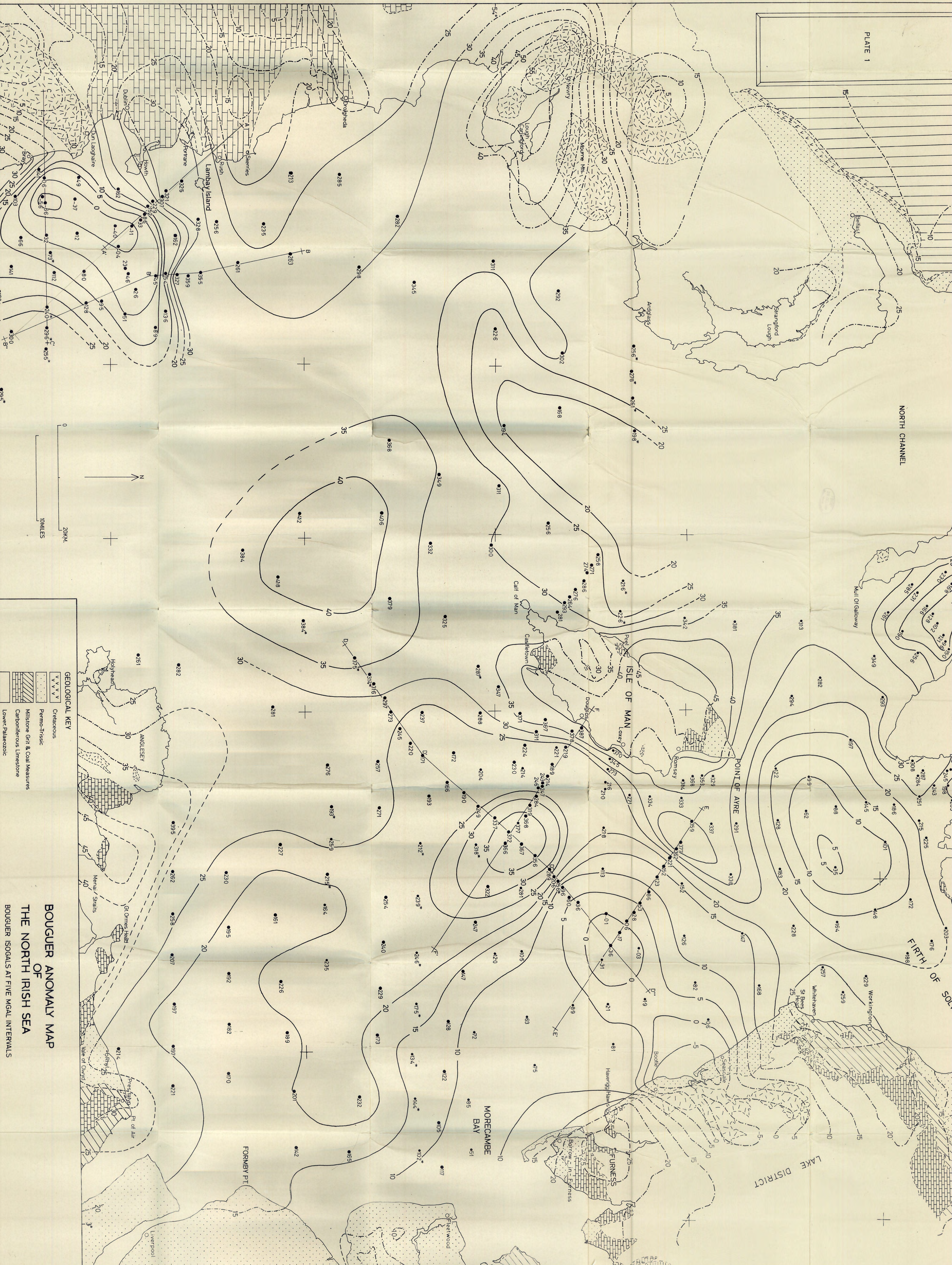


PLATE 6



NORTH CHANNEL

FIRTH OF SOL

LAKE DISTRICT

FURNESS

MORECAMBE BAY

FORMBY PT

LIVERPOOL

LAKE DISTRICT

FURNESS

MORECAMBE BAY

FORMBY PT

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