INSTITIÚID ÁRD-LÉINN BHAILE ÁTHA CLIATH
SCOIL NA FISICE COSMAÍ

Dublin Institute for Advanced Studies
SCHOOL OF COSMIC PHYSICS

GEOPHYSICAL MEMOIRS NO. 2, PART 2

# MEASUREMENTS OF GRAVITY IN IRELAND

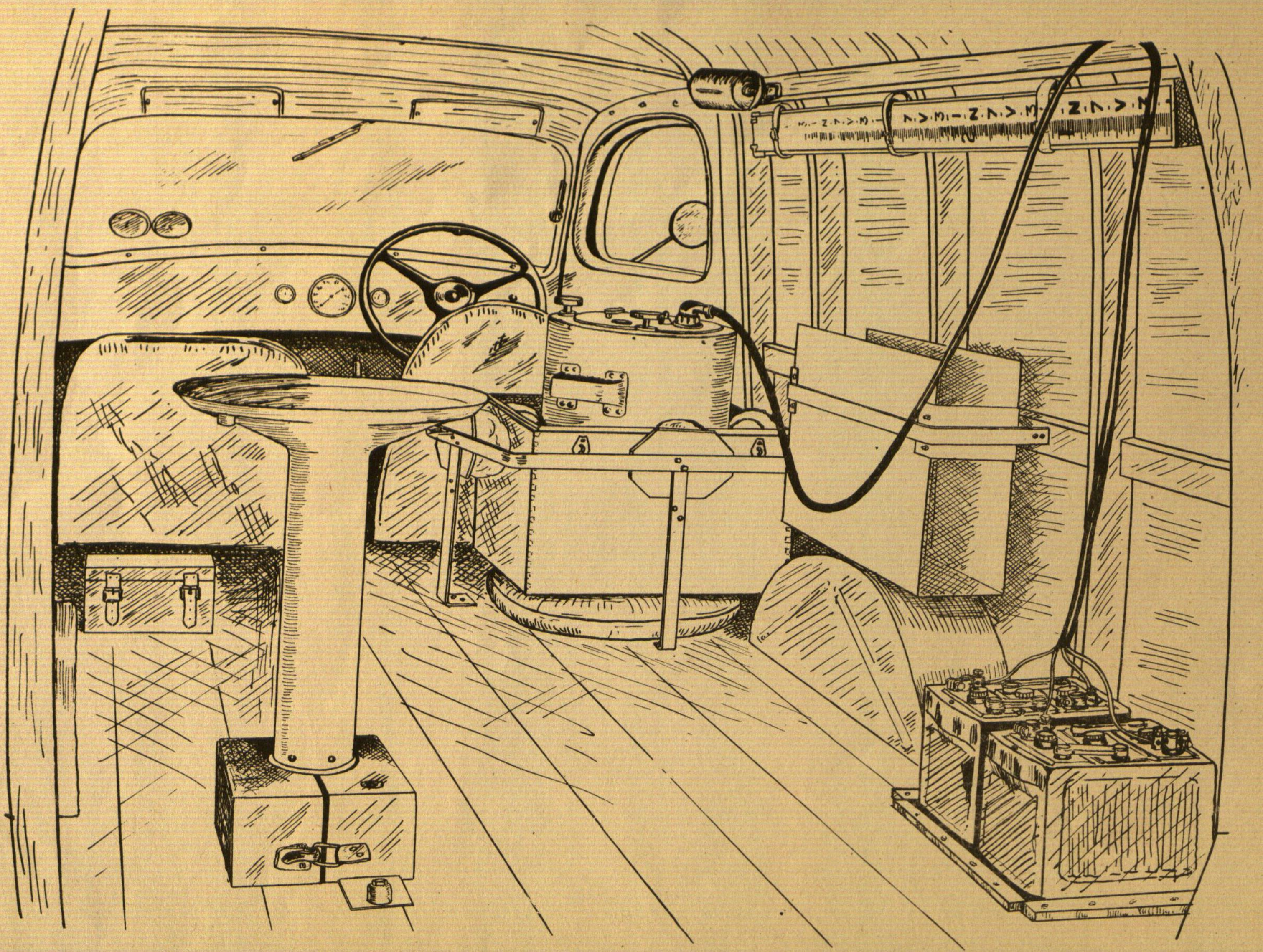
## GRAVIMETER OBSERVATIONS
BETWEEN
## DUBLIN, SLIGO, GALWAY AND CORK

BY

H. I. S. THIRLAWAY

DUBLIN
1951

Price: 12s. 6d.



Layout of Gravimeter Equipment in Motor Van

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# CONTENTS

# PREFACE

This memoir describes the gravimeter measurements made in Ireland by the author during the summer of 1949 when Dr. A. H. Cook and he were invited to make a gravity survey in that country. At that time they were both members of the Department of Geodesy and Geophysics at Cambridge University, and Mr. B. C. Browne initiated the arrangements which made the survey possible.

The assistance accorded by individuals and institutions in Ireland, to the work described in the following pages, was given in " good measure pressed down and overflowing ".

The gravimeter observations over such a large section of the country could not have been made in the time available without the co-operation of Mr. T. Murphy of the School of Cosmic Physics, Dublin with whom the field work was carried out. From him the author learned much of the detailed geology of the areas traversed and was guided in his selection of stations. In particular, the readings on the Avoca mineralised belt were made on Mr. Murphy's suggestion.

Mr. D. W. Bishopp, Director of the Geological Survey of the Department of Industry and Commerce and his staff met every request and went out of their way to clear administrative difficulties as they arose, Mr. M. A. Cunningham of this Survey helped with transport and also pointed out the interest of the Trias exposure at Kingscourt. He gave further valuable assistance by arranging for the station positions to be duplicated on 6 inch maps.

The Ordnance Survey of Ireland supplied all the maps used throughout the survey and determined the co-ordinates of all the Pendulum and Gravimeter stations.

To Professor L. W. Pollak, Director of the School of Cosmic Physics, we owe special thanks for his general direction of the work, for arranging for the publication of this paper and for inviting the author to deliver the substance of it to a special meeting of the Dublin Meteorological and Geophysical Seminar held at the School on the 30th June, 1949. The School also met the cost of all field expenses.

Finally we are indebted to Professor H. A. Brück, Director of Dunsink Observatory; the President and Physics staffs of University College, Galway and of University College, Cork; and the County Council of Sligo, for placing at our disposal rooms required for the Pendulum observations and for use as headquarters. In each case preliminary arrangements were made which enabled the observations to be commenced immediately, thus materially assisting in completing the whole programme.

The author was able to take part in this Survey by virtue of a maintenance grant from the British Ministry of Education.

H. I. S. Thirlaway,

*February*, 1950

Department of Geology,
The University,
Sydney, N.S.W.,
Australia

## ABSTRACT

Results of gravity observations made between pendulum stations at Dublin, Sligo, Galway and Cork are described, together with a regional gravity survey of the province of Leinster and a small area centered on Kingscourt, County Cavan. A Graf (Askania) gravimeter was used and stations were observed at 4 to 8 mile intervals. The standard deviation of a single observation was estimated to be $\pm 0.29$ mgal.

Results are presented as Bouguer anomalies and the single traverses between the pendulum stations show regional trends of amplitude up to 20 mgals. due to anomalous masses at great depth. Elimination of these trends reveals anomaly variations due to structural features in the Lower Palaeozoic rocks which are covered uncomformably by gently dipping Carboniferous Limestone. A broad region of low anomalies coincides with thick Devonian sediments which were folded during the Armorican orogeny.

Equal anomaly lines over the Leinster granite " batholith " locate the probable focus of intrusion and suggest that the granite thins out from the source. Relatively low anomalies over the granite are in common with those over the Galway and Carnsore Point granites and with observations over granite masses in other parts of the world.

Observations on the Trias rocks of Cavan provide further confirmation of the well known geology of the area.

Attention is drawn to anomalies of over 40 mgals. on the coasts of the Irish Channel and the possibility of determining the structure of the Channel is briefly discussed.

## I. INTRODUCTION

The gravimeter traverse lines were planned with several objects in view. In the first place, the well marked geological strike of the country required that the traverse should be made across the strike. (See *Fig.* 2). In the North the dominant geological line is Northeast-Southwest, the Caledonian direction. The rocks are of Lower Palaeozoic age, and are the eroded remains of the Caledonian mountain system which involved the ancient geosynclinal areas of Wales, Ireland, the English Lake District, and the Southern Uplands of Scotland. The main mass of Devonian rocks lies South of a line drawn from Tralee to Waterford, and their East-West fold lines are of American age. In the Central Plain of Ireland the Lower Palaeozoic rocks are covered by the Carboniferous Limestone series, with a maximum thickness of about 3000 ft. These rocks are generally flat and lie uncomformably on the folded Lower Palaeozoics, whose structure they effectively conceal. The gravimeter traverses were planned to cross all the geological features outlined above.

The second factor which determined the siting of the gravimeter stations, was the unexpectedly high anomalies observed as the Welsh coast was approached from Devil's Bridge to Aberystwyth. (Cook and Thirlaway, 1949). No explanation has been offered to account for this rise to 35 mgals. at the coast, and the matter is further complicated by a Bouguer anomaly of –37 mgals. observed by Browne and Cooper (1949) in the Irish Channel at position 52° 28′ North, 5° 14′ West.

A regional survey of the East coast between Dublin and Wexford was therefore planned, and this was extended West to cover the Leinster granite. Granite masses in other parts of the world are known to give rise to large negative anomalies, as for example the granites of S.W. England (Bullard and Jolly, 1936).

In the following sections, an outline of the field procedure and determination of the anomalies, is followed by a detailed account of the anomalies together with a tentative interpretation of the results.

## II. THE METHOD AND ERRORS OF MEASUREMENT

### 2.1. Field Equipment

The gravimeter measurements were made with one of the small Graf instruments manufactured by Askania Werke, Berlin belonging to the Department of Geodesy and Geophysics, Cambridge. It has been described by Graf (1942).

A ten hundredweight Fordson van was used to carry the equipment as shown in the *Frontispiece*. As gravimeter springs are susceptible to vibration, care must be taken when travelling that the gravimeter is not subjected to shocks. In this survey the gravimeter in its case rode in the vehicle on " Dunlopillo " foam rubber cushions, balanced by a brass framework padded with rubber sponges. This arrangement was found very satisfactory for damping and absorbing vibrations in the moving vehicle.

On the left in the *Frontispiece* can be seen the quick levelling tripod, mounted through a small hole in the floor of the vehicle. Before measuring, this stand was unclamped, lowered to the road, and roughly levelled. The gravimeter was then placed on the top plate and accurately levelled by means of its own levelling screws. Five minutes at each station was sufficient to complete a single measurement.

The rest of the equipment consisted of two six volt car batteries for the heating and measuring circuits of the gravimeter, and a level and staff. Levelling was necessary to determine the station height from a nearby benchmark. Very little time was spent on this part of the work, as it was nearly always possible to select a position near enough to a bench mark or surface level to be able to estimate the height of the gravimeter by eye to 0·5 ft.

Station positions were selected from, and plotted on maps, scale six inches to one mile. Subsequently the Ordnance Survey of Ireland determined the co-ordinates of each station. Details of each position, height, and gravity result were entered on index cards. On the reverse of the cards, a sketch was made showing the precise position of each station. A station index map on the scale of 16 miles to one inch was also prepared. Some indexing system of this sort is essential, as the gravity survey of the country will result eventually in the occupation of many thousands of stations.

The original maps and index cards are kept at the Department of Geodesy and Geophysics, Cambridge University and there are copies of these at the School of Cosmic Physics, Dublin. A third copy of the positions of the stations on a series of " six-inch " maps are kept at the Ordnance Survey Office, Phoenix Park, Dublin.

*Fig.* 1 shows the extent of the present survey. A total of 137 gravity stations were measured.

### 2.2. Field Procedure

All gravimeters suffer from the disadvantage that the reading changes with time. This is due primarily to the plastic change, under load, of the materials from which the springs are fabricated, and at ordinary temperatures is only noticed when measurements of a high order of accuracy are attempted. If the beam is left unclamped, the drift rate of this gravimeter is 0·05 mgal/hr.

In order to determine this change and eliminate it from the results, the drift rate is determined by measuring twice at the base station. If the drift is due only to plastic changes, then it should be very nearly constant throughout a day's reading, and only the base station need be repeated. In practice the drift of the gravimeter used was not always constant, so each station measured on the outward journey was repeated on the return. When the drift was found to be constant in a particular day (within ±0·1 mgal./hr.), then it was sufficient to determine the base reading at each station by a straightforward graphical method. On many days, however, the rate varied up to a maximum of between −0·1 mgal/hr., and +0·4 mgal/hr. and on these days a representative drift rate (*d*) was determined from the relation

$$d.\Sigma(\Delta t)^2 = \Sigma\Delta t.\Delta r$$

where $\Delta r$ is the difference between the readings observed at each station where measurements were made at two different times separated by the interval $\Delta t$.

*Table* 1 shows how the drift was eliminated, and the differences of gravity found for a few stations based on Cork. In this case $\Sigma(\Delta t)^2$ for the full day was 275·4, and $\Sigma\Delta t.\Delta r$ was 156·7, so that $d=0{\cdot}57$ scale divs./hr. =0·04 mgal/hr.

### 2.3. Errors

Surveys with the gravimeter in England have shown a correlation between the standard deviation of a single observation, as determined from the residuals from the mean of the repeated observations, and the time interval between the base measurements. For time intervals of less than one hour, the standard deviation is estimated as ±0·13 mgal.; from one to two hours at ±0·18 mgal.; and from two to three hours at ±0·25 mgal. Since the maximum instrumental error is estimated to be 0·17 mgal., it appeared that the large residuals associated with the longer time interval were due to random and systematic variations in the drift rate.

The survey in Ireland was designed to cover a large area of the country in order to obtain a general idea of the gravity field for guidance in future work and, since the time available was short, this meant that the base station checks had to be made at much larger intervals. On the other hand, an accuracy of about 0·25 mgal. was desirable. Before the survey started, therefore, an effort was made to determine the causes of drift variation. An obvious cause was excessive vibration, and some of the undesirable drift characteristics were removed by using the damping arrangement already described. Other variations were traced to the fact that the gravimeter beam, when clamped, was not fixed in its null or reading position. The clamping pins were adjusted just before travelling to Ireland to rectify this defect.

The average time interval between base readings in Ireland was 8 to 9 hours, and the standard deviation of a single observation is estimated to be ±0·29 mgal. The average drift rate was +0·15 mgal/hr. It is believed that drift variations due to vibrations and incorrect clamping have now been eliminated. A study of drift rates found during this survey has exposed a further source of error, due to changes in ambient temperature affecting the thermostat chamber. The temperature coefficient of Young's Modulus

TABLE 1

EXTRACT FROM CORK-WEXFORD LINE RECORD

3 April 1949

Calibration factor : 1 scale division = 0·06387 mgal.*

| Station Number | Time | Scale | Scale at base | Station -base | *g*-base | Residual |
|---|---|---|---|---|---|---|
| | hr. | divs. | | divs. | mgals. | mgals. |
| 1403 | Out 1030 | 2655·0 | 2649·7 | | | ±0·34 |
| Cork | In 1906 | 2649·3 | 2654·7 | | | |
| 1413 | Out 1106 | 2677·4 | 2650·1 | 27·3 | + 1·69 | ±0·07 |
| | In 1838 | 2680·0 | 2654·4 | 25·6 | | |
| 1414 | Out 1132 | 2791·7 | 2650·3 | 141·4 | + 9·01 | ±0·03 |
| | In 1819 | 2795·0 | 2654·2 | 140·8 | | |
| 1415 | Out 1152 | 2840·7 | 2650·5 | 190·2 | +12·03 | ±0·12 |
| | In 1800 | 2850·7 | 2654·0 | 186·7 | | |
| 1416 | Out 1217 | 2941·7 | 2650·7 | 291·9 | +18·78 | ±0·19 |
| | In 1737 | 2950·0 | 2653·9 | 296·9 | | |

* The extension/load characteristic of the measuring spring is not exactly linear, so the calibration factor varies with the total attraction of gravity. To determine a calibration factor at any place, the instrument is provided with a known mass which can take up one of two positions on the moving beam. (See COOK, A.H., *M.N.R.A.S.* Geoph. Suppl. **6**, pp. 13-14). Observations in Ireland over half the total range of the measusing spring showed an increase of 0·00151 mgal./scale division for every increase of 100 scale divisions. Preliminary reductions were made using four calibration factors appropriate to the scale position. Later reductions, using twice this number significantly reduced closure errors. This accounts for the small changes between the observed differences in *Fig.* 3 and those on p. 22, Pt. 1 of this *Memoir.*

of the gravimeter mainspring is about $+3\times10^{-6}$/°C., and a rise in room temperature of 5°C. was observed to cause a change of about +0·5 mgal. after allowing for normal drift. The time constant of the lagging is 1 to 2 hours. Such changes will easily account for the difference between the instrumental error and the errors observed in Ireland. Errors from this source can be eliminated by close control at a base station. This is illustrated by the Kingscourt survey when the base station was visited at time intervals of about 1 hour ; the standard deviation was ±0·12 mgal. For rapid regional surveys however, the ideal method is to visit the base station at the beginning and end of the day only, and the accuracy and speed of future surveys in Ireland with this gravimeter may be improved, either by constructing a second thermostat with a ±1° C. control, or by making temperature corrections.

*Fig.* 3 shows that the gravimeter connections between the pendulum stations have an estimated accuracy of about ±0·5 mgal. The overall mean closure error over a road distance of about 600 miles is 1·70 mgals., while that of the two smaller loops is 0·23 mgal., and 0·69 mgal. over road distances of 150 miles and 142 miles respectively. The two latter closures are comparable to those obtained in the English Midlands, where a network of loops averaging 50 road miles each connect Cambridge to Worcester.

## III. GRAVITY ANOMALIES AND THEIR INTERPRETATION

### 3.1. THE GRAVIMETER DIFFERENCES

The Appendix to this paper gives details of each station. In this table, the adjusted pendulum and gravimeter differences from Pendulum House, Cambridge, at Dublin, Sligo, Galway and Cork have been used (see Part 1 of this *Memoir*) and the error distributed between the intervening stations.

*Table* 2 shows the height corrections required to convert the adjusted values to the gravimeter station, and compares the resultant with the adjusted gravimeter differences alone. This adjustment was made by distributing the closure error of the three polygons in the ratio of the standard deviations of the differences.

TABLE 2

ADJUSTED GRAVITY DIFFERENCES FROM CAMBRIDGE AT PENDULUM STATION CORRECTED TO GRAVIMETER STATION

| Station | Adjusted pendulum and gravimeter value | Height correction | Pendulum and gravimeter at gravimeter position | Gravimeter results alone | Difference $P-G$ |
|---|---|---|---|---|---|
| | mgals. | mgals. | mgals. | mgals. | mgals. |
| Dublin | 120·84±0·56 | −0·4 (actual − 0·38) | 120·4 | 120·4 (assumed) | — |
| Sligo | 197·3 ±0·82 | +0·2 | 197·5 | 197·9 | −0·4 |
| Galway | 96·9 ±0·64 | −0·1 (actual −0·5) | 96·8 | 97·5 | −0·7 |
| Cork | −22·5 ±0·87 | +0·1 | −22·4 | −21·5 | −0·9 |

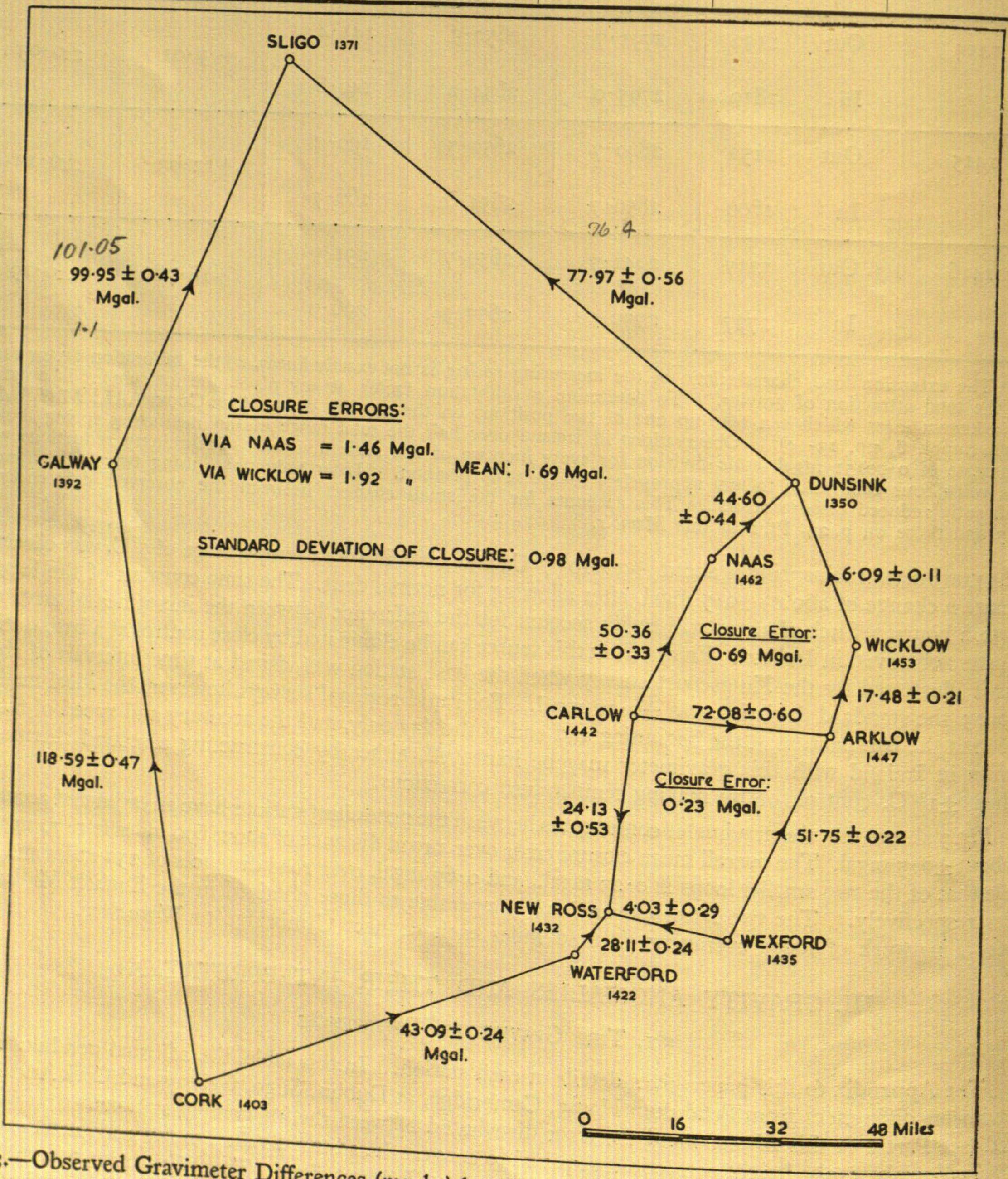


*Fig.* 3.—Observed Gravimeter Differences (mgals.) between Base Stations and Closure Errors of Polygons (Arrow heads point to the larger values of gravity)

1350 − 1392

1) Sligo 21·98

2) Cork + Carlow 23·44

### 3.2. The Bouguer Anomaly

In this paper the results are presented as Bouguer gravity anomalies. The term is ambiguous as it covers the result of correcting values of gravity in a number of different ways ; therefore a short explanation of the determination of the anomaly is given.

In free air the rate of change of gravity with height can be shown to be very nearly 0·09406 mgal./ft. in these latitudes. This rate is modified in practice by the presence of rock between the observer and the surface of reference, in this case mean sea level. It is very nearly correct to assume that this rock mass is in the form of an infinite slab. Only at very high altitudes does the curvature correction become significant, and only in rugged country does the topographic corrections modify the regional field.

Wrong. nearer 0·09403

The gravitational attraction of an infinite slab is given by :

$$\Delta g = 2\pi f \varrho h \text{ mgals.} = 0\cdot01277\varrho h \text{ mgals.} \qquad \ldots(1)$$

where $f$ is the gravitational constant, $\varrho$ the mean density of the slab, and $h$ its thickness (height above mean sea level).

Using Heyl's value of $6\cdot670 \times 10^{-8}$ for $f$, and a rock density of 2·67 grams/cm³ (the assumed average value for the crustal rocks), the gradient due to the rocks is $-0\cdot03409$ mgal./ft. This is modified by the free air gradient to give an actual gradient of 0·05997 mgal./ft. A density of 2·67 grams for the outcropping rocks has been assumed throughout this work except in the more detailed study in the Kingscourt area. There is little point in using more accurate estimates until the gravity field is known in much greater detail.

A correction to the observed gravity values for change in latitude is also necessary. The gradient in these latitudes due to the figure of the earth is about $+1\cdot2$ mgals./mile North. The reference station for the gravity differences was the pendulum station at Pendulum House, Cambridge. A correction table giving the value " Observed gravity at Pendulum House ($g_{P.H.}$) minus normal gravity at latitude of the station ($\gamma_0$)" enabled this correction to be applied. The values of normal gravity were obtained from tables based on the International Gravity Formula (The U.S. Coast and Geodetic Survey, 1942). For future surveys it will be more convenient to use Dunsink as the reference station.

Topographic corrections are required when sharp hill and valley features in the vicinity of the station modify the assumption of an infinite slab. In Ireland these corrections are rarely required since, as the effect falls off rapidly away from the feature, the stations can usually be sited in more suitable places without seriously modifying the station distribution. Only stations 1426 and 1428 situated in the Kerry mountains require topographic correction, but these are estimated to be not more than 1 mgal.

The Bouguer anomaly as used in the following results has therefore been derived as follows :

$$\text{Anomaly} = g_{Station} - g_{P.H.} + h(0\cdot09406 - 0\cdot01277\varrho) + (g_{P.H.} - \gamma_0) \text{ mgals.}$$

The errors which may be committed in the estimation of this anomaly, apart from the errors of the observed gravity already discussed, arise from the estimation of height, latitude, and density of the rocks between the station and sea level. Heights were estimated from bench marks and surface levels and are corrected to Irish mean sea level (See Dixon, 1949). They are probably correct to 1·0 ft. or 0·06 mgal.

Latitudes were determined by transferring the stations from the " six inch " to the " inch " sheets and the Ordnance Survey of Ireland estimate that they are correct to ±2″ of arc, or less than ±0·1 mgal. Rock densities over the greater part of the area covered are believed to be within the limits 2·6 to 2·8 grams/cm³. By using an overall density of 2·67 grams/cm³, the maximum error for the few stations at elevations of about 1000 ft. is nearly 1 mgal. The only stations above the 1000 ft. contour are situated on the Leinster granite and the Devonian of Kerry and the densities of these rocks are probably very close to 2·67 grams per cm³. The great majority of the stations are below 500 ft., so that the error arising from the use of incorrect densities is less than 0·4 mgal. This error can be reduced when required by taking into account the observed densities of the surface rocks.

### 3.3. Interpretation Methods

While the Bouguer anomaly error caused by using incorrect densities cannot be very great in areas of relatively low elevation, the inaccuracy of the interpretation of these anomalies in terms of geological structure below sea level is more serious, since many thousands of feet of rock are involved.

The variation of the observed anomalies show that the rock densities do in fact vary and in order to attempt an interpretation of these variations, certain density values have been assumed. These values are, for the most part, based on measurements and experience in the rocks of the West Midlands of England, and Central Wales. Only the Leinster granite density is based on a laboratory estimation.

TABLE 3

ASSUMED DENSITY OF IRISH ROCKS

| Rocks | Density |
|---|---|
| | grams/cm$^3$ |
| Trias | 2·4 |
| Carboniferous Limestone | 2·7 |
| Devonian (O.R.S.) | 2·6 |
| Silurian | 2·8 |
| Granite | 2·6 |

The density relations are probably nearly correct in general, but may not be so in detail. For example, it will be seen later that some of the interpretation depends on the assumption that the Devonian rocks are less dense than both the Carboniferous Limestone and the Silurian rocks, as they are in the Welsh Borders. This assumption requires experimental verification.

Apart from the uncertainty of the rock densities, the interpretation of this survey can only be of a general and qualitative nature, as the station density is insufficient to give more precise results. Estimates of variation in thickness are based on the infinite slab assumption already discussed (see equation 1). Certain depth estimations have been made by assuming the buried mass to approximate the shape of a long cylinder. NETTLETON (1940) has summarised the theoretical gravity fields due to this and other simple shapes.

## IV. INTERPRETATION OF RESULTS

### 4.1. GENERAL DESCRIPTION OF THE GRAVITY FIELD

A map showing the lines of equal Bouguer anomaly is given in *Fig.* 2. The anomaly map will be altered in detail as more measurements are made but the results are sufficient to show the regional anomaly field on the East, and to give a rough indication of the anomalies which may be expected over the rest of the area.

The outstanding feature of the gravity field, as far as it is known is the fall of anomaly (2·3 mgals. per mile) from the East coast to the Leinster granite. The lines of equal anomaly are closely parallel to the geological strike in this area.

Over the Leinster and Galway granites, the Central Plain west of Dublin, and the Devonian rocks of Cork and Kerry, the anomalies are low relative to the rest of the field and are either negative or very nearly zero. The Lower Palaeozoic rocks in the East and in the vicinity of Carrickmacross, the area just South and South-east of Sligo, and South of Galway are the high anomaly areas. The anomalies on the East coast, however, reach values nearly twice those of any other observations.

In general the lines of equal anomaly follow the geological strike Northeast-Southwest in the North, where the Caledonian folding predominates and East-West over the Amorican folding of the South. There may be some deviation from this agreement over the Carboniferous Limestone plain East of Dublin, where there is a suspicion of an East-West trend. Further observations are required to determine this point.

The gravity anomalies observed are due to anomalous density distributions between sea level and some depth below which the material of the earth is homogeneous over a large area. Gravity observations all over the world, in the main, support the idea that the topographical irregularities of the earth's surface are isostatically compensated in depth, either at different levels by a homogeneous layer of high density (Airy's hypothesis) or at one level by a corresponding density variation in the supported column (Pratt's hypothesis).

It is unlikely that the depth of compensation can be unique, but it appears to be somewhere between 20 kms. and 100 kms., and is almost certainly influenced from place to place by the varying degree to which the strength of the crust contributes to the support of its own irregularities. Curves in *Figs.* 7*a* and 8*a* show the corrections which must be applied to the curve of the Bouguer anomaly variations in order to obtain the isostatic anomalies. This correction is based on figures for the contribution by compensation calculated at the Department of Geodesy and Geophysics, Cambridge, assuming a depth of compensation of 30 kms. and a regionality of 56 kms. (MEINESZ, 1941). If perfect equilibrium exists, and all geological factors are included in the gravity reductions, then the anomalies would be very nearly zero.

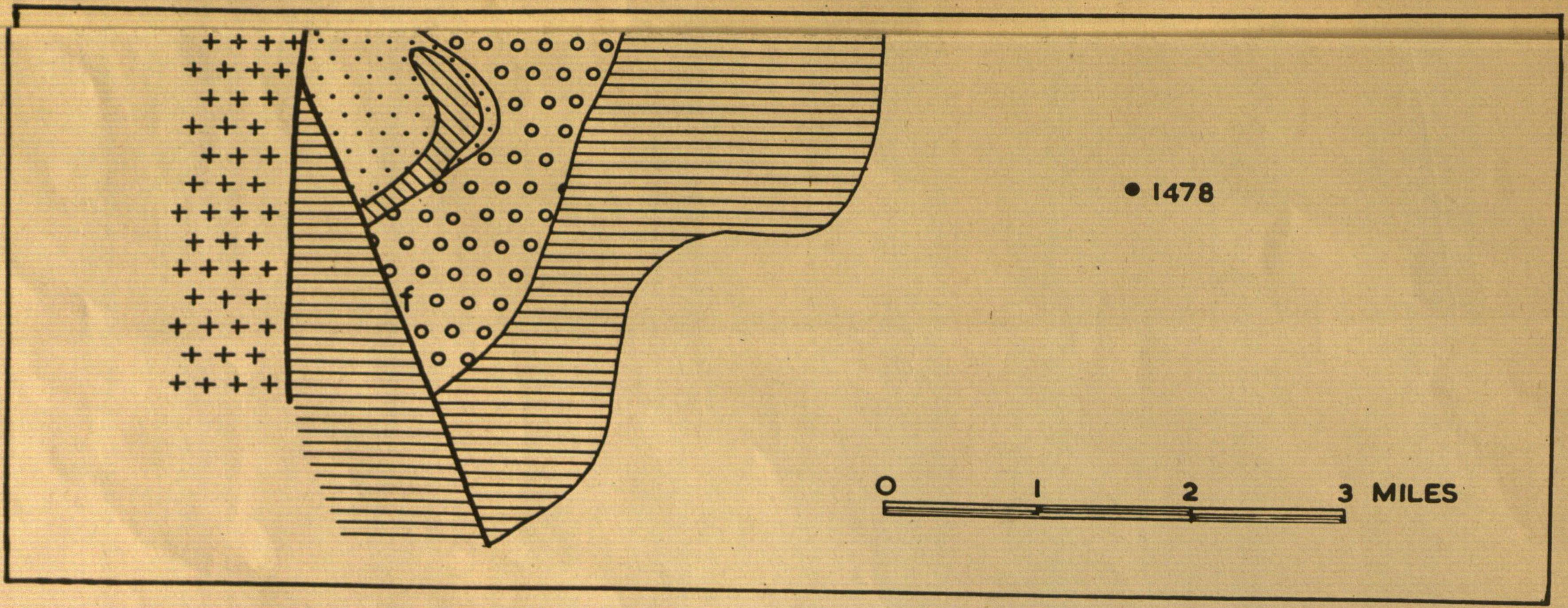


*Fig. 4.*—Geological Sketch Map and Gravimeter Stations for the Kingscourt—Carrickmacross Area

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This is not the case with the Irish observations, and in many cases the isostatic anomalies are larger than the Bouguer anomalies. Nevertheless, the isostatic anomalies are not very large, being less than about 25 mgals., except for a strip along the East coast, so that the areas involved are not necessarily wholly uncompensated. The density of the sedimentary rocks resting on the crystalline basement complex is an unknown factor which should be included in the reductions before the true isostatic anomaly can be calculated. In Ireland these rocks are mainly of Lower Palaeozoic age and it is very likely that their mean density is higher than that of the granitic layer, and this may partly account for the larger positive anomalies. Since, therefore, some of the major anomaly variations appear to be due to variations in level at the base of the sedimentary series, or even deeper, the effect of this primary control of the gravity field has been removed empirically by drawing a curve of regional trend through the two major traverses (*Figs.* 7*a* and 8*a*) and subtracting the observed values (*Figs.* 7*b* and 8*b*). These residual Bouguer anomalies with relatively high gradients are due to density variations near to the surface and an attempt will now be made to interpret them in relation to the geological structure. This will be followed by a note on the regional trends.

### 4.2. The Kingscourt Survey

The survey of the small Triassic area centred on Kingscourt is described first, as the geology in depth of this area is known in more detail than elsewhere owing to the sinking of boreholes to determine the ex-

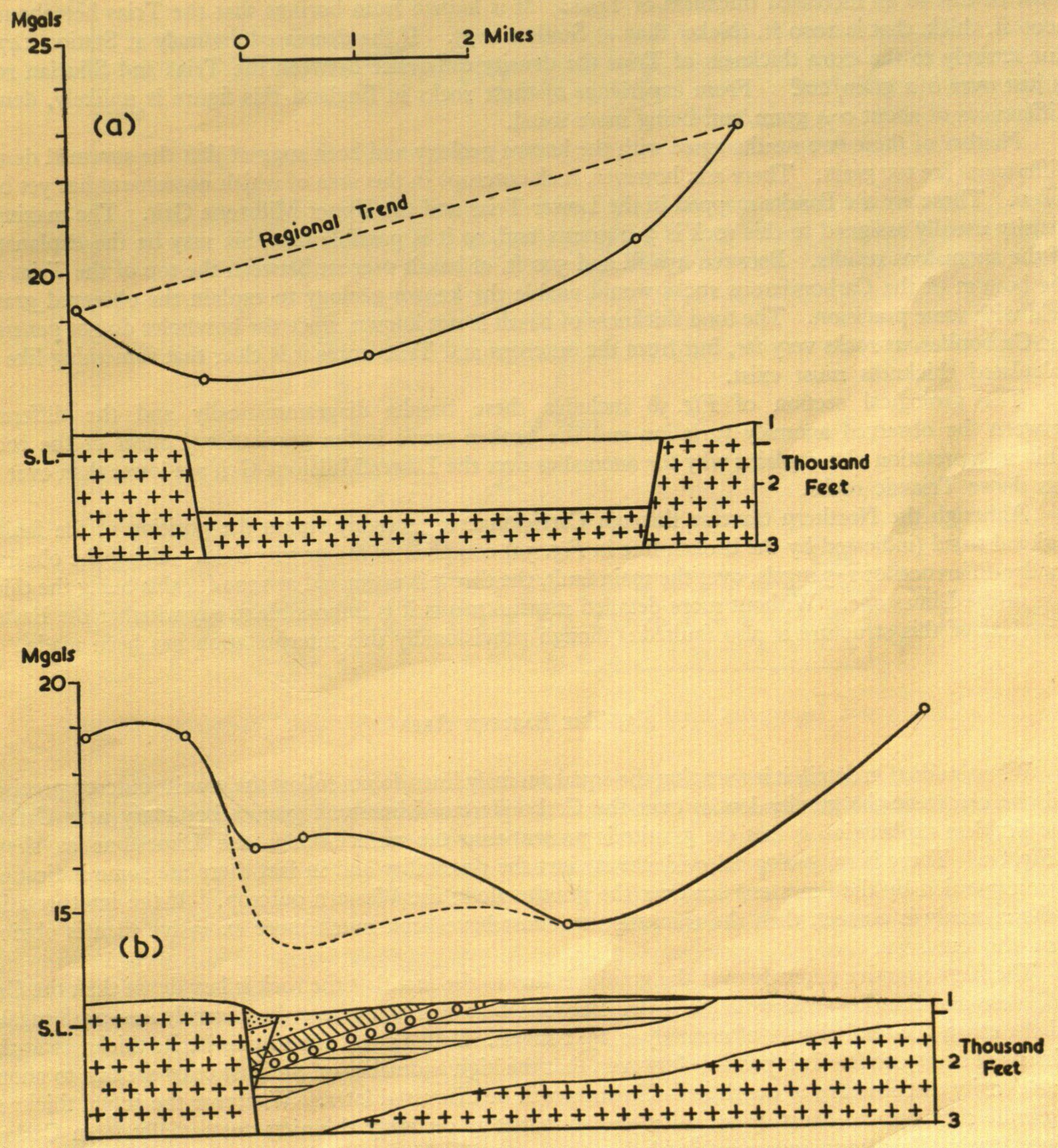


*Fig.* 5.—Anomaly Profiles across the Kingscourt Area with Geological Sections
(Geological Symbols as in *Fig.* 4)

tent of the gypsum deposits in the Trias. It will therefore serve as an example to show to what degree geology can be determined from the gravity field.

The geological sketch map of *Fig.* 4 was supplied by the Geological Survey of Ireland and the gravimeter stations are plotted on this map. It was not possible to traverse by van across the thickest portion of the Trias and only a single observation was made there (Station 1479).

*Fig.* 5 shows how the gravity anomalies vary over the two traverses. The large gradient East of Kingscourt (4 mgals./mile) occurs over the North-South fault, which has an estimated throw there of 2000 ft. This fall of 2·5 mgals. is due to lighter rocks (Carboniferous and Trias) being thrown down by the fault against the denser Silurian rocks to the West. Assuming the mean density of the downthrown rocks to be 2·6 grams/cm$^3$ then the density difference of the rocks on opposite sides of the fault is 0·2 gram/cm$^3$ and the thickness of the downthrown rocks (the throw of the fault) is therefore 1170 ft. It is known that the thickness of Trias under Station 1475 is about 1000 ft., leaving only 170 ft. for the Carboniferous rocks. From the Geological map however, it is certain that the Carboniferous rocks are thicker than this.

?

No observations were made on the Silurian West of Station 1479, but the anomalies at Stations 1482 and 1472 are respectively 19·2 mgals. and 18·7 mgals. With such a small regional gradient the anomaly West of Station 1479 must be in the region of 19 mgals., and the fall of anomaly here, over the fault, is therefore about 5·5 mgals. There is no reason to suppose that the Carboniferous rocks thicken Northwards; if anything they appear to thin out so that the anomaly fall of 3 mgals. relative to Station 1475 must be due to an increased thickness of Trias. It is known from borings that the Trias hereabouts is 2000 ft. thick, that is 1000 ft. thicker than at Station 1475. If the decreased anomaly at Station 1479 is due entirely to the extra thickness of Trias the density difference between the Trias and Silurian rocks is just over 0·2 gram/cm$^3$ From experience of these rocks in England this figure is unlikely, density differences of about 0·4 gram/cm$^3$ being more usual.

X

Position of 1479 now known Jan 1962

Neither of these two results agree with the known geology and both suggest that the assumed density differences are too great. There are, however, rock outcrops in this area of which no account has yet been taken. These are the Basalts mapped in the Lower Trias and the Upper Millstone Grit. The maximum density usually assigned to this rock is 3·2 grams/cm$^3$, so it is possible that this may be the explanation of the anomalous results. Between 450 ft. and 500 ft. of basalt present between the top of the Trias and the bottom of the Carboniferous rocks would enable the known geology to explain the observed gravity field with some precision. The total thickness of basalt is not known, since the boreholes do not penetrate the Carboniferous rocks very far, but from the outcrops and Trias cores it is clear that something like the calculated thickness must exist.

The geological section of *Fig.* 5*b* includes these basalts diagrammatically and the difference between the observed anomaly variation and the broken curve is the gravitational effect of the rocks. This interpretation also explains why the anomalies over the Lower Millstone Grit are lower than over the less dense Triassic rocks.

Although the Northern traverse through Carrickmacross roughly shows the position of the fault, a regional trend (indicated by the broken line in *Fig.* 5*a*) complicates the gravity field. Using the observed gravity differences of 1·5 mgals. over the main fault, the throw is estimated at 1200 ft., this being the thickness of the Limestone. Without more detailed measurements it is impossible to say whether the Eastern boundary of this structure is also faulted: though provisionally this interpretation has been made.

### 4.3. The Eastern Area

When studied in detail, it is seen that the equal anomaly lines do not follow the granite outcrop precisely and the centre of the gravity low is over the Carboniferous Limestone granite boundary near Carlow. The simplest explanation is that the granite is present near the surface under the Limestone as shown in *Fig.* 6*a*. There is no geological evidence against the possibility and in fact there are some indications of transgression by the limestone sea over the granite along the Western outcrop. If the interpretation of the anomaly is correct, then the transgression must have been much more extensive than is obvious from the outcrops.

The large negative anomaly over the granite is due to the fact that the rock is less dense than the Carboniferous and Silurian rocks on either side. Between Station 1442, where the anomaly is −24·8 mgals., and the coast, the total change of anomaly is 65·1 mgals. If this is all due to granite its thickness at this point must be 25,000 ft. It is possible however, that the high anomalies on the East coast are due to anomalous density distributions at depth and this point will be discussed later. Whatever the actual thickness of granite may be, the anomaly variation shows that it is certainly thinning out radially from Carlow, suggesting that the magma source existed below this area. Dr. Nockolds has pointed out that the form of the equal anomaly lines reminds one of the flow lines mapped by Cloos and his colleagues on the Riesenge-

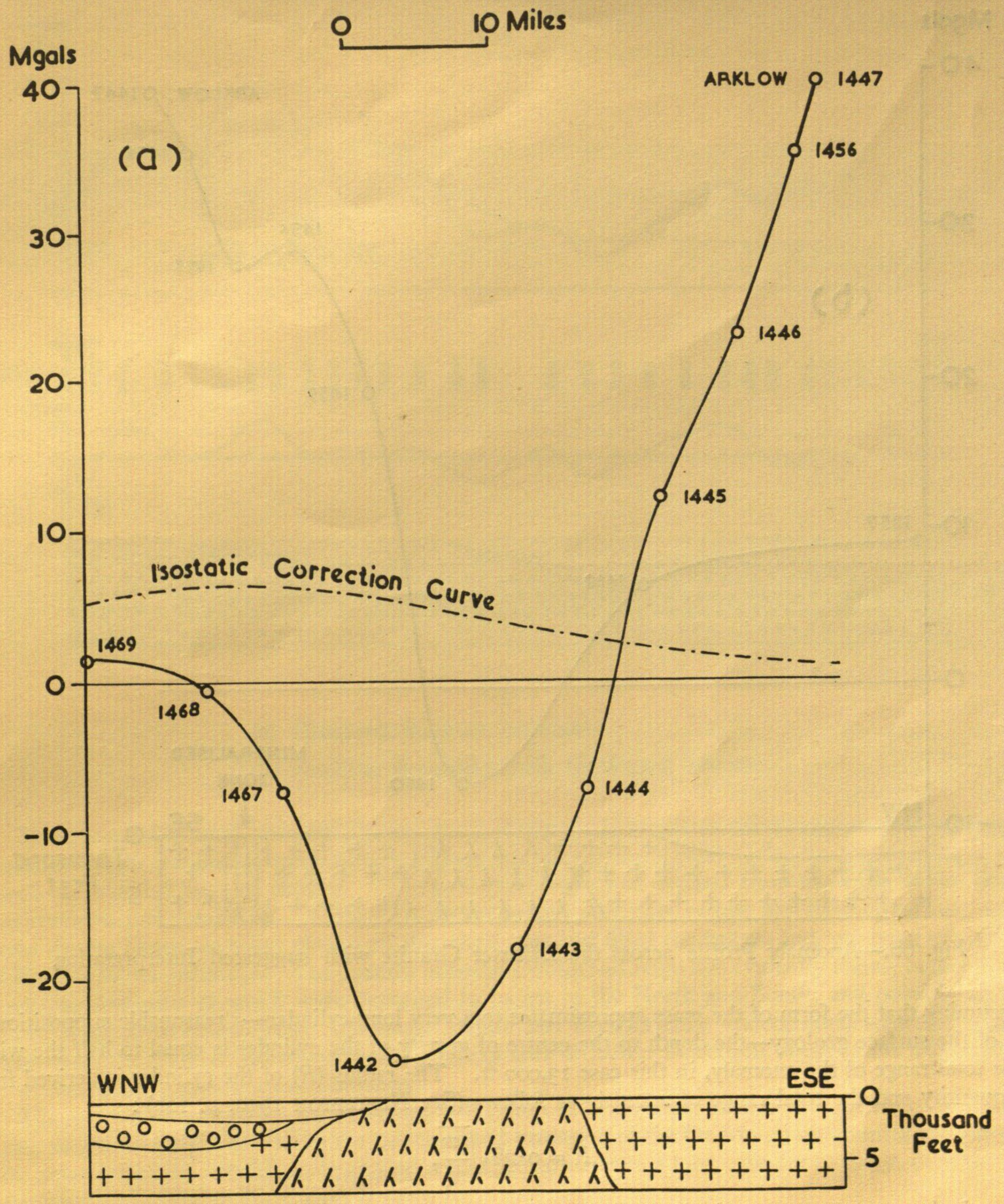


*Fig.* 6a.—Anomaly Profile across the Leinster Granite with suggested Interpretation

birge granite of Bohemia (Cloos, 1925), where they found two asymmetric domes, and concluded that the maximum supply of magma came from beneath the apices of these two domes and that the massif is connected with the interior of the earth only below the apical zones.

It is possible that the lines of equal anomaly may be closely parallel to the flow lines of this type of intrusion and, if there are sufficient exposures, efforts should be directed to the determination of the Leinster granite flow structure. If the relation between the variation in thickness of an igneous mass and its flow structure can be confirmed, further studies of flow structures and the form of igneous rocks will be greatly facilitated by the gravimeter.

The variation of anomaly over the Avoca mineralised area (*Fig.* 6*b*) is of interest in view of the doubt regarding the genesis of the mineral veins. Because of the size and proximity of the granite and the intrusive relationships, it is generally supposed that the granite is closely connected with the mineralisation, though no granite has been found in these mines. The fall of anomaly at Avoca confirms this view by showing the presence in depth of a long narrow mass of material less dense than the country rocks. This material is not likely to be the mineral zone itself, as the enrichment of the country rocks and the associated basic intrusives would result in denser material. If the material causing the small gravity low is granite, then

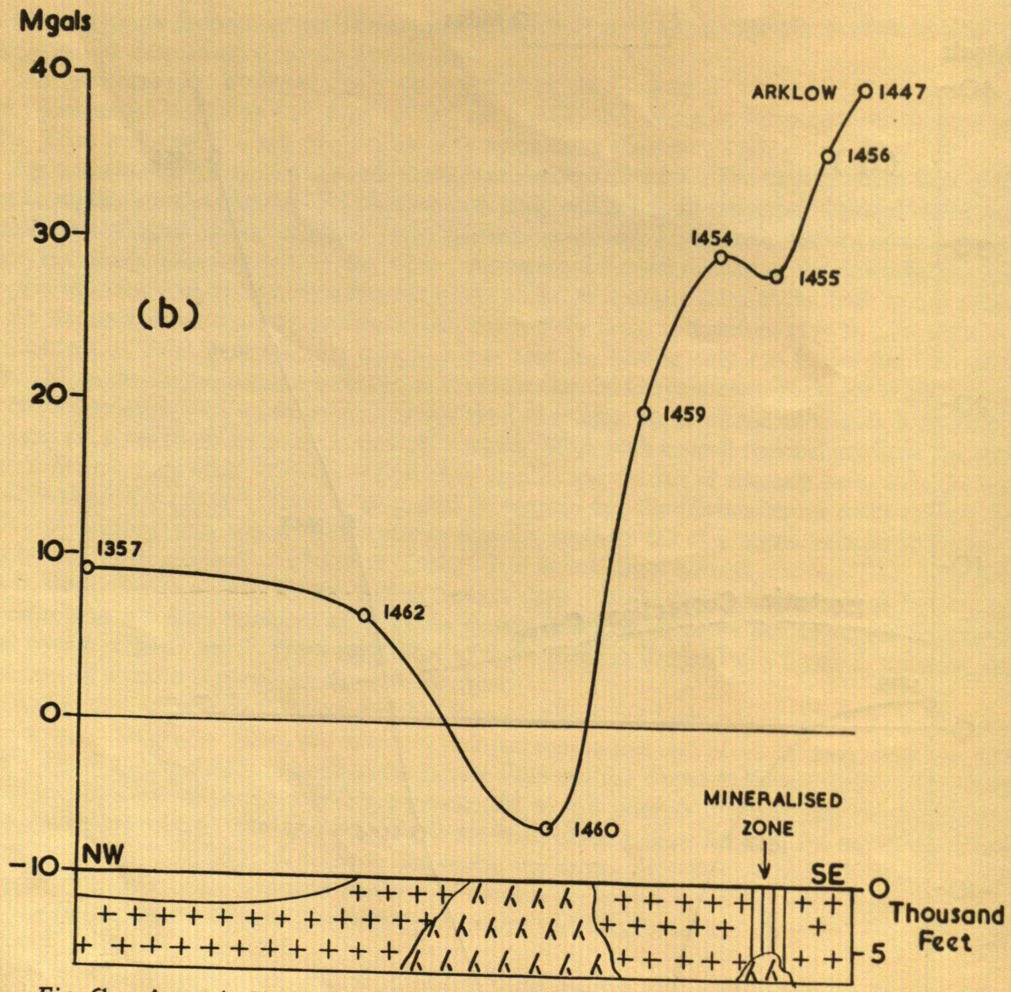


*Fig.* 6b.—Anomaly Profile across the Leinster Granite with suggested Interpretation

by assuming that the form of the mass approximates to a very long cylinder—a reasonable supposition in view of the surface geology—the depth to the centre of gravity of the cylinder is equal to half the width of the total range of the anomaly, in this case 13,000 ft. The radius (*R*) of the cylinder is derived from this quantity and the total range of anomaly as follows (See Nettleton 1940, p. 122):

$$R = 0{\cdot}28\sqrt{\frac{tw}{\Delta\varrho}},$$

where *t* is the anomaly range, *w* is the half width of the anomaly in thousands of feet, and $\Delta\varrho$ the density difference between the cylinder and the surrounding rock. In this case the anomaly range is 12 mgals. and the density difference is 0·2 gram/cm$^3$, so that the radius is 7800 ft., and the depth to the top of the granite is therefore about 5000 ft. This is a maximum figure, for it can be shown that if the shape of the anomalous mass is not a cylinder, then the depth of the mass must be less to give the same anomaly.

There are indications of similar local variations of anomaly in the Eastern area, and there is much to be said for observing the gravity field of this whole area in great detail.

## 4·4. The Dublin-Sligo Traverse

After removing the regional trend, the anomaly variations due to surface and near surface geology are shown in *Fig.* 7*b*, together with a suggested interpretation. The anomalies vary by only ±4 mgals. along the whole traverse, so there cannot be any great thickness of rocks near the surface with large density differences. The small anomaly variation is explained adequately by the visible variations in thickness of the Carboniferous Limestone, and possibly also by small variations in the underlying Old Red Sandstone, though the surface evidence suggests that these rocks are either very thin or absent.

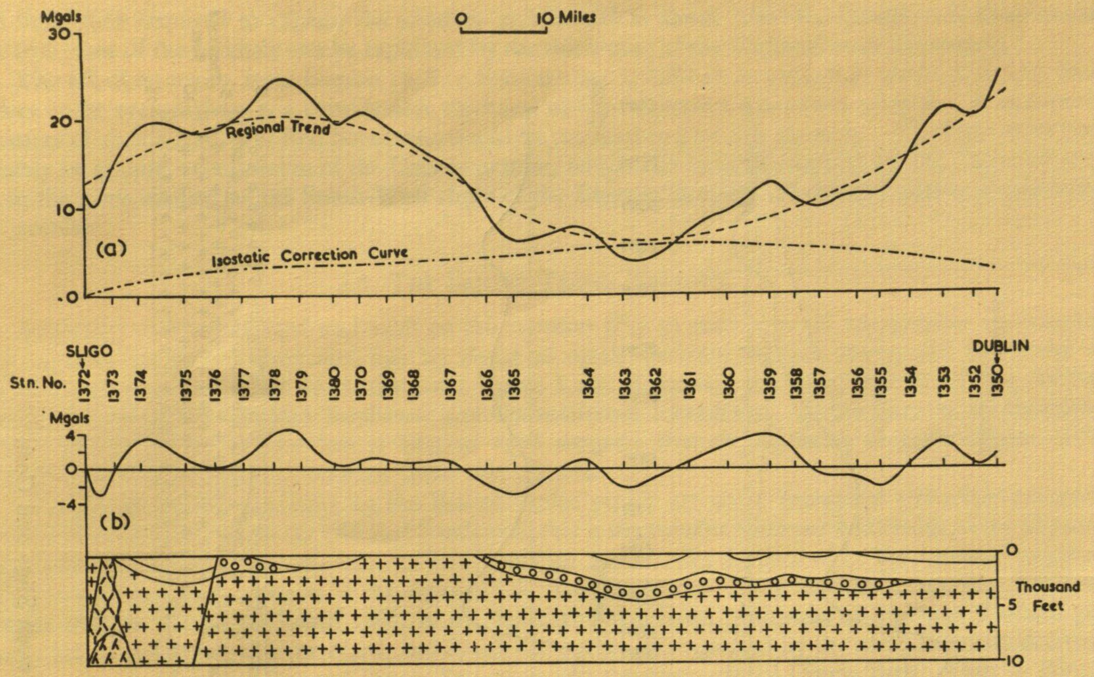


*Fig. 7*

(a) Observed Bouguer Anomalies

(b) Residual Anomalies with Geological Section

This remarkably small anomaly change over a distance of about 150 miles suggests that the Carboniferous Limestone was laid down on a flat or slightly warped surface of older rocks, the greater mass of which showed no lateral change of density. The geological history of Ireland from the close of the Silurian times confirms this possibility. After the Caledonian fold mountain system had been completed, intense erosion during Devonian times planed off the whole area and filled the valleys and low-lying ground with Old Red Sandstone sediments. The country between Dublin and Sligo was evidently mainly higher ground, the eroded sediments of which were deposited in basins to the North and South, and possibly also in a basin to the East in Roscommon. Between Dublin and Longford the underground structure seems to be essentially the same as that of the great triangular area of Lower Palaeozoic rocks to the North, with a skin of overlying Carboniferous Limestone.

The low anomaly over the metamorphic belt South of Sligo must be due to light rocks beneath the surface, and these may very well be the underground extension of the Ox Mountain granites and the cause of the metamorphism. If this underground mass approximates to a long cylinder in shape, then the maximum depth to the top of the granite is 9,000 ft.

## 4.5. The Sligo-Cork Traverse

The outstanding anomaly variation on this traverse is the fall of about 26 mgals. from the Carboniferous Limestone on to the Galway granite (*Fig. 8b*). This is of the same order of magnitude as the fall on to the Leinster granite off the Carboniferous rocks to the West, and if the variation is entirely due to the thickness of the lighter granite, about 20,000 ft. of the rock is required to give the observed anomaly.

To the North, the anomalies increase up to Station 1388 which is on the strike of the Silurian rocks near Longford, before decreasing again by about 15 mgals. This low could be due to the Old Red Sandstone thickening by a maximum of about 5500 ft. These rocks outcrop near Station 1385 at the centre of the low. Where the Silurian outcrops at Station 1383, the anomaly is again relatively high.

South of Galway the anomalies vary in much the way that would be expected from the surface geology. For example, relatively high anomalies were observed at Station 1400 situated on the strike of the Silurian rocks exposed in the core of Slieve Bernagh, at Station 1398 on the strike of Slieve Aughty, and on the anticlinal belt between Stations 1410 and 1411. The nature of the Old Red Sandstone boundary North of Limerick and the sharp fall of the anomalies suggest that this is a faulted boundary but the density of the observations are not sufficient to show this clearly. The maximum increase in thickness of the Old

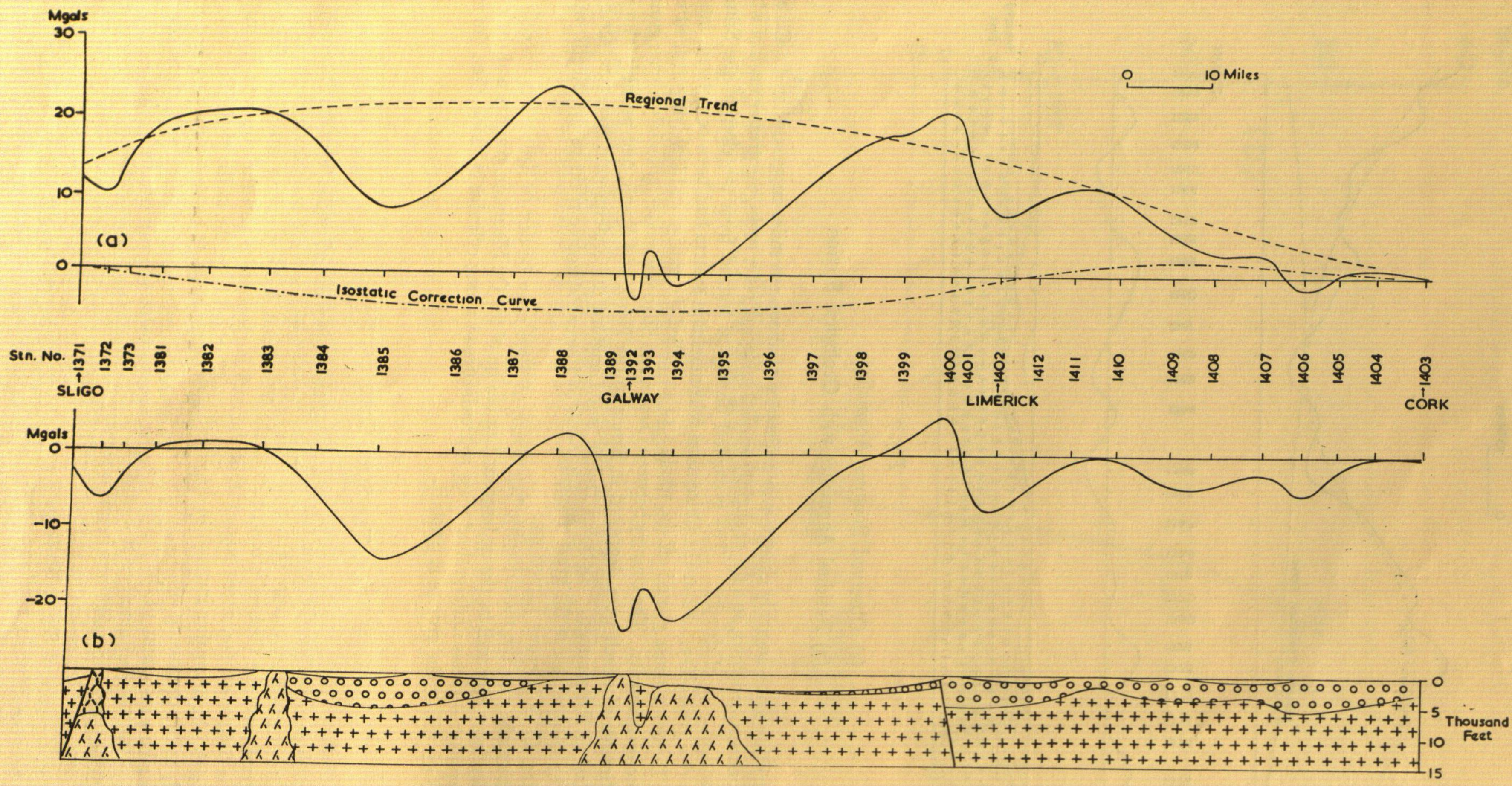


*Fig.* 8

(a) Observed Anomalies

(b) Residual Anomalies with suggested Geological Section between Sligo and Cork

Red Sandstone required to explain the anomaly at Limerick is about 5,000 ft., though it is clear in this case that some of the anomaly can be explained by the thickening of the Carboniferous Limestone.

The fall of 22 mgals. from Station 1398 to Station 1394 is difficult to explain in terms of lighter sub-surface rocks even if there is a considerable thickness of Carboniferous Limestone present. A maximum thickness of 10,000 ft. of Old Red Sandstone would be required to give this anomaly. The light mass may possibly be granite, an extension of the Galway granite, which has been overlapped by the Carboniferous sea in the same manner as the South-West shore of the Leinster granite. A detailed survey would solve the problem.

### 4.6. The Bantry-Tralee Traverse

Anomalies at Stations 1426 and 1428 on this traverse (*Fig.* 9) require small topographic corrections. The curve of the gravity anomalies falls by about 20 mgals. between the two towns, and the centre of the low is situated at a point overlooking the Upper Lake, Killarney, six miles South of the faulted boundary between the Old Red Sandstone and Carboniferous Limestone. To the East on the Amorican strike a much smaller gravity low at Station 1406 suggests that the thickness of these lighter rocks decreases by about 10,000 ft. between these two stations.

Though the gravity gradients on the Bantry-Tralee profile are small enough to allow interpretation in terms of rocks lying below the Old Red Sandstone, this is improbable from our knowledge of the physical character of the Lower Palaeozoic and the Pre-Cambrian rocks. On the face of it, the anomaly variation is due to a variation in thickness of the exposed Old Red Sandstone. The maximum recorded thickness of these rocks is 10,000 ft. (Jukes, 1866) in the Inveragh-Dunkerron peninsula, at the base of which the gravity low is observed. To the North and South the thicknesses reported by the same authority decrease to about 4000 ft. at Bantry Bay and Dingle Bay, excluding the controversial Dingle Beds. Only in Dingle Bay however is the base of the system exposed. If this interpretation is correct, the Old Red Sandstone thins out also to the South and South-East against a steadily rising Lower Palaeozoic floor.

A further point of interest is, that if the gravity field is related to the Amorican structure, and this would appear to be the case, then the major synclinal axis of Cork and Kerry passes through the Station 1428 ENE to Station 1406.

### 4.7. The Regional Trends

The major anomaly variations over the lines traversed in Ireland can therefore be explained by the presence of granite intrusions and by a series of warps which alternately depress and elevate the heavier L. Palaeozoic rocks. This broad structural picture must, of course, be modified by local structures, which

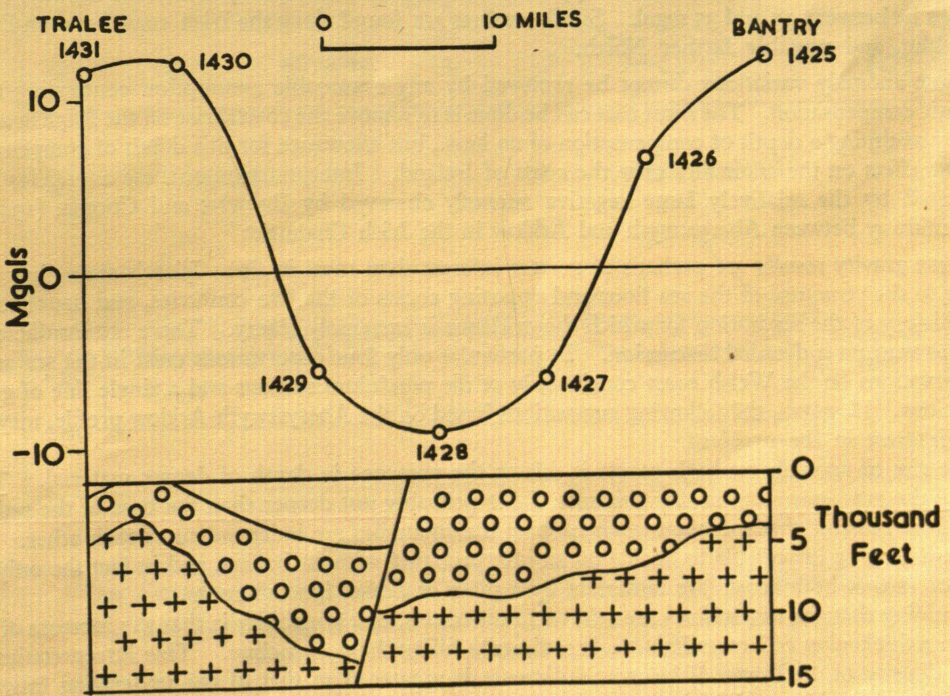


*Fig.* 9.—Observed Anomalies and suggested Geological Section between Bantry and Tralee

(Added in proof: A reversed fault explains the anomalies rather better) the gravity observations can only detect by increasing the station density. This interpretation is in agreement with the known geological history subsequent to the end of Silurian times.

It is almost axiomatic to say, however, that when interpretations of gravity fields come to be proved, there are usually too many or too few milligals to fit the geological section. Systematic survey of the country should show whether or not the suggested interpretation is correct in principle, since the gravity lows and highs would trend in an NE-SW direction over the Central Plain, and E-W in the Southern part of the country.

It is clear from the variation in regional trends that deep seated rocks are exercising the primary influence on the gravity field as a whole. In general, areas where Silurian and older rocks are exposed or are expected to be near the surface the anomalies are relatively high, ranging from 15 to 40 mgal. This is expected from density relationships of the rocks but combined with similar results from Wales there are indications that these high anomaly areas coincide with areas which have been uplifted and perhaps held in position by the strength of the crust. In general the level of the anomaly on the two major traverses is highest over Lower Palaeozoic strata, or where these rocks are near the surface. If the Lower Palaeozoic rocks are denser than the upper crust this probably means that the major control of the gravity field is to be found at the base of the sedimentary series due to thickening of denser material.

Compared with the Eastern half of England, Ireland is apparently not in isostatic equilibrium since the contribution of the compensation only increases many of the anomalies, and the ancient mountain roots of the Caledonides appear to have vanished. A study of the gravity observations made so far reveals that the Western half of the British Isles, with the exception of the granite areas, have anomalies of over 15 mgals., so that denser material relatively near the surface appears to be present throughout this Western area. Since Ireland is the most westerly part of Europe where gravity observations can be made, completion of the systematic survey of the country is essential to the correct interpretation of this gravity field.

### 4.8. The Structure of the Irish Channel

The gravity observations on either side of and in the Irish Channel are summarised in *Fig. 10a*. A West to East profile is given in *Fig. 10b*. A remarkable feature of the curve is that the increase of anomaly from Devil's Bridge to the Welsh coast is repeated with almost perfect symmetry on the Irish coast. The pendulum observations in North Wales (Bullard and Jolly, 1936) and the gravity observations of the Anglo American Oil Co. (White, 1949), show that there is a general tendency for Bouguer anomalies to increase as the West coast of Britain is approached. Between Aberystwyth and the Solway, the gravity anomalies lie between 15 and 35 mgal. Similar values are found along the Irish coast between Dungarvan and Dublin, and possibly farther North.

These anomaly variations cannot be removed by any reasonable assumption concerning the depth of isostatic compensation. The most that can be done is to remove the coastal rise on the English and Welsh coasts by assuming a depth of compensation of 20 kms., but allowance for this depth of compensation has negligible effect on the anomalies near the coast of Ireland. Interpretation of these anomalies is further complicated by the relatively large negative anomaly observed by Browne and Cooper (1949) almost exactly midway between Aberystwyth and Arklow in the Irish Channel.

These gravity results are perhaps of greater interest than most in these Islands since they may hold the clue to the structure of the sea floor and opposing coasts of the two countries, and hence to the geological history of the separation for which the evidence is extremely scanty. There are insufficient observations to warrant a detailed discussion. In particular only four observations exist in the sea area, while the observations on the Welsh coast consist only of the pendulum stations and a single line of gravimeter observations. However, the following suggestions based on the Aberystwyth-Arklow profile, may promote further interest in the problem.

The rise of anomaly on both coasts is due to the presence in depth of denser material. The magnitude of the gradients suggest that this material is probably not deeper than the base of the sedimentary rocks. It is possible that the two masses causing the anomalies are independent of each other. If this is the case, it may be impossible to decide on an interpretation without boring, and in fact the only possible suggestion is that both coasts are underlain by a mass of denser igneous rocks.

Assuming that the two masses are related to one cause, one possibility is that the increase of anomaly is due to a thickening of Lower Palaeozoic sediments filling the geosyncline. This interpretation implies that the density of the Lower Palaeozoic sediments is greater than that of the underlying crustal rocks, and also that the Irish and Welsh geosynclines were separated for long periods by a land mass occupying the site of the Irish Channel.

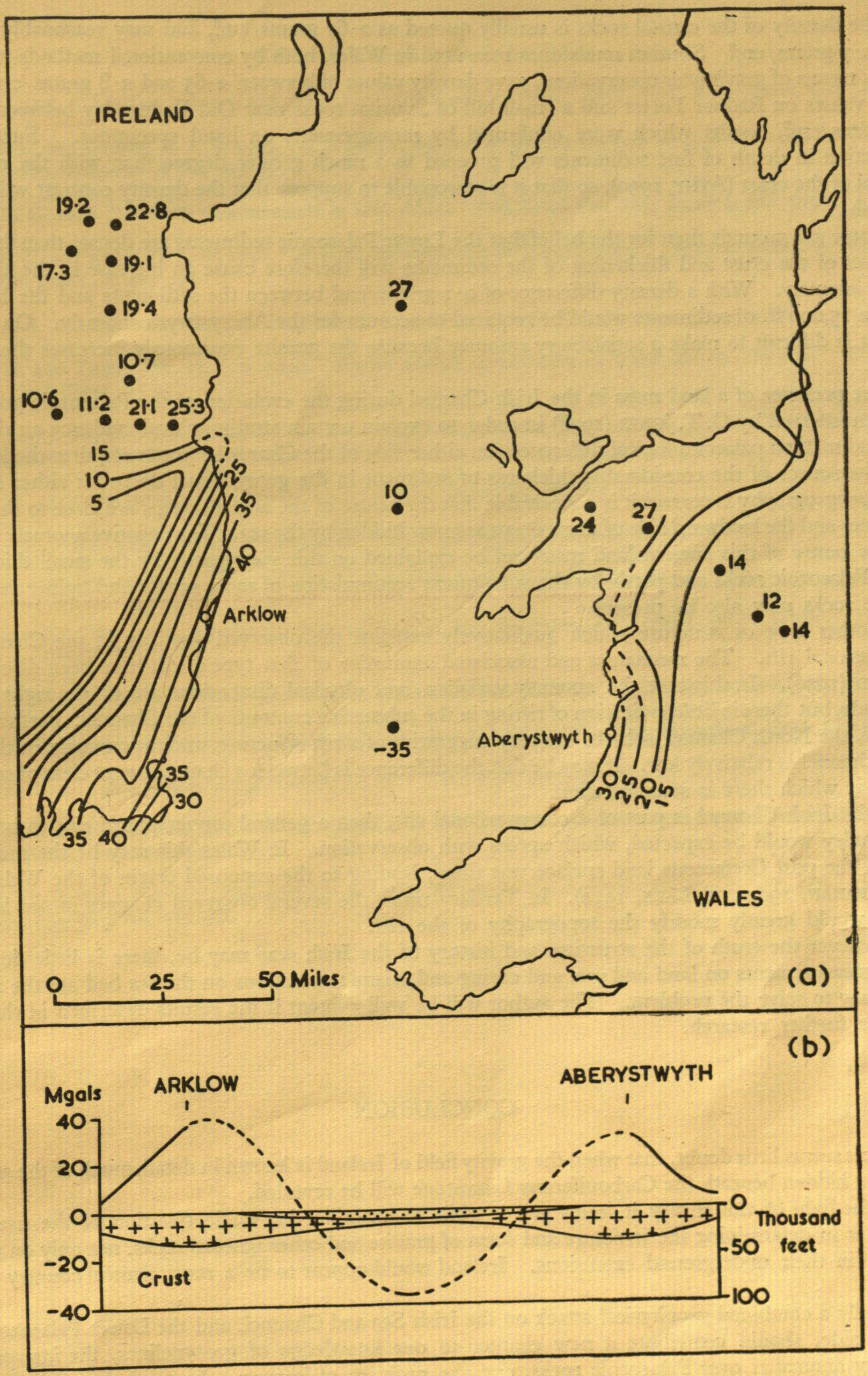


*Fig.* 10

(a) Summary of Bouguer Anomalies over and bordering the Irish Sea

(b) Anomaly Profile between Arklow and Aberystwyth with possible Geological Interpretation to natural Scale

The density of the crustal rocks is usually quoted as 2·67 grams/cm³, and may reasonably be taken up to 2·7 grams/cm³ Silurian mudstones measured in Wales, both by conventional methods and in the field by means of gravimeter observations, gave density values of between 2·65 and 2·8 grams/cm³ Gravimeter values on Radnor Forest and a small hill of Silurian rocks near Old Radnor lay between 2·7 and 2·8 grams/cm³, results which were confirmed by measurements on hand specimens. Furthermore, compaction in depth of fine sediments will proceed to a much greater degree than with the crystalline material of the crust (ATHY, 1930), so that it is reasonable to suppose that the density contrast will increase in depth.

There are grounds then for the belief that the Lower Palaeozoic sediments are denser than the crystalline layer of the crust and thickening of the sediments will therefore cause an increase in the size of the gravity anomaly. With a density difference of 0·1 grams/cm³ between the sediments and the basement, an extra 15,000 ft. of sediments would be required to account for the Aberystwyth anomaly. On the Irish coast, it is difficult to make a satisfactory estimate because the granite enormously increases the anomaly range.*

The presence of a land mass in the Irish Channel during the evolution of the Palaeozoic geosyncline has been inferred by O. T. JONES (1938) in order to explain certain stratigraphical evidence on the Welsh coast and marked palaeontological differences on either side of the Channel. JONES requires the land mass to be the source of the considerable thickness of sediment in the geosynclinal deeps on either side. If this palaeogeography is correct it is conceivable that the centre of the ancient deeps are close to the present coast lines and the landward side of these deeps are now hidden by the sea. The negative anomaly observed over the centre of this ancient land mass can be explained on this view partly by the small thickness of denser Palaeozoic rocks and partly by the subsequent accumulation of more recent and lighter sediments. Granite rocks may also be present.

Another type of structure which qualitatively explains the observed anomaly in the Channel is a compressional rift. The mechanics and associated anomalies of this type of rift have been discussed by BULLARD (1936). In this case the anomaly variation and physical dimensions are of the right order of magnitude, but there is little indication of rifting in the submarine contours of the Channel. Farther North, however, the North Channel isobaths are very suggestive of a rift structure, and the anomaly in the centre of this channel is relatively low. It may be that the difference is between a channel swept clear of sediments and one in which there is sedimentation.

If the Irish Channel is part of a compressional rift, then a general topographical rise to both sides of the valley would be expected, which agrees with observation. In Wales this may be the mechanism whereby the post Cretaceous land surface was tilted, leading to the supposed origin of the Welsh rivers (See STRAHAN, 1902 and LAKE, 1934). In Tertiary times the several observed changes in sea level and erosion would greatly modify the topography of the rift.

Whatever the truth of the structure and history of the Irish seas may be, there is little doubt that gravity measurements on land and sea, and coring and seismic operations on the sea bed are the methods most likely to solve the problem. The author will be well content if the results described in this paper stimulate further research.

## CONCLUSION

There seems little doubt, that when the gravity field of Ireland is known in detail, much of the structure at present hidden beneath the Carboniferous Limestone will be revealed.

In the light of this survey it seems worth while to examine the whole question of the use of the gravimeter in determining the structure and form of granite and other igneous rocks, not only on the surface, but in their underground extensions. Ireland would appear to be a most fruitful country for this study.

Finally a combined geophysical attack on the Irish Sea and Channel, and the Lower Palaeozoic areas on each side, should contribute a new chapter to our knowledge of geosynclines, the interpretation of gravity anomalies over Palaeozoic rocks, and the problem of isostasy. In particular, if further observations in Wales, where Lower Palaeozoic thicknesses are known, confirm that correction for these denser rocks reduces the isostatic anomalies, it will be reasonable, in similar areas to estimate thickness variations from regional trends by assuming compensation exists.

*This interpretation raises again the question of isostatic anomalies. Correction for 40,000 ft. of L. Palaeozoic rocks, (under Arklow and Aberystwyth), denser by 0·08 grams/cm³ than "normal" (2·67 grams/cm³), reduces isostatic anomalies nearly to zero. Corrections using O. T. JONES' (1938) thickness estimates in other parts of Wales similarly reduce isostatic anomalies in those areas where gravity is known.

## REFERENCES TO LITERATURE


ATHY, L. F. 1930. " Density, porosity, and compaction of sedimentary rocks." *Bull. Amer. Assoc. Petrol. Geol.*, **14**, 1–24.

BROWNE, B. C. and COOPER, R. I. B. 1949. " The British Submarine Gravity Surveys of 1938 and 1946." *Phil. Trans. Roy. Soc.*, London. A **242**, 243–310.

BULLARD, E. C. 1936. " Gravity measurements in East Africa." *Phil. Trans. Roy. Soc.*, London, **235**, 513.

BULLARD, E. C. and JOLLY, H. L. P. 1936. " Gravity measurements in Great Britain." *Monthly Not. Roy. Astron. Soc. Geoph. Suppl.*, **3**, 443–477.

COLE, G. A. J. and HALLISSY, T. 1924. *Handbook of the Geology of Ireland*, p. 60 ; London, Murby.

COOK, A. H. and THIRLAWAY, H. I. S. 1949. " Recent gravity observations in Wales and the Borders." *Trans. 18th Int. Geol. Congr.*

CLOOS, H. 1925. *Einführung in die tektonische Behandlung Magmatischer Erscheinungen*, pt. 1 : Das Riesengebirge in Schlesien ; Berlin, Gebr. Borntraeger.

DIXON, F. E. 1949. " Irish Mean Sea Level." *Sci. Proc. Roy. Dublin Soc.*, **25**, No. 1.

GRAF, A. 1942. " Ein neuer kleiner Schweremesser." *Beitr. zur Angew. Geophysik.*, **10**, 18.

JONES, O. T. 1938. " On the evolution of a geosyncline." *Q. J. Geol. Soc.*, London, **94**.

JUKES, J. B. 1866. " On the Carboniferous slate and the Old Red Sandstone of S. Ireland and N. Devon." *Q. J. Geol. Soc.*, London, **22**, 320–371.

LAKE, P. 1934. " The rivers of Wales and their connection with the Thames." *Sci. Prog.*, London, **113**, 23.

MEINESZ, F. A. V. 1941. " Tables for regional and local Isostatic reduction." *Pub. Netherlands Geod. Commission.*

NETTLETON, L. L. 1940. *Geophysical prospecting for oil* ; New York, McGraw Hill.

STRAHAN, A. 1902. " On the origin of the river system of S. Wales and its connection with the Severn and the Thames." *Q. J. Geol. Soc.*, London, **58**, 202.

WHITE, P. H. N. 1949. " Gravity data obtained in Great Britain by the Anglo-American Oil Coy. Ltd." *Q. J. Geol. Soc.*, London, **104**, 339–364.

## APPENDIX

### Details of Gravimeter Stations and Gravity Values

| Station Number | Map Sheet Number: Six inch | Map Sheet Number: One inch | Latitude N | Longitude W | Height above M.S.L. | g(Station) minus g(Dunsink) | Bouguer Anomaly |
|---|---|---|---|---|---|---|---|
| | | | ° ′ ″ | ° ′ ″ | ft. | mgals. | mgals. |
| 1350 | Dublin 14 | 112 | 53 23 15 | 6 20 16 | 271·0 | 0 | 25·3 |
| 1351 | Dublin 18 | 112 | 53 21 00 | 6 21 02 | 55·0 | 5·3 | 21·0 |
| 1352 | Dublin 17 | 111 | 53 21 34 | 6 25 36 | 155·0 | − 0·9 | 19·9 |
| 1353 | Kildare 6 | 111 | 53 22 22 | 6 31 18 | 187·0 | − 0·5 | 21·1 |
| 1354 | Kildare 5 | 111 | 53 23 12 | 6 38 00 | 206·0 | − 5·1 | 16·4 |
| 1355 | Kildare 5 | 111 | 53 24 52 | 6 42 59 | 289·0 | − 13·0 | 11·2 |
| 1356 | Kildare 4 | 111 | 53 24 56 | 6 47 17 | 249·0 | − 10·0 | 11·6 |
| 1357 | Kildare 3 | 100 | 53 25 42 | 6 54 45 | 229·0 | − 9·8 | 9·5 |
| 1358 | Kildare 1 | 100 | 53 25 58 | 6 58 48 | 239·0 | − 8·0 | 10·6 |
| 1359 | Meath 46 | 100 | 53 26 54 | 7 03 37 | 270·0 | − 7·8 | 12·2 |
| 1360 | Westmeath 27 | 100 | 53 28 37 | 7 09 33 | 312·0 | − 10·9 | 9·2 |
| 1361 | Westmeath 19 | 99 | 53 30 39 | 7 15 29 | 311·0 | − 9·4 | 7·7 |
| 1362 | Westmeath 19 | 99 | 53 32 04 | 7 21 03 | 326·0 | − 11·6 | 4·3 |
| 1363 | Westmeath 11 | 89 | 53 35 54 | 7 23 35 | 355·0 | − 8·3 | 3·9 |
| 1364 | Westmeath 11 | 89 | 53 37 17 | 7 27 29 | 224·0 | 5·3 | 7·6 |
| 1365 | Longford 14 | 89 | 53 42 01 | 7 38 31 | 352·0 | 2·7 | 5·9 |
| 1366 | Longford 14 | 88 | 53 43 03 | 7 44 31 | 237·0 | 17·1 | 11·9 |
| 1367 | Longford 8 | 88 | 53 45 12 | 7 49 11 | 198·0 | 24·8 | 14·2 |
| 1368 | Longford 8 | 78 | 53 48 02 | 7 52 52 | 131·0 | 35·0 | 16·4 |
| 1369 | Roscommon 24 | 78 | 53 49 52 | 7 55 36 | 140·0 | (mean) 40·1 | 19·3 |
| 1370 | Roscommon 18 | 78 | 53 52 05 | 8 00 03 | 137·0 | 45·1 | 21·0 |
| 1371 | Sligo 14 | 55 | 54 16 12 | 8 28 15 | 35·5 | 77·1 | 12·3 |
| 1372 | Sligo 20 | 55 | 54 13 08 | 8 30 04 | 14·0 | 71·8 | 10·1 |
| 1373 | Sligo 26 | 55 | 54 10 26 | 8 29 08 | 140·0 | 65·5 | 15·2 |
| 1374 | Sligo 26 | 55 | 54 07 53 | 8 26 38 | 193·0 | 63·0 | 19·6 |
| 1375 | Sligo 40 | 66 | 54 04 05 | 8 21 42 | 251·0 | 52·7 | 18·2 |
| 1376 | Sligo 40 | 66 | 54 01 09 | 8 19 42 | 368·0 | 42·5 | 19·3 |
| 1377 | Roscommon 6 | 66 | 53 58 14 | 8 16 55 | 244·0 | 47·7 | 21·1 |
| 1378 | Roscommon 6 | 66 | 53 57 33 | 8 11 05 | 165·0 | 54·6 | 24·3 |
| 1379 | Roscommon 11 | 78 | 53 56 36 | 8 06 39 | 138·0 | 54·2 | 23·5 |
| 1380 | Roscommon 11 | 78 | 53 55 28 | 8 01 07 | 163·0 | 47·3 | 19·9 |
| 1381 | Sligo 32 | 54 | 54 07 15 | 8 35 55 | 280·0 | 56·6 | 19·3 |
| 1382 | Sligo 37 | 65 | 54 02 04 | 8 45 30 | 236·0 | 52·8 | 20·2 |
| 1383 | Mayo 63 | 65 | 53 56 44 | 8 47 33 | 247·0 | 45·1 | 20·9 |
| 1384 | Mayo 82 | 76 | 53 50 19 | 8 45 47 | 292·0 | 28·2 | 15·8 |
| 1385 | Mayo 103 | 86 | 53 43 44 | 8 45 35 | 260·0 | 13·2 | 8·5 |
| 1386 | Galway 17 | 86 | 53 36 36 | 8 45 14 | 209·0 | 11·1 | 13·5 |
| 1387 | Galway 43 | 96 | 53 30 04 | 8 53 10 | 119·0 | 14·3 | 20·7 |
| 1388 | Galway 57 | 96 | 53 25 30 | 8 54 08 | 132·0 | 10·9 | 24·7 |
| 1389 | Galway 82 | 106 | 53 19 20 | 8 58 21 | 43·0 | − 2·5 | 14·9 |
| 1390 | Galway 94 | 105 | 53 15 30 | 9 06 19 | 38·0 | (mean) − 31·6 | − 9·0 |
| 1391 | Galway 93 | 105 | 53 14 53 | 9 11 31 | 42·0 | − 34·5 | − 10·8 |
| 1392 | Galway 94 | 105 | 53 16 34 | 9 03 40 | 28·5 | − 23·6 | − 3·1 |
| 1393 | Galway 95 | 106 | 53 15 51 | 8 55 46 | 22·0 | − 17·3 | 3·8 |
| 1394 | Galway 103 | 115 | 53 12 11 | 8 51 49 | 53·0 | − 29·5 | − 1·1 |
| 1395 | Galway 113 | 115 | 53 07 10 | 8 49 40 | 86·0 | − 33·9 | 3·6 |
| 1396 | Galway 129 | 124 | 53 01 55 | 8 48 47 | 143·0 | − 40·9 | 7·1 |
| 1397 | Clare 18 | 124 | 52 57 17 | 8 52 53 | 125·0 | − 41·1 | 13·1 |
| 1398 | Clare 26 | 133 | 52 52 47 | 8 57 24 | 46·0 | − 38·6 | 17·4 |
| 1399 | Clare 42 | 133 | 52 48 20 | 8 55 54 | 36·5 | − 42·9 | 18·8 |

## APPENDIX—*continued*

| Station Number | Map Sheet Number | | Latitude N | Longitude W | Height above M.S.L. | g(Station) minus g(Dunsink) | Bouguer Anomaly | |
|---|---|---|---|---|---|---|---|---|
| | Six inch | One inch | ° ′ ″ | ° ′ ″ | ft. | mgals. | mgals. | |
| 1400 | Clare 51 | 133 | 52 43 42 | 8 52 29 | 56·0 | − 47·8 | 21·9 | |
| 1401 | Clare 62 | 143 | 52 41 37 | 8 45 26 | 57·0 | − 57·9 | 14·9 | |
| 1402 | Limerick 13 | 143 | 52 38 19 | 8 39 09 | 19·0 | − 67·2 | 8·0 | |
| 1403 | Cork 74 | 187 | 51 53 32 | 8 29 30 | 60·5 | −142·8 | 0·3 | |
| 1404 | Cork 62 | 186 | 51 58 12 | 8 32 52 | 395·0 | −155·2 | 1·2 | |
| 1405 | Cork 51 | 175 | 52 02 08 | 8 36 29 | 510·0 | −156·6 | 0·9 | |
| 1406 | Cork 33 | 175 | 52 06 18 | 8 39 15 | 293·0 | −139·8 | − 1·4 | |
| 1407 | Cork 25 | 175 | 52 10 34 | 8 40 11 | 318·0 | −130·0 | 3·7 | |
| 1408 | Cork 17 | 164 | 52 15 18 | 8 39 50 | 286·0 | −121·3 | 3·5 | |
| 1409 | Cork 3 | 164 | 52 20 07 | 8 40 28 | 389·0 | −118·7 | 5·2 | |
| 1410 | Limerick 39 | 153 | 52 25 38 | 8 41 26 | 160·0 | − 91·2 | 11·0 | |
| 1411 | Limerick 30 | 153 | 52 30 44 | 8 43 04 | 78·0 | − 78·0 | 11·9 | |
| 1412 | Limerick 21 | 143 | 52 34 12 | 8 43 12 | 106·0 | − 76·2 | 10·4 | |
| 1413 | Cork 75 | 187 | 51 54 32 | 8 17 18 | 23·0 | −141·3 | − 1·9 | |
| 1414 | Cork 77 | 188 | 51 54 51 | 8 06 44 | 44·0 | −133·9 | 6·2 | |
| 1415 | Cork 67 | 188 | 51 56 13 | 7 57 07 | 68·0 | −130·9 | 8·8 | |
| 1416 | Waterford 37 | 188 | 51 58 33 | 7 50 11 | 12·0 | −124·0 | 8·9 | |
| 1417 | Waterford 35 | 189 | 52 00 57 | 7 41 39 | 494·0 | −144·1 | 14·1 | |
| 1418 | Waterford 31 | 178 | 52 06 49 | 7 34 02 | 110·5 | −117·8 | 8·9 | |
| 1419 | Waterford 15 | 178 | 52 11 17 | 7 28 03 | 263·5 | −124·2 | 5·2 | |
| 1420 | Waterford 16 | 167 | 52 14 10 | 7 17 13 | 125·0 | −102·5 | 14·3 | |
| 1421 | Waterford 9 | 168 | 52 14 58 | 7 07 10 | 16·0 | − 91·3 | 17·8 | |
| 1422 | Kilkenny 43 | 168 | 52 17 11 | 7 03 35 | 243·0 | − 99·4 | 19·5 | |
| 1423 | Cork 110 | 194 | 51 44 47 | 8 46 06 | 119·0 | −155·3 | 4·1 | |
| 1424 | Cork 107 | 193 | 51 42 41 | 9 07 26 | 226·0 | −162·5 | 6·4 | |
| 1425 | Cork 105 | 192 | 51 41 54 | 9 26 31 | 55·0 | −147·9 | 11·9 | |
| 1426 | Cork 90 | 192 | 51 46 59 | 9 35 13 | 1009·5 | −203·7 | 6·1 | |
| 1427 | Kerry 93 | 184 | 51 52 29 | 9 35 00 | 12·0 | −148·1 | − 6·4 | |
| 1428 | Kerry 84 | 184 | 51 57 53 | 9 35 27 | 434·0 | −169·2 | −10·1 | |
| 1429 | Kerry 66 | 173 | 52 04 11 | 9 31 01 | 127·5 | −137·5 | − 6·0 | |
| 1430 | Kerry 48 | 137 | 52 11 35 | 9 33 59 | 47·0 | −103·0 | 12·0 | |
| 1431 | Kerry 29 | 162 | 52 15 55 | 9 40 41 | 36·0 | − 97·5 | 11·5 | |
| 1432 | Kilkenny 41 | 168 | 52 22 12 | 6 59 17 | 11·0 | − 71·1 | 27·2 | |
| 1433 | Wexford 35 | 157 | 52 22 44 | 6 51 30 | 263·0 | − 83·7 | 29·0 | |
| 1434 | Wexford 36 | 169 | 52 21 40 | 6 40 08 | 246·0 | − 77·6 | 35·5 | |
| 1435 | Wexford 37 | 169 | 52 20 19 | 6 30 37 | 134·0 | − 75·1 | 33·2 | |
| 1436 | Wexford 47 | 169 | 52 15 43 | 6 27 37 | 13·0 | − 67·6 | 40·3 | |
| 1437 | Wexford 53 | 181 | 52 10 37 | 6 21 42 | 27·0 | − 86·9 | 29·2 | |
| 1438 | Kilkenny 33 | 157 | 52 27 47 | 6 57 29 | 425·0 | −107·8 | 7·2 | |
| 1439 | Kilkenny 25 | 147 | 52 34 21 | 6 57 11 | 231·0 | −102·6 | − 8·8 | |
| 1440 | Carlow 19 | 147 | 52 40 09 | 6 57 51 | 147·0 | − 99·3 | −19·0 | |
| 1441 | Carlow 12 | 137 | 52 46 58 | 6 56 48 | 154·0 | − 94·7 | −23·9 | |
| 1442 | Carlow 7 | 137 | 52 49 15 | 6 52 56 | 202·5 | − 95·2 | −24·8 | |
| 1443 | Wicklow 37 | 138 | 52 48 09 | 6 41 41 | 290·0 | − 95·2 | −17·9 | |
| 1444 | Wicklow 43 | 138 | 52 46 05 | 6 34 06 | 355·0 | − 90·8 | − 6·6 | |
| 1445 | Wicklow 38 | 138 | 52 47 41 | 6 25 59 | 286·0 | − 64·5 | 13·2 | |
| 1446 | Wicklow 39 | 139 | 52 50 57 | 6 17 23 | 161·0 | − 41·9 | 23·6 | |
| 1447 | Wicklow 40 | 139 | 52 48 34 | 6 08 58 | 73·0 | − 23·4 | 40·3 | |
| 1448 | Wexford 33 | 158 | 52 24 51 | 6 25 15 | 61·0 | − 61·3 | 36·2 | |
| 1449 | Wexford 21 | 159 | 52 31 04 | 6 21 49 | 240·0 | − 63·6 | 35·5 | |
| 1450 | Wexford 11 | 149 | 52 36 56 | 6 18 22 | 92·0 | − 43·9 | 37·8 | |
| 1451 | Wexford 7 | 139 | 52 43 21 | 6 14 59 | 152·0 | − 37·4 | 38·6 | |
| 1452 | Wicklow 31 | 130 | 52 55 26 | 6 06 54 | 92·0 | − 23·7 | 31·1 | |
| 1453 | Wicklow 25 | 130 | 53 00 24 | 6 05 01 | 29·0 | − 6·0 | 37·8 | −36·0 |
| 1454 | Wicklow 30 | 130 | 52 56 19 | 6 13 04 | 361·0 | − 40·2 | 29·4 | |

## APPENDIX—*concluded*

| Station Number | Map Sheet Number | | Latitude N | Longitude W | Height above M.S.L. | g(Station) minus g(Dunsink) | Bouguer Anomaly |
|---|---|---|---|---|---|---|---|
| | Six inch | One inch | | | | | |
| | | | ° ′ ″ | ° ′ ″ | ft. | mgals. | mgals. |
| 1455 | Wicklow 35 | 139 | 52 51 52 | 6 13 05 | 114·0 | − 33·1 | 28·2 |
| 1456 | Wicklow 40 | 139 | 52 49 52 | 6 11 21 | 422·0 | − 45·7 | 37·1 |
| 1457 | Dublin 23 | 112 | 53 15 51 | 6 09 24 | 132·0 | − 20·3 | 7·4 |
| 1458 | Wicklow 13 | 121 | 53 08 00 | 6 04 44 | 107·0 | − 4·9 | 32·7 |
| 1459 | Wicklow 24 | 130 | 53 00 45 | 6 16 39 | 599·0 | − 57·9 | 19·6 |
| 1460 | Wicklow 17 | 129 | 53 03 23 | 6 24 48 | 1292·0 | −121·7 | − 6·4 |
| 1461 | Wicklow 9 | 120 | 53 05 24 | 6 36 24 | 567·5 | − 70·8 | − 1·9 |
| 1462 | Kildare 24 | 120 | 53 11 12 | 6 38 29 | 427·0 | − 44·7 | 7·4 |
| 1463 | Dublin 21 | 111 | 53 16 35 | 6 29 57 | 452·0 | − 34·3 | 11·6 |
| 1464 | Kildare 32 | 129 | 53 03 48 | 6 46 02 | 411·0 | − 62·9 | − 1·1 |
| 1465 | Kildare 38 | 129 | 52 57 43 | 6 49 34 | 335·0 | − 72·2 | − 6·1 |
| 1466 | Kildare 40 | 137 | 52 52 47 | 6 52 25 | 199·0 | − 85·9 | −20·8 |
| 1467 | Leix 32 | 137 | 52 53 51 | 7 01 36 | 362·0 | − 79·9 | − 6·6 |
| 1468 | (Queen's 19 | 128 | 53 00 18 | 7 07 47 | 441·0 | − 68·9 | − 0·2 |
| 1469 | County) 13 | 127 | 53 02 24 | 7 18 31 | 293·0 | − 55·0 | 1·8 |
| 1470 | Meath 38 | 101 | 53 31 35 | 6 33 24 | 347·5 | − 7·2 | 10·7 |
| 1471 | Meath 18 | 91 | 53 43 07 | 6 41 54 | 284·0 | 21·9 | 19·4 |
| 1472 | Cavan 35 | 80 | 53 54 22 | 6 48 17 | 367·0 | 32·7 | 18·7§ |
| 1473 | Cavan 35 | 80 | 53 54 37 | 6 49 49 | 408·0 | 30·6 | 18·7§ |
| 1474 | Cavan 34 | 80 | 53 55 17 | 6 56 52 | 602·0 | 18·1 | 17·3 |
| 1475 | Cavan 35 | 81 | 53 54 12 | 6 47 27 | 151·0 | 42·0 | 16·4* |
| 1476 | Meath 2 | 81 | 53 54 05 | 6 46 48 | 189·0 | 39·6 | 16·6* |
| 1477 | Meath 3 | 81 | 53 52 55 | 6 44 04 | 371·0 | 26·0 | 14·5¶ |
| 1478 | Meath 6 | 81 | 53 51 29 | 6 40 18 | 152·0 | 41·5 | 19·1 |
| 1479 | Monaghan 30 | 70 | 53 56 ~~33~~ 28 | 6 47 57 | 145·0 | 43·0 | 13·6* |
| 1480 | Monaghan 31 | 70 | 53 58 46 | 6 43 43 | 134·0 | 52·1 | 18·1 |
| 1481 | Monaghan 31 | 70 | 53 59 18 | 6 45 49 | 257·0 | 45·2 | 17·8¶ |
| 1482 | Monaghan 30 | 70 | 53 59 43 | 6 46 57 | 395·0 | 39·2 | 19·2§ |
| 1483 | Monaghan 31 | 70 | 53 58 18 | 6 40 52 | 93·5 | 56·1 | 20·4 |
| 1484 | Monaghan 31 | 70 | 53 58 36 | 6 39 10 | 118·0 | 57·5 | 22·8§ |
| 1485 (University College, Dublin) : Site at ground level alongside Advanced Physical Laboratory | | | | | | 5·9 | |
| 1486 (Trinity College, Dublin) : Site at ground level immediately in front of main entrance to Physics Building | | | | | | 10·1 | |

* Density = 2·3 grams/cm.³
§ „ = 2·75 „
¶ „ = 2·70 „

**Note for Calculating Anomalies :**

$g$(Pendulum House, Cambridge) = 981·265 cm./sec.²

$g$(Dunsink Gravimeter Station) − $g$(Pendulum House) = 120·4 mgals.

Rock density between Station and Mean S.L. = 2·67 grams/cm.³ except where indicated.

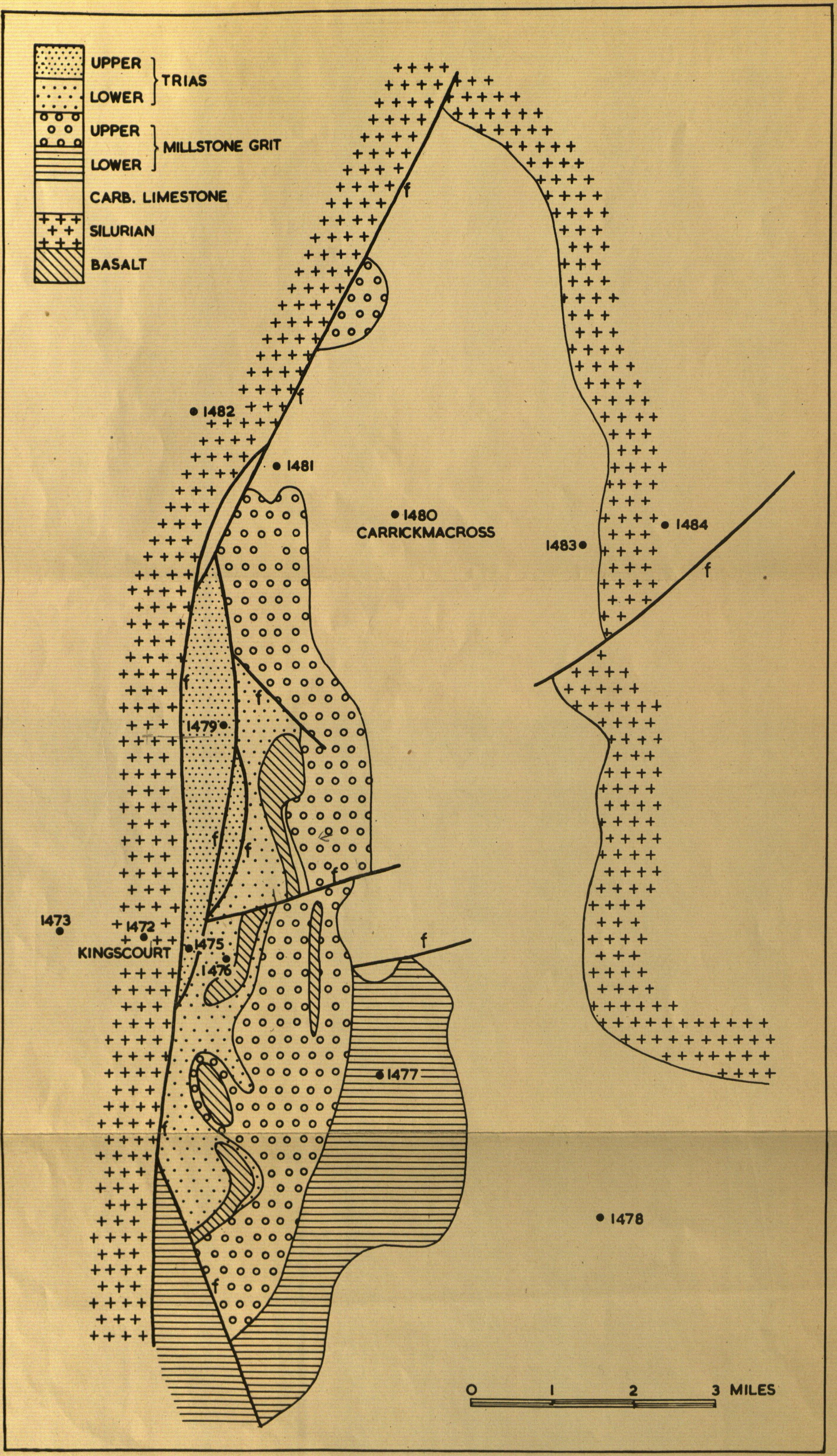


*Fig. 4.*—Geological Sketch Map and Gravimeter Stations for the Kingscourt—Carrickmacross Area

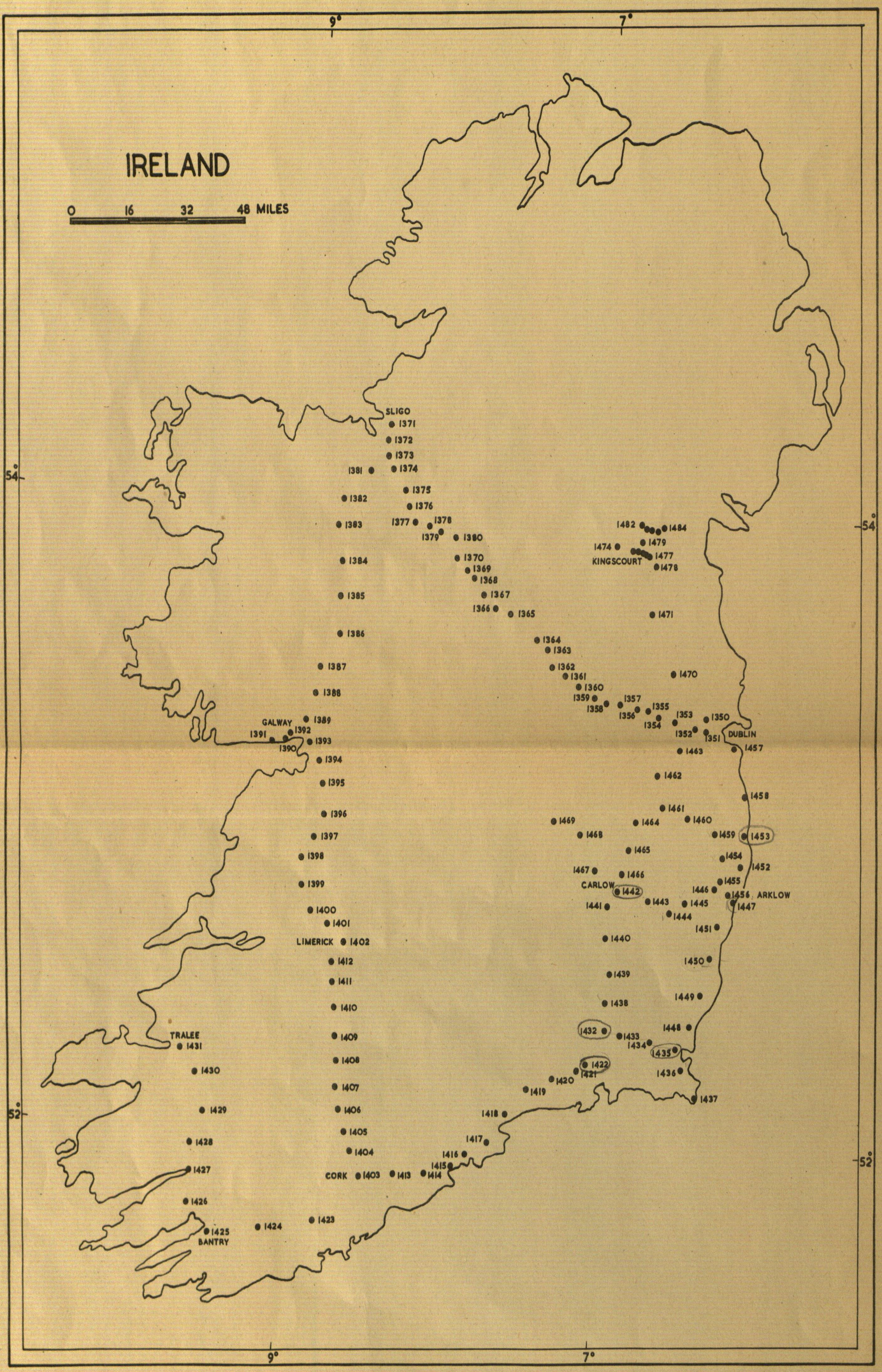


*Fig. 1.*—Gravimeter Stations

## GEOPHYSICAL MEMOIRS

No. 1: L. W. POLLAK and U. N. EGAN, Eight-Place Supplement to Harmonic Analysis and Synthesis Schedules for three to one hundred equidistant values of empiric functions ; Dublin 1949.

Part 1: Register.

Part 2: Index.

No. 2: Measurements of Gravity in Ireland.

Part 1: A. H. COOK, Pendulum Observations at Dublin, Sligo, Galway and Cork; Dublin 1950.

Part 2: H. I. S. THIRLAWAY, Gravimeter Observations between Dublin, Sligo, Galway and Cork; Dublin 1951.

No. 3:

Part 1: P. RYAN NOLAN and L. W. POLLAK, On the Prediction of the Yield and Sugar Content of Sugar Beet in Ireland; Dublin 1950.

### In Course of Printing or in Preparation

No. 2: Measurements of Gravity in Ireland.

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Part 4: A. H. COOK and THOMAS MURPHY, Gravity Survey of Ireland north of the line Sligo-Dundalk.

Part 5: A. H. COOK, The Adjustment of the Pendulum and Gravimeter Observations in Ireland 1949-51.

No. 3:

Part 2: L. W. POLLAK, On the Prediction of Sugar Beet Yield in Bohemia.

Part 3: L. W. POLLAK, Effect of Temperature during the Growing Season on the Yield and Sugar Content of Sugar Beet in Ireland.

No. 4: THOMAS MURPHY, The Magnetic Survey of Ireland for the Epoch 1950·5.

## GEOPHYSICAL BULLETINS

No. 1: THOMAS MURPHY, Provisional Results of the Gravity Survey of Central Ireland; Dublin, March 1950.

No. 2: THOMAS MURPHY, Provisional Values for Magnetic Declination in Ireland for the Epoch 1950·5; Dublin, February 1951.

### In Course of Printing or in Preparation

No. 3: L. W. POLLAK, Frequency of the Centres of Closed Low Pressure Systems over the North Atlantic Ocean.

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