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MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Geological Interpretation of Gravity and Magnetic Surveys in Devon and Cornwall

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THE GEOLOGICAL INTERPRETATION OF GRAVITY AND MAGNETIC SURVEYS IN DEVON AND CORNWALL

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CONTENTS

The main feature of the gravity field of Devon and Cornwall is a belt of large negative Bouguer anomalies which follows the line of the granite outcrops. These low anomalies are shown to originate from a shallow structure and are interpreted as being caused by the relatively low

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density of the granite itself. They indicate that the exposed granites are cupolas on a single elongated batholith which reaches a depth of at least 8 and possibly 20 km. The magnetic anomalies between Dartmoor and Bodmin Moor support the idea of interconnexion. A more detailed interpretation of the gravity anomalies shows that the contacts between the granite and the enveloping country rocks generally slope outwards. For Dartmoor, at least, the base of the batholith seems to be deeper in the south. A mechanism of emplacement combining forcible intrusion with stoping, in which the magma rose in the south, is consistent with the shape suggested. In marked contrast to the granites of the mainland and Scilly Isles there is only a small drop in the Bouguer anomalies over the Lundy granite, suggesting a laccolithic space form.

The present high ground corresponding with the granite exposures of the mainland is shown to be isostatically compensated, or even overcompensated, by mass deficiencies implied by the negative anomalies. As the anomalies seem to be caused by the low density of the granite the compensation is almost certainly caused by the relatively low density of the batholith itself. The distribution of the compensating mass deficiency thus suggested is in closest agreement with Pratt's hypothesis. The depth of compensation is unusually low at about 10 or 15 km.

There is a marked southward increase of the Bouguer anomalies over the Start and Lizard peninsulas which is thought to be related to the presence of a thrust affecting these regions. Similarly, the northward decrease of the gravity anomalies across Exmoor is attributed to a major overthrust beneath which a great thickness of Carboniferous and Devonian rocks is likely to be present. It is thus possible that Coal Measures are to be found at no great depth beneath the Devonian rocks of the Dunster–Minehead region.

Over the Culm synclinorium three east-west ridges of higher Bouguer anomalies are superimposed on a westerly regional gradient and are shown to be of shallow origin. The high magnetic anomalies in this area suggest the presence of magnetic rocks extending to a considerable depth.

A smaller gravity 'low' coincides with the Crediton trough of Permo–Triassic rocks. A detailed traverse at North Tawton indicates that the trough here is V-shaped and has a maximum depth of 340 m. Depth estimates have also been obtained for the Tertiary lacustrine deposits of Bovey Tracey and at Petrockstow.

1. Introduction

The results of two independent geophysical investigations together covering the counties of Devon and Cornwall, part of Somerset, the Scilly Isles and Lundy are presented in this paper. The southern and western part has been covered by a regional network of gravity stations by one of us (A. A. D), assisted, at times, by other members of the Department of Geodesy and Geophysics, Cambridge University; this work was originally planned to supplement geophysical observations in the English Channel. The rest of the region, comprising central and north Devon, was surveyed by the remaining authors working from the Sedgwick Museum, Cambridge. A series of vertical field magnetic traverses were also observed (by M. H. P. B. and D. M.-S.) to strengthen the interpretation of the gravity anomalies and in particular to investigate the possible continuity at depth of the Dartmoor and Bodmin Moor granites.

The only previous geophysical work of relevance is the pendulum gravity survey made by Bullard & Jolly (1936). The general level of the Bouguer anomalies obtained by Bullard & Jolly seems to be about 2 mgal above our gravimeter values. Otherwise their values, which they did not interpret, are in general agreement with ours.

2. Summary of the stratigraphy and structure

A simplified geological map covering the region surveyed is shown in figure 1. The region consists of intensely contorted and thrust Palaeozoic rocks intruded by granite masses and overlain in parts by relatively undisturbed Permian and later deposits. The main structural

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feature is a complex synclinorium whose axis, composed of Carboniferous Culm Measures (Ussher 1892, Owen 1950), passes east-west through central Devon. To the north, Devonian marine rocks with three important sandstone intercalations of Old Red Sandstone type crop out between Barnstable and Minehead. South of the synclinorium Devonian marine rocks consisting of slates, sandstones and limestones crop out throughout south Devon and Cornwall except for the low-grade schist area of the Start peninsula (Tilley 1923) and the igneous complex of the Lizard (Flett & Hill 1946). A synthesis of the structure is given by Hendriks (1937).

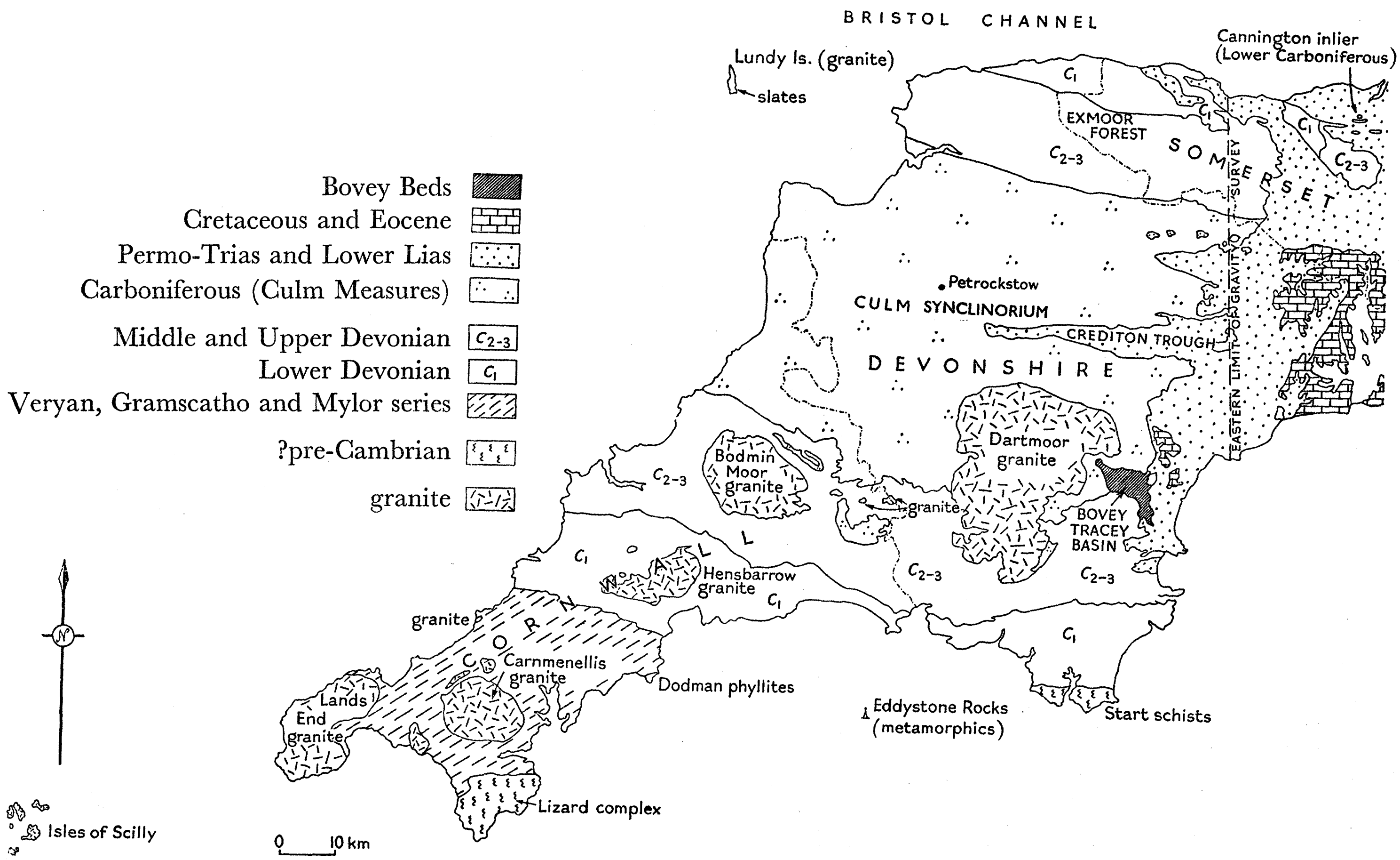

Figure 1. Simplified geological map of Devon, Cornwall and part of Somerset.

The alkali granite masses (figures 1 and 2) cut across the pre-Permian structures but have caused considerable doming particularly around Dartmoor. Associated with the granite chain is a belt of mineralization (Dewey 1925; Hosking 1950; Dines 1956). Apart from a small patch of supposed Devonian slates in the south-east corner Lundy Island is formed of a granite which has been described by Dollar (1942).

The New Red Sandstone deposits (Hutchins 1954) unconformably overlie the folded rocks and include volcanic rocks around Exeter (Tidmarsh 1932). A small but deep basin of Upper Oligocene lacustrine deposits lies south-east of Bovey Tracey and there is a similar basin (of uncertain age) near Petrockstow.

For a detailed treatment of stratigraphy and structure the reader is referred to the Regional Guide (Dewey 1948) and to the individual papers mentioned.

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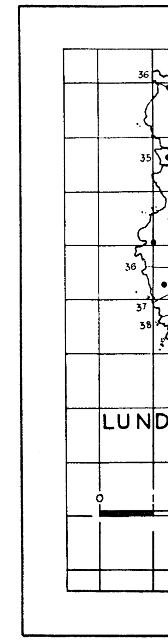


	Densities used for Bouguer correction			
Permian	New red	2·50	mica schist	2·70
granite	Culm measures	2·68	hornblende schist	3·00
BAMPTON base station	Devonian	2·57, 2·73	serpentine	2·60
station	granite	2·58, 2·63	gabbro	3·00
5 mgal isogal	Bouguer anomalies referred to I.G.F.			
1 mgal isogal	National Grid and coast lines after Ordnance Survey			

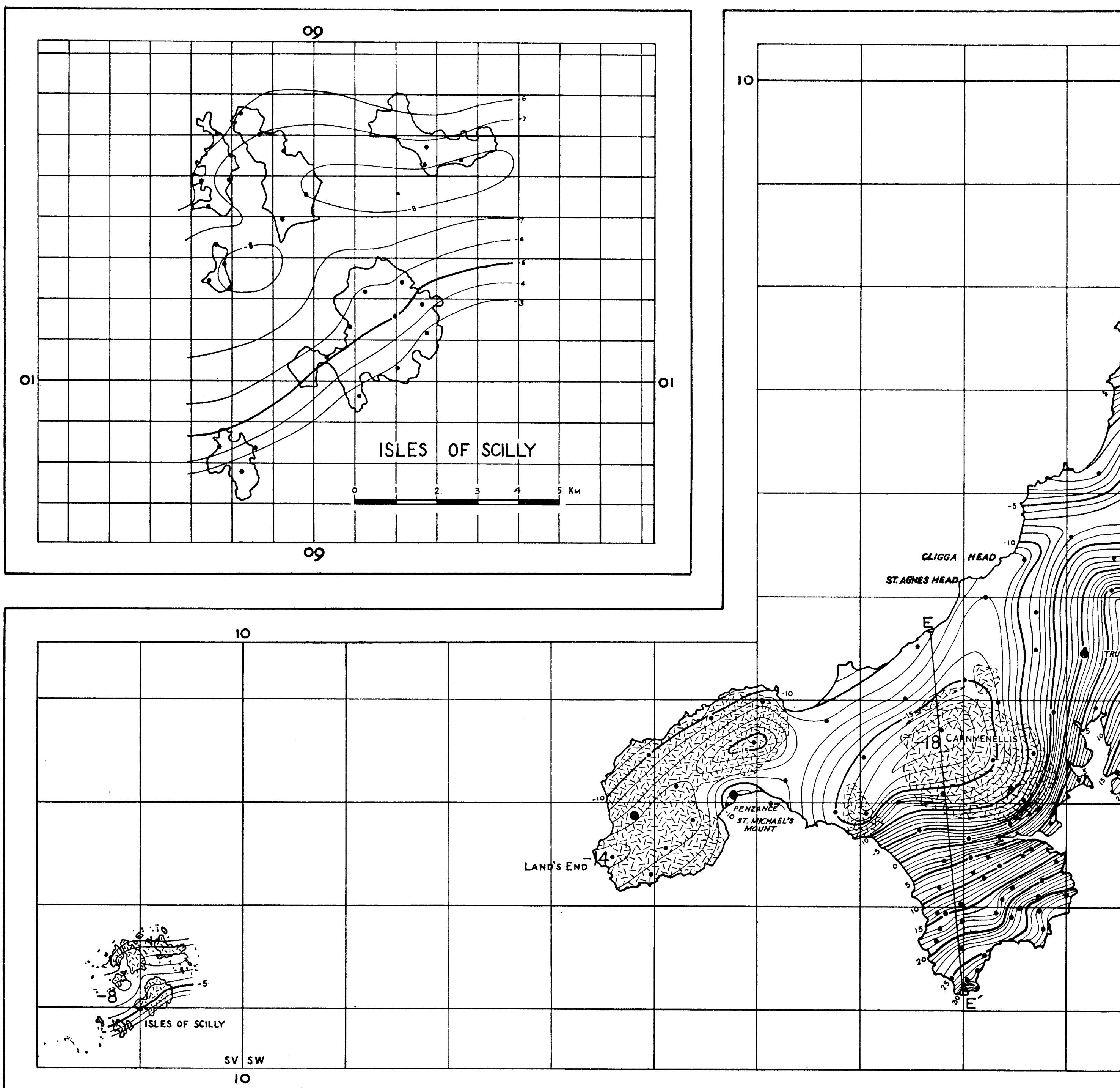
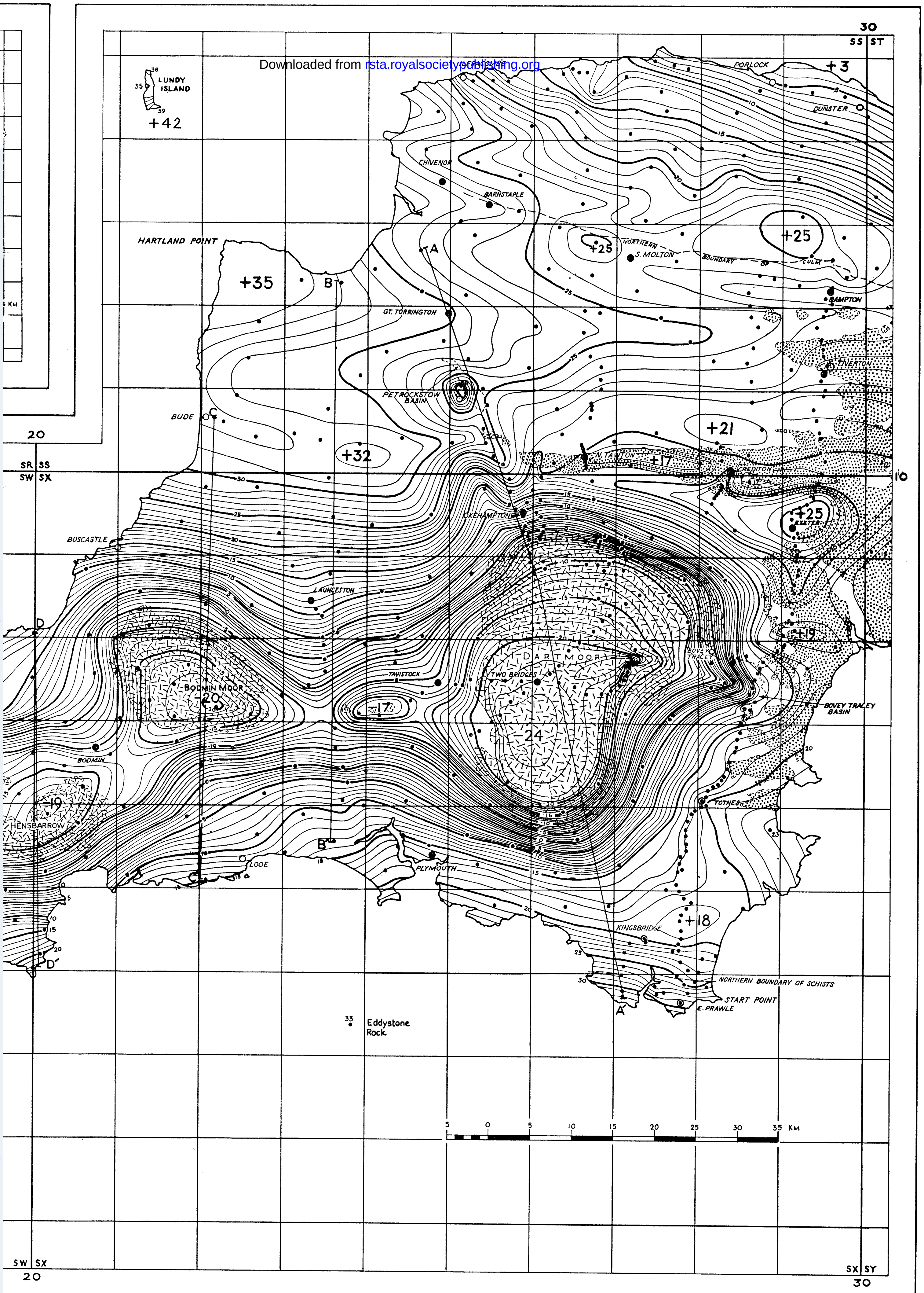


FIGURE 2. Bouguer ano



of south-west England.

3. General description of the gravity and magnetic surveys

3·1. *The gravity surveys*

All our gravity measurements were made with a Worden gravimeter belonging to the Geological Survey of Great Britain. Dr W. Bullerwell (private communication) considers the probable error in the calibration of this instrument to be 0·06%.

The positions of the base stations are shown on figure 2. These are mostly connected to two or more neighbouring bases and the average closing error for the resulting network is about 0·02 mgal. However, the base stations at Truro, Penzance, St Just, Hughtown and Lundy Island do not lie on closed loops, but errors of the same order are estimated from the drift curves. The base network is connected to the British Petroleum Company's gravity survey in Somerset at the Bampton and Exeter bases. Cook's (1953) value of absolute gravity at Bampton is used for relating the Bouguer anomalies to normal gravity.

The errors at the intermediate stations are estimated from the drift curves to be about 0·06 mgal. In north Devon the interval between drift control readings at base stations was usually less than 3 h, but longer intervals were necessary in south Devon and Cornwall and particularly for the connexions to the Scilly Isles, Lundy Island and Eddystone Lighthouse.

The elevation corrections are based on the Newlyn datum and the rock densities stated in §4. Most of the terrain corrections were estimated, the zone method of Hammer being used only where precision was required for the interpretation of small anomalies. These estimated corrections appear to be correct to 0·2 mgal.

The stations' positions are marked on the Bouguer contour map for south-west England (figure 2). A traverse from Bampton to East Prawle made by the British Petroleum Company has been included by their kind permission. The numerical gravity results are not reproduced here but are deposited at the Geological Survey and Museum, London, and at the Departments of Geology and Geophysics, Cambridge.

3·2. *The magnetic survey*

A few exploratory magnetic traverses were made with two Watts vertical field magnetometers belonging to the Department of Geodesy and Geophysics, Cambridge. At many of the stations readings were taken on both instruments set up about 100 yards apart.

The magnetic base station was situated near Launceston. No other base stations were established since each traverse could be completed within a day. However, a number of intermediate stations were reoccupied several times for drift control.

The correction for daily variation was obtained from Abinger Magnetic Observatory. The correction applied for the gradient of the earth's field was determined by the method of least squares from the observed values at fifty selected stations and is shown in the title of figure 3. The reduced magnetic values of figure 3 are relative to the average field for the region and are not related to any observatory measurement of the absolute field.

4. Rock densities in Devon and Cornwall

The density values (which are needed both for the calculation of the elevation correction and for the interpretation of the anomalies) are based on 400 direct density measurements on rock specimens and four gravimeter density traverses. These are summarized in table 1.

It is thought that the estimates of the bulk densities of the individual formations are likely to be subject to errors of about 0·03 g/cm³, although the uncertainty may be slightly greater for the Culm and Devonian rocks because of the difficulty in assessing the litho-logical proportions. The consequent error in the elevation correction for a station at 1000 ft. O.D. is less than 0·5 mgal.

TABLE 1

formation	lithology	number of specimens	number of exposures	saturated bulk density (g/cm³)	range (g/cm³)	estimated lithological proportions	mean surface density (g/cm³)	upper limit of density (at depth) (g/cm³)
Permo-Trias	sandstone	8	1	2·35	0·05	40 %		
	conglomerate	7	1	2·60	0·03	60 %	2·50	2·65
Culm	sandstone		D	2·49	0·04	40 %		
	shale	18	2 and D	2·67	0·07	50 %		
	limestone	12	2	2·69	0·01	10 %	2·61	2·72
Devonian (north Devon)	arenaceous	31	3 and D	2·55	0·03	55 %		
	shale	29	4	2·72	0·02	45 % (shale and slate)	2·62	2·71
	slate	25	5	2·69	0·03			
Devonian (south Devon)	arenaceous	15	3	2·61	0·03	15 %		
	limestone	10	3	2·70	0·01	27 %		
	slate	42	7	2·73	0·06	58 %		
	volcanics	9	4	2·86	0·03		2·69	2·75
Devonian?	Lundy slate	3	1	2·71	0·02			
Start complex	mica-schist	3	1	2·70	0·04	80 %		
	green schist	(Lizard value used)				20 %	2·75	2·78
Lizard complex	hornblende schist	18	3	2·99	0·04			
	gabbro	18	3	2·94	0·08			
	serpentine	63	7	2·65	0·10			
	granite gneiss	6	1	2·65	0·05			
	Dartmoor granite	12	2 and 2D	2·61	0·02	(The upper limit to the granite densities is about 0·04 larger than the saturated bulk densities)		
	Bodmin Moor granite	11	2	2·64	0·02			
	Hensbarrow granite	7	2	2·58	0·01			
	Carnmenellis granite	1	1	2·64				
	Land's End granite	33	4	2·61	0·01			
	Scilly Isles granite	2	2	2·60	0·02			
	Lundy granite	8	2	2·58	0·01			

D = gravimeter determination.

The variation of density with depth for a given formation depends both on the pore collapse from increasing pressure and on the water content in the pores; apart from the arenaceous divisions the pre-Permian rocks are practically non-porous and thus provided there is no major change in mineral composition, the saturated surface densities should give a good estimate to considerable depths. Nevertheless, the uncertainties in the density contrasts needed for interpretation are liable to be about 0·04 g/cm³ or even greater.

5. DESCRIPTION OF THE GRAVITY AND MAGNETIC ANOMALIES

5·1. *The gravity anomalies*

The gravity contours for the regions surveyed are shown in figure 2. It can be seen that there are a sufficient number of gravity stations to give an adequate delineation of the larger anomalies. A more detailed survey, however, would no doubt refine these contours.

Before proceeding to the interpretation of the anomalies, it is desirable to relate them to a probable background field, and, if possible, to discover how it varies regionally. Since metasedimentary formations seem generally to have a moderately constant value of density in bulk—about $2·75 \pm 0·05$ g/cm³—the undisturbed Bouguer anomaly over out-cropping metasediments provides the best background estimate. The average Bouguer anomaly for the whole region surveyed is 9·2 mgal, the low value of the average obviously

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being due to the negative anomalies over the Cornubian granite chain which occupies nearly half of the area. A moderate number of measurements out to sea would be necessary to obtain a reliable assessment of the background field. In the absence of such information, the values over the Culm synclinorium, increasing from about 20 mgal in the east to about 35 mgal in the west, are used in the following interpretations, bearing in mind that some form of increase of mass must be postulated to account for the higher values in the west. The magnitude of the Bouguer anomalies to the immediate north-east of Kingsbridge suggests that the field to the south-east of Dartmoor attains approximately the same background value as found over the eastern end of the Culm outcrop. The main anomaly changes may be summarized as follows:

(i) A belt of negative anomalies follows the line of the Cornubian granite chain. Over the exposed granites are individual minima of the order of 40 to 50 mgal below the background field; their precise relative values cannot be determined because of our lack of knowledge of regional changes away from the Culm synclinorium.

(ii) A smaller decrease of gravity is associated with the Lundy granite.

(iii) The anomalies increase rapidly southwards over the Start and Lizard peninsulas. In a similar way they fall relatively uniformly by about 20 mgal in a north-north-easterly direction across Exmoor.

(iv) Over the Culm synclinorium three east-west striking positive ridges are superimposed on the background anomaly which increases to the west.

(v) Local decreases in the Bouguer field, much disturbed by the large neighbouring anomalies, coincide with the Crediton trough of New Red Sandstone rocks and the sedimentary basins of Bovey Tracey and Petrockstow.

5·2. *The magnetic anomalies*

The values of the corrected vertical magnetic field that have been observed are shown in figure 3, and a profile from Exmoor to Totnes (in south Devon), illustrating the main character of the anomalies, is given in figure 4.

A striking feature of the map is that the mean reduced field to the north of the granites is conspicuously higher than the field over the granites and in the region further south, which could be taken to mean that our value for latitude and longitude correction may not be reliable. However, the regional gradient obtained from the least-squares reduction is about the same as the average gradient over the greater distances between magnetic observatories in south England and Scotland. And any uncertainty remaining could not possibly be large enough to prejudice the existence of the rapid changes of anomalies which are discussed.

The main change of the field from relatively high over the Culm synclinorium to relatively low to the south, marked on figures 3 and 4, is remarkably abrupt. It corresponds with the northern margins of the Dartmoor and Bodmin Moor granites, and is embayed to the south in the intervening region. Along this line large negative anomalies are to be found locally, while immediately to the north is a belt of the largest positive anomalies. To the south the anomalies do not vary greatly, but northwards they again fall as Exmoor is approached from the south. Occasionally in south Devon basic igneous rocks produce large but very localized anomalies.

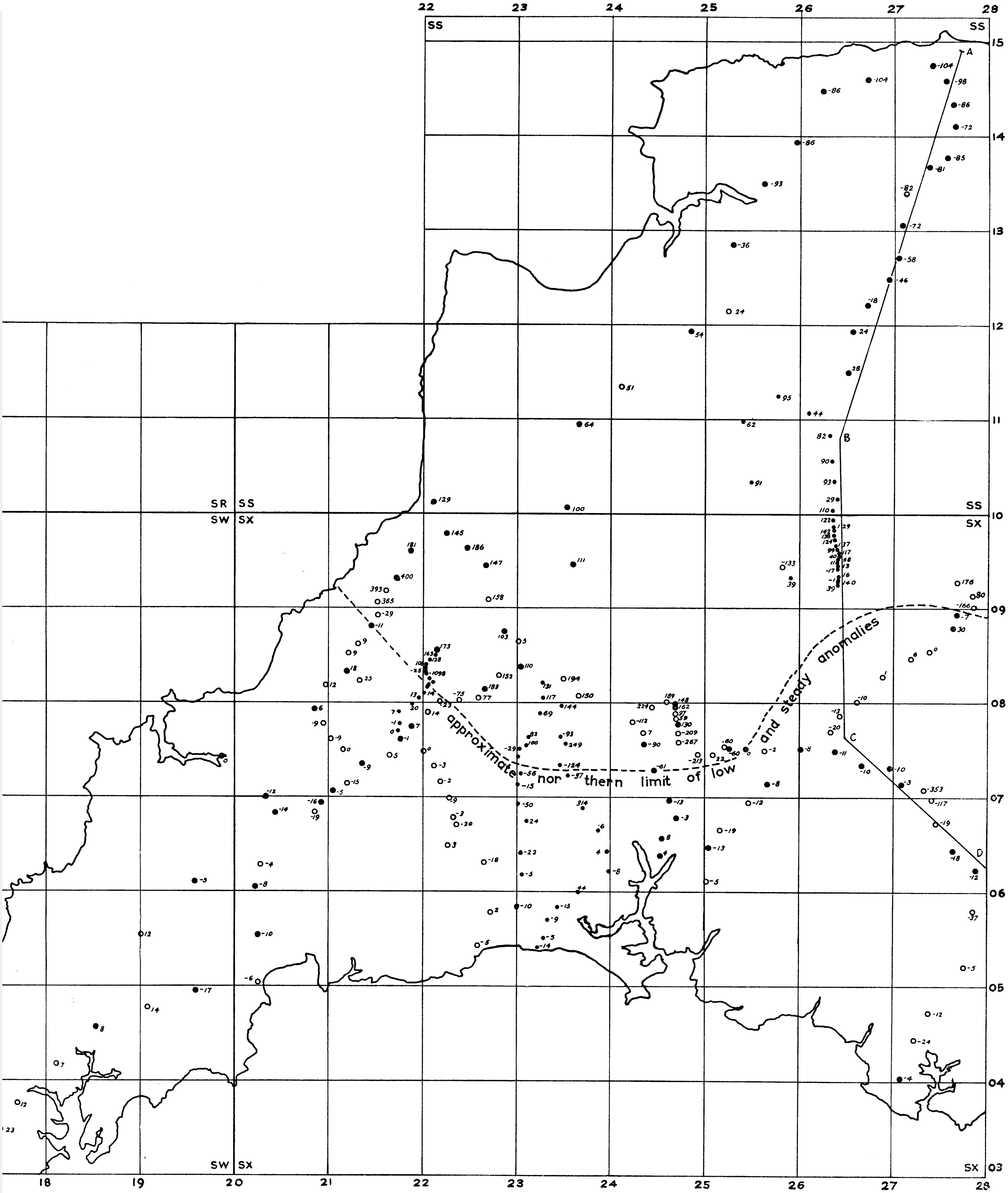

FIGURE 3. Vertical magnetic field of south-west England. ●, ○, two magnetometers: ●, difference $\leqslant 8\gamma$; ○, $> 8\gamma$. •, one magnetometer. 10 km National Grid squares are shown. Regional gradient: $5{\cdot}69\gamma$/km, grid north; $0{\cdot}28\gamma$/km grid west.

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6. The main belt of negative gravity anomalies

6·1. *A preliminary interpretation of the anomalies*

The most conspicuous feature of the Bouguer anomaly map (figure 2) is the belt of large negative anomalies passing down the centre of the peninsula and continuing in the Scilly Isles. This belt is somewhat variable in width and irregular in its course: it closely follows the Cornubian granite belt. The outcrops of the granites are also marked on figure 2 and it can be seen that each corresponds to a local minimum anomaly. Hence the belt of negative anomalies is clearly associated with the granites. It may be remarked that it is now becoming apparent that post-tectonic granites are usually accompanied by negative gravity anomalies (see, for example, Bean 1953; Bott 1957; Cook & Murphy 1952).

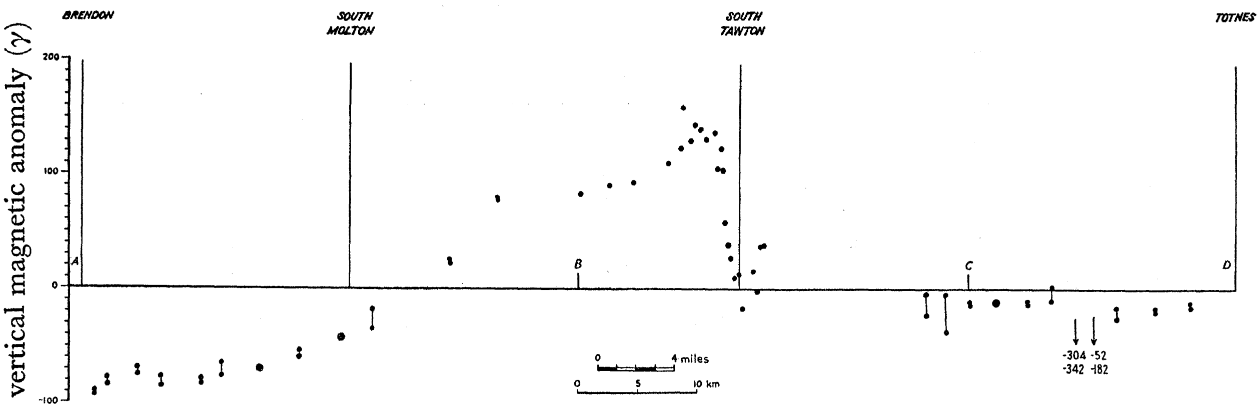


FIGURE 4. Profile of the vertical field magnetic anomalies across Devon from north to south. The line of the profile is shown on figure 3.

Our first step in the interpretation of the anomalies is to discover their cause. The measurements of density (see § 4) show that the granites are consistently about 0·1 g/cm^3 lower than the Culm and Devonian rocks, and about 0·15 g/cm^3 less dense than the metamorphics. On mineralogical grounds an upper limit to the possible density contrast between the granites and metasediments would appear to be about 0·2 g/cm^3. Thus a direct density contrast between granite and country rocks, perhaps increasing in magnitude if metamorphic rocks are reached at depth, is likely to provide the source of the anomalies. Further confirmation can be obtained by estimating, from the anomalies themselves, the maximum possible depth to the top of the mass deficiency responsible. Using a formula given by Bullard & Cooper (1948), it may be shown that the topmost part of the upper surface of the structure producing the Dartmoor anomalies cannot be deeper than about 11 km. An alternative method of estimating the maximum possible depth to the top of the anomalous mass, depending on the following formula for a point mass (Bott & Smith 1958)

$$\text{depth} = 0{\cdot}86 \times \frac{\text{maximum anomaly}}{\text{maximum horizontal gradient}},$$

gives a limiting depth of about 10 km for the Dartmoor anomalies. Thus the origin of the anomalies is shallow. A direct density contrast best satisfies this requirement.

The magnitude of the individual minima of the anomaly belt diminishes westwards. This could be caused by a smaller extent in depth for the anomalous body in the west, or alternatively by the regional gradient observed over the Culm synclinorium (see §6·6).

The magnetic survey covers Dartmoor and Bodmin Moor. The field over the granites (figure 3) is stable compared with the greater local and regional fluctuations over the country rocks to the north, suggesting a relatively uniform polarization in the granites. Koulomzine & Brossard (1947) noted a similar low magnetic relief over granites in Canada. The anomalies along the northern margins of both granites are much disturbed by highly magnetic basic igneous rocks. The broader regional change from the persistent 'high' of the north to the persistent 'low' over the granites indicates a polarization contrast between the country rock (high) and the granite (low) extending to considerable depths. There is no comparable anomaly change along the southern margins of the granites which shows that the polarization of the granite and southern country rocks are similar.

6·2. *The Dartmoor anomalies*

The Dartmoor granite is the largest and easternmost member of the Cornubian chain. The associated gravity anomaly is also larger in extent and has greater marginal gradients than the anomalies over the other granites.

A profile across the Dartmoor anomaly is shown in figure 5, AA'. The undisturbed regional field in the vicinity is at least 20 mgal and it is probably not greater than 25 mgal. The least value of the Bouguer anomaly which has been measured is $-24\cdot4$ mgal at a station near Two Bridges but the actual minimum value may be slightly lower. The total extent of the anomaly over Dartmoor is therefore likely to lie between 45 and 55 mgal. The greatest gravity gradients are to be found across the southern boundary of the granite, where average values of 5 mgal/km extend over horizontal distances of up to 5 km. Steep gradients also occur across the northern and eastern boundaries.

The size of the total anomaly indicates that the body of lower density rock (i.e. the granite) continues downwards to a great depth. Taking the total anomaly as 45 mgal, rough estimates of the depth for a variety of density contrasts (table 2) have been obtained by treating the granite as a vertical cylinder with a radius of 20 km.

TABLE 2

density contrast (g/cm^3)	depth of base (km)
−0·055	infinite*
−0·10	17
−0·15	9
−0·20	6

* Hence 0·055 g/cm^3 is the minimum acceptable contrast.

An estimate of the total mass deficiency can be obtained by applying Gauss's theorem to the anomaly (see also § 6·8). The theorem states that the total gravitational flux of the anomaly through a horizontal infinite plane is equal to $2\pi G$ times the mass deficiency. Calculated in this way the mass deficiency of Dartmoor is found to be $1\cdot15\times10^{18}$ g. This is likely to be a low estimate (perhaps by 15%) as the flux was summed only for a finite area.

If the contact between the granite and the country rocks is taken as the density interface there is a simple criterion available to test its attitude, arising as follows. The steepest gravity gradients theoretically lie within the granite boundary should the contact slope inwards and without should the contact slope outwards. In either case there is an abrupt change of gradient at the exposed contact. The magnitude of the change provides a measure of the angle of slope provided the density contrast is known, or vice versa, by the following 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 of the contact.

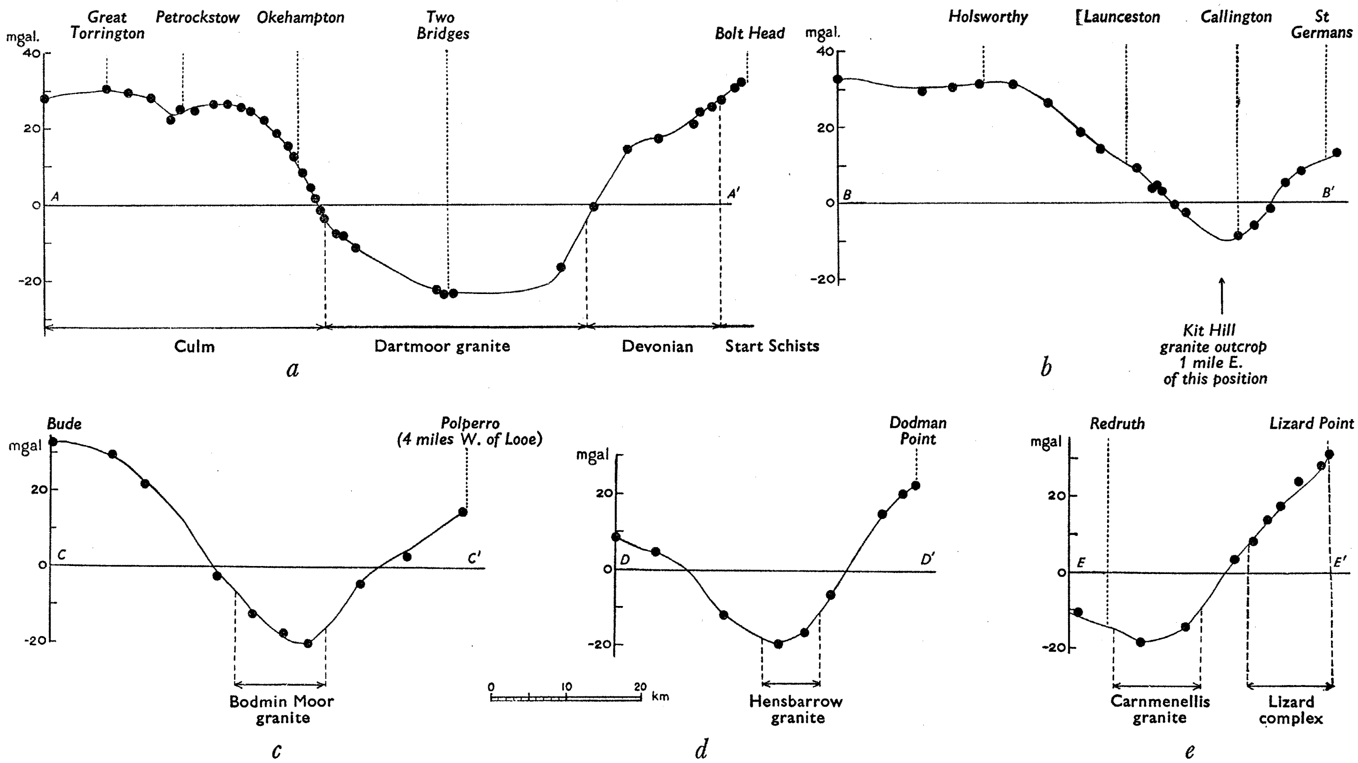


FIGURE 5. Profiles of the Bouguer anomalies across the granite belt, constructed from the gravity contours. The lines of the profiles are shown on figure 2. Gravity stations on or close to the profiles are included.

The illustrated profile across the Dartmoor granite (figure 5, *AA′*) clearly shows that there is an abrupt outward increase of gradient at the position of the northern contact, thus qualitatively demonstrating the outward slope of the boundary. The observed change of gradient for two traverses across the northern contact is estimated as about 1·9 mgal/km (±0·6 say), corresponding to a slope of 45° for a density contrast of 0·09 g/cm^3 and either 18° or 72° for 0·15 g/cm^3. Other features of the profile are inconsistent with a slope lower than about 40°, so that our figures suggest an outward slope of between about 40° and 75°.

The gradients of the extreme southern part of the margin are the steepest observed, suggesting that the contact is nearly vertical or perhaps slopes slightly outwards. The contact also dips steeply outwards along the whole of its south-eastern, eastern and north-eastern exposure. The western margin clearly slopes outwards at a much lower angle.

The remaining important feature of the Dartmoor granite is that the minimum anomaly lies to the south of the centre of the outcrop. There are two alternative explanations which we can suggest. The granite may extend deeper in the south; or there may be a lower density for the southern part of the granite body. The gravity results cannot themselves decide between these hypotheses, but we incline to favour the former.

A more definite conception of the space form has been obtained by a model (figure 6) which satisfies some of the main features of the anomaly for an assumed uniform density contrast of 0·16 g/cm³. At the surface the model is co-extensive with the exposed granite, and is in the form of a vertical cylinder in the south and a rectangular block in the north. The main implication of the model is that the granite is thicker in the south than in the

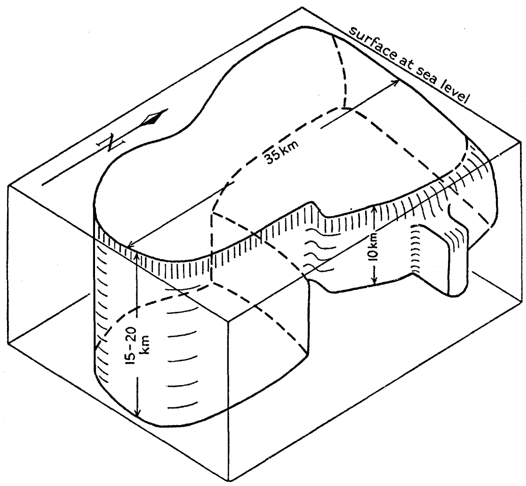


FIGURE 6. Three-dimensional model showing a possible shape of the Dartmoor granite. The granite density has been taken as 0·16 g/cm³ lower than the country rocks.

north if the density contrast is actually approximately uniform. It should be pointed out that the model is only intended as a representation of the density distribution and is in no way incompatible with the base in the southern part merging into a uniform layer of granitic composition below.

In conclusion, the granite has the space form of a batholith terminated along its northern, eastern and southern margins by a contact which is nearly vertical or slopes steeply outwards. The southern contact is steepest and the depth reached by the granite in the south probably greatest.

6·3. *The anomalies between Dartmoor and Bodmin Moor*

A continuous belt of negative anomalies connects the Dartmoor and Bodmin Moor anomalies (figure 5, *BB′*). The two small outcrops of granite at Hingston Down and Kit Hill lie on the axis of the belt and coincide with a subsidiary region of minimum anomalies (figure 2). The absence of steep gradients and large changes of anomaly along the axis implies that the mass deficiency causing the Dartmoor and Bodmin Moor anomalies is continuous in the intervening region. Interpreting on the basis of § 6·1, our conclusion is that the Dartmoor and Bodmin Moor granites are joined by a ridge of granite which is exposed at Hingston Down and Kit Hill.

There are not enough gravity stations to justify a detailed interpretation of the behaviour of the granite ridge. However, the Bouguer values, as they stand on the map (figure 2), seem to indicate that the roof is at most always within 2 or 3 km of the surface.

The north-south magnetic traverses between Dartmoor and Bodmin Moor demonstrate the intervening continuity of the abrupt magnetic change (§6·1) which elsewhere coincides with the northern boundary between the granites and the country rocks. This provides additional independent confirmation that the Dartmoor and Bodmin Moor granites are joined. The position of this abrupt change in the magnetic anomalies (figure 3) is presumed to mark the abutment of the more magnetic country rocks of the north against the subsurface granite.

6·4. *The Bodmin Moor and Hensbarrow anomalies*

The lowest observed anomaly over Bodmin Moor is about −20 mgal. Allowing for the westerly regional increase observed to the north, the total anomaly is probably as great or even greater than over Dartmoor.

The marginal gradients (figures 2 and 5, *CC′*) are significantly lower than those observed around Dartmoor. Along the northern and southern margins the steepest gradients appear to commence a mile or two beyond the contact. The overall interpretation is that the interface between the granite and the country rocks slopes outwards at a low angle for up to two miles and then plunges more steeply outwards. The steeper dips are likely to be lower than those deduced for Dartmoor.

The minimum anomaly occurs well to the south of the centre of the granite as it is exposed at the surface. Thus the granite is probably thickest beneath the southern part of the Moor where the anomaly is most negative.

Owing to the relative narrowness of the Cornish peninsula to the west of Bodmin Moor a complete interpretation of the remaining anomalies cannot be given. A further complication arises from the independent positive anomalies immediately to the south of the line of granites (described in § 7). Consequently, the remaining interpretations are mainly concerned with the roof regions of the granites.

The minimum anomaly over the Hensbarrow granite (figure 5, *DD′*) lies a little to the north of the central line of the outcrop. The closure of the gravity contours indicates that the main outcropping granite belongs to the southern half of the actual roof region. The granite extends northwards for several miles beneath a thin covering of sedimentary rocks and amply embraces the small inlying masses at Castle-en-Dinas (marked on figure 2). In marked contrast, the steep Bouguer gradients along the southern margin show that the southern boundary of the roof approximately coincides with the contact and that it slopes outwards at about the same angle of dip as the southern boundary of the Bodmin Moor granite.

The intervening gravity anomalies suggest that the Bodmin Moor and Hensbarrow granites are joined by a ridge, on the north flank of which the town of Bodmin is situated. The greatest depth of the granite roof along the culmination of this ridge (as estimated from the anomaly at the station lying 2 km south-east of Bodmin town) is probably not greater than $1\frac{1}{2}$ km. The anomalies (figure 2) show that these two granites are closely connected and related to each other and can really be considered as a single mass split by a depression of the roof.

From the Hensbarrow anomaly a narrow belt of negative anomalies interpreted as representing an unexposed granite ridge trends slightly south of westwards. It joins the north-eastern corner of the next large negative region at Cligga Head where there is another small outcrop of granite.

6·5. *The Carnmenellis and Land's End anomalies*

In the western part of Cornwall the belt of negative anomalies expands into a broad region of low gravity relief enclosing the following outcropping granites: (1) The Carnmenellis granite; (2) the Land's End granite; (3) the Godolphin granite lying between the Carnmenellis and Land's End masses; (4) the small granite outcrop forming the island of St Michael's Mount—about 5 km directly east of Penzance; (5) the Carnbrea and Carn Marth granites situated immediately to the north of the Carnmenellis mass; and (6) the isolated granite outcrops of St Agnes Head and Cligga Head. These granites are therefore outcrops within the roof region of a large interconnecting mass, which probably considerably exceeds the Dartmoor granite in areal extent.

The only part of the boundary to the roof region that can be seen from the gravity anomalies follows the southern contact of the Godolphin granite and continues along the southern and eastern contact of the Carnmenellis granite. The contact apparently dips nearly vertically at the south-eastern corner of the Carnmenellis granite. Elsewhere the steep gradients lie beyond the limits of the outcropping granites, and the contact dips outwards at a similar angle to the southern wall of the Bodmin Moor and Hensbarrow granites.

The remaining boundaries of the roof region are situated beneath the sea. The gravity contours show that the Land's End granite is elongated in a north-east–south-west direction and that it may have a considerable extension under the sea.

An approximate estimate of the thickness of the killas overlying the granite can be obtained by use of the formula giving the gravity effect of an infinite sheet of material. The anomalies on the Godolphin granite and the northern end of the Land's End granite both have minima of very nearly -16 mgal. In the intervening region the anomaly rises to -11 mgal. The gravity anomaly due to the slab of killas is therefore about 5 mgal. Assuming a density contrast of 0·15 g/cm^3 between the killas and the underlying granite, the thickness of killas below sea level required to produce this anomaly is 800 m. In general, it seems unlikely that the killas overlying the granite is very much more than 1 km thick in the region between the outcropping granites.

6·6. *The Scilly Isles anomalies*

The gravity contours of the Scilly Isles are elongated in a north-east–south-west direction sugesting that the Scilly Isles granite extends in this direction. There exists a gap in the gravity data between Land's End and the Scilly Isles, and consequently it is not possible to determine to what extent the intervening region is underlain by granite.

The minimum value of the gravity anomalies on the Scilly Isles (-8 mgal) is higher than that on any of the mainland granites. If the regional gradient over the Culm synclinorium continues out to sea, the total negative anomaly of the Scilly Isles relative to the regional value may be as large as, or larger than, the Dartmoor anomaly. Alternatively, the granite batholith may decrease in depth and width, but an unambiguous interpretation must await further gravity measurements at sea.

6·7. *General discussion of the structural features, mineralization and origin of the granites*

(1) **The structural features.** From the gravity anomalies it has been possible to estimate the approximate shape of the Dartmoor granite body and to delineate the roof region and obtain a qualitative estimate of the attitude of the walls for the remaining granites.

Perhaps the most important conclusion is that the granites of the mainland are interconnected. As early as 1837 Sedgwick and Murchison postulated an underground connexion to account for the continuity of the tract of mineralization. The idea of interconnexion has since been frequently held, and Rastall (1931), for example, considered the exposed granites to be cupolas on a large batholith of considerable depth separated by a relatively thin sedimentary cover. The gravity and magnetic anomalies thus amply confirm the accuracy of Rastall's interpretation of the belt.

The outer boundary of the Dartmoor granite roof region coincides with the exposed contacts on the north, east and south. It clearly forms the eastern end of the whole granite belt. The roof regions of the remaining granites are only partly exposed, the sub-sedimentary extensions characteristically lying to the north of the exposures. The walls may be locally vertical but more usually slope steeply or moderately steeply outwards. The gravity results suggest that the southern wall is usually the steeper.

The size of the total anomalies gives evidence that the granite continues to depths of 10 and 20 km, which is about half the width of the roof. The persistent displacement of minimum anomalies to the south of the axis of the batholith may mean that the floor is consistently deeper in the south. In several ways, then, the granite belt is geometrically asymmetrical.

(2) **The mineralization.** A belt of mineralization (figure 7) which was once of considerable economic importance follows the length of the granite belt. Along the eastern part of its course it is displaced to the south of the axis of the minimum gravity anomalies. It is also displaced here to the south of the granite exposures.

A connexion seems to exist between the granite belt and the mineralization although the exact relations are not clear. Hosking (1950) has suggested that the mineralization is caused by unexposed granite ridges, and there is a close general correlation between these postulated ridges and the interconnecting granite ridge suggested by the gravity anomalies. It is thought, however, that if the patches of mineralization *south* of the main granite ridge are caused by proximity of granitic material then it must be in the form of thin sheets occupying only a small proportion of the total country rocks; sheets more than 200 m thick should produce a detectable anomaly.

It is possible that the peculiar position of the belt of mineralization is related to the asymmetry of the granites. Thus the mineralization may be connected with crustal or magmatic conditions leading to or resulting from the apparently deeper floor in the south.

(3) **The emplacement and origin of the granites.** The bearing of the various geometrical conclusions deduced from the gravity anomalies on our ideas of the mode of emplacement and origin of the granites is discussed in this paragraph. The discussion is mainly restricted to the Dartmoor granite as it has been interpreted in greatest detail. Our conclusions, however, are likely to apply also to the other masses. Some of our results have already been briefly mentioned in a theoretical study of negative gravity anomalies over granites (Bott 1957).

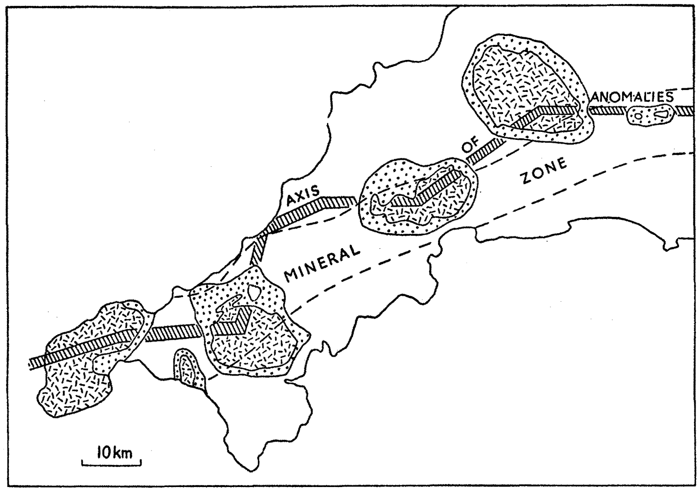


FIGURE 7. Relation of the axis of the belt of the negative gravity anomalies to the belt of mineralization. The exposed granites (usual ornament) and their contact aureoles (stippled) are shown. The geology is based on Geological Survey maps and memoirs.

From an examination of the orientation of felspar phenocrysts, Brammall (1926) concluded that the magma of Dartmoor rose vertically in the south and then flowed horizontally northwards. Such an interpretation is consistent with the shape of the model (figure 6) and could be taken to indicate emplacement by forcible intrusion. Balk (1937) also favoured forcible emplacement because of the similarity with the schlieren domes of Europe. However, the outward slope of the contacts also satisfies one of the requirements of the stoping hypothesis, which similarly provides a consistent explanation of the shape if it be taken that the southern half of the country rocks stoped to the greater depth. Stoping can also account best for the removal of the 1000 cubic miles of denser rocks which have disappeared beneath Dartmoor alone.

Perhaps a complete explanation is provided by a combination of the forcible emplacement and stoping hypotheses. It is suggested that the magma first rose in the south, possibly by stoping. The gravitational body forces which would then necessarily arise from the presence of a chamber of magma of density lower than the surrounding rocks would cause an outward hydrostatic pressure on the upper regions of the chamber. The outward pressure would then be relieved by a horizontal forcible migration to the north along fractures initiated by incipient stoping of the chamber walls. The country rocks would then be displaced downwards and perhaps partially forced upwards, making room for a further supply of magma from the south.

It may be noted that there is no sign of a basic front of sufficient width to accommodate the enormous bulk mass removed during emplacement. Nor does the gravity field reveal the presence of a stoped block of a size comparable to the granitic body, suggesting that if it is present it is either at great depth or compensated gravitationally by an additional deep-mass deficiency such as could arise from a crustal downwarp. There is certainly no indication of a basic intrusion beneath of sufficient size to give rise to the granites by differentiation; this strongly supports Brammall & Harwood's (1932) conclusion of non-basaltic parentage for the magma.

6·8. *The bearing of the granites on the isostatic compensation of the south-west*

It has already been suggested (§ 6·7 (3)) that the gravitational body forces necessarily arising from the existence of a body of low-density granite magma within the denser country rocks around were partly responsible for the mechanism of the granite emplacement. It has also been seen (§ 6·1) that the gravity anomalies suggest the solid granite still to be significantly lower in density than the country rocks. Consequently, gravitational body forces must still exist. These can only be relieved by opposing stresses such as

TABLE 3. TEST OF ISOSTASY IN THE SOUTH-WEST

region	assumed background anomaly (mgal)	mass deficiency (10^{18} g)	mass of ground above sea level (10^{18} g)
Dartmoor	25	1·15 (integration east of 25, south of 10)	1·42 (between 25 and 30, roughly south of 11)
Between Dartmoor and Bodmin Moor	30	0·51 (between 23 and 25, south of 10)	0·47 (between 23 and 25, south of 13)
Bodmin Moor and Hensbarrow	30	1·26 (between 19 and 23, south of 10)	0·68 (all land between 19 and 23)
Carnmenellis and Land's End	30	1·17 (all land west of 19)	0·27 (all land west of 19)

The areas are defined by national grid lines; the average rocks density is taken as 2·7 g/cm³.

could be produced by a load on the crust, in the form of ground raised above the general level of the surrounding region. The process of the uplift of the region with a deficient crustal mass in relief of these stresses is in effect an isostatic mechanism tending to produce conditions of lowest gravitational potential energy. The actual incidence of uplift depends on whether the crust is able to withstand the stress differences caused by the granites.

The hypothesis that an isostatic mechanism is responsible for the present uplift of Dartmoor, and the south-west peninsula generally, can be crudely tested by comparing the mass deficiency below sea level with the total mass of the corresponding land above the average height of the neighbouring countryside. The mass deficiencies below sea level for the various portions of the granite belt (obtained by integrating the Bouguer anomaly) are compared with the corresponding masses of the ground above sea level in table 3.

Dartmoor appears to be slightly undercompensated. This may be because of an underestimate of the mass deficiency, or alternatively Dartmoor may be uplifted merely above the surrounding country rather than above sea level. Bodmin Moor and Hensbarrow are overcompensated; Carnmenellis and Land's End considerably overcompensated. The overcompensation may not be as great as appears on first sight, since these granite mass deficiencies may be responsible for the uplift above the general level of the sea floor on either side of the peninsula.

The main conclusion seems to be that an isostatic mechanism can reasonably account for the uplift of Dartmoor, and of the south-west peninsula generally, above the surrounding parts. The general tendency for the south-west to form a 'positive' region throughout the Mesozoic and Tertiary can also be understood in this way.

It should be remarked that the negative gravity anomalies, in themselves, are not conclusive evidence that the uplift is isostatic. They simply show that the Archimedean upthrust of the granites is as great as or even greater than the weight of the surrounding terrain. It is not known whether this upthrust is alone sufficient to overcome the resistance of the rocks to fracture and flow, or whether conditions of general crustal tension or instability are necessary before the upthrust can become effective.

The type of compensation envisaged here is much shallower than is normally suspected. Geometrically there is closest agreement with Pratt's hypothesis with the lower density rocks extending in the form of granite beneath the high ground. In the south-west the preceding interpretation of the gravity anomalies suggests that the depth of compensation (i.e. the depth of the base of the density contrast) varies between 10 and 20 km.

The uplifted region of the peninsula extends beyond those parts underlain by granite. This leads to the concept of 'inverse regional compensation'. In other words, the mass deficiencies are responsible for the uplift which takes place mainly locally but partly over a more widespread region.

7. South Devon and the Lizard peninsula

7·1. *The Start peninsula*

On the Start peninsula an important geological discontinuity, 'the Start Boundary', separates the folded but little-metamorphosed Devonian rocks of the north from the highly contorted low-grade schists which lie to the south. The Start Boundary is a plane of major dislocation (Tilley 1923) and probably part of an extensive overthrust system. However, the evidence for the dip of the Boundary plane at the surface suggests that it is vertical (Tilley 1923).

From a value of about 20 mgal at Kingsbridge, the gravity anomalies increase nearly uniformly to a value of 32 mgal on the south coast of the peninsula (figure 8). The gradient is about 1·5 mgal/km, indicating that the anomalies are unlikely to originate below a depth of 10 km. The local irregularities of the stations on the traverses shown in figure 8 are probably caused by local outcrops of doleritic dykes and green schists.

The Devonian rocks of south Devon seem to have a density of about 2·69 g/cm^3 (table 1). The bulk density of the Start metamorphics, estimated as 80% mica schist and 20% green schist, is likely to be close to 2·75 g/cm^3. The density contrast should not greatly exceed 0·06 g/cm^3 and may even be negligible.

The gravity anomaly profiles across the Start Boundary (figure 8) cannot be entirely explained on the hypothesis that the metamorphics are thrust over the Devonian rocks, because the increase of anomaly commences abruptly 5 km north of the Boundary, instead of coinciding with it. For similar reasons the anomaly profiles cannot be explained on the hypothesis that the Boundary dips to the north. The remaining simple possibility is that the Boundary is vertical or nearly so. To test this hypothesis the observed gravity profiles are compared in figure 8 with calculated profiles for models with vertical density interfaces reaching depths of 10 km (for a density contrast of 0·05 g/cm^3) and 4 km (for 0·10 g/cm^3). The agreement is seen to be poor for both models.

It is therefore clear that the anomaly on the Start peninsula is at least partly caused by an unseen structure or body of rocks. An explanation as a crustal upwarp affecting the Mohorovičić and Conrad discontinuities is incompatible with the character of the observed

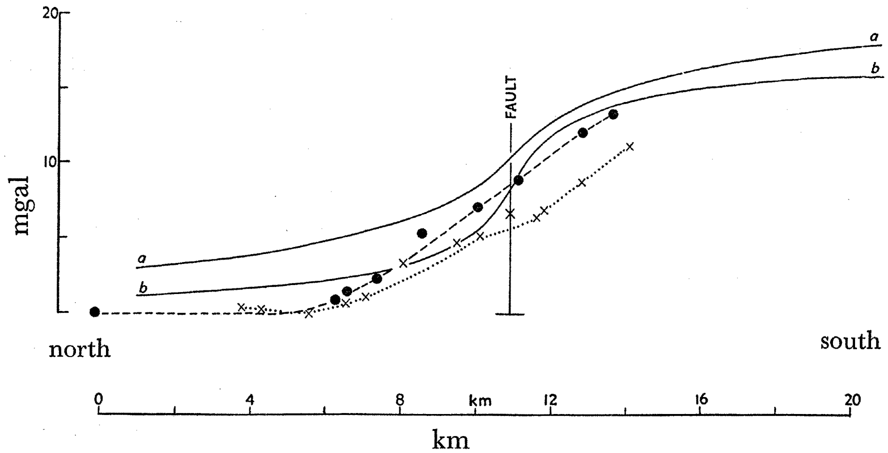


FIGURE 8. Comparison of observed gravity profiles along the Start peninsula with profiles calculated for vertical density interfaces extending to depths of 4 and 10 km. Throw (km): *a*, 10; *b*, 4. density (g/cm^3): *a*, 0·05; *b*, 0·10. ●, western profile; ×, eastern profile.

anomalies, because such a structure would not be able to account for the magnitude of the observed gradients or for their abrupt commencement near Kingsbridge.

The Start anomalies can perhaps best be explained as being caused by an unexposed wedge-shaped body of denser rocks, which thins northwards and extends about as far north as the 20 mgal contour passing through Kingsbridge. It is tentatively suggested that the denser body may be associated with the Start metamorphics and that it may take the form of a thrust slice.

7·2. *The Lizard peninsula*

The geology of the Lizard peninsula is complex, but the area is essentially composed of patches of hornblende and mica schists subsequently intruded by serpentinite, gabbro and granite gneiss. Flett & Hill (1946) consider that these rocks have been thrust from the south or south-east over the killas. A simplified map of the geology showing also the Bouguer anomalies is given in figure 9.

The steep and moderately uniform gradients extend from the Carnmenellis granite along the whole length of the peninsula. The gradient is slightly greater than on the Start peninsula, but the maximum anomalies observed in the two areas differ only by 1 mgal. In the north the gradient forms part of the Carnmenellis anomaly, but its southward persistence suggests an independent cause on the Lizard, with the two anomalies merging into each other in the intervening region.

The average density of the Lizard rocks, calculated according to the areal extent of each lithology, is hardly likely to be significantly greater than the density of the killas. Nevertheless, within the complex there are large density variations, the serpentinite and granite gneiss being about 0·3 g/cm^3 less dense than the gabbro and hornblende schist (table 1).

Superimposed on the general gravity gradient are small residual anomalies associated with the gabbro and granite gneiss, but there are no large changes of anomaly from one igneous lithology to another. These features of the anomalies combine with the geological

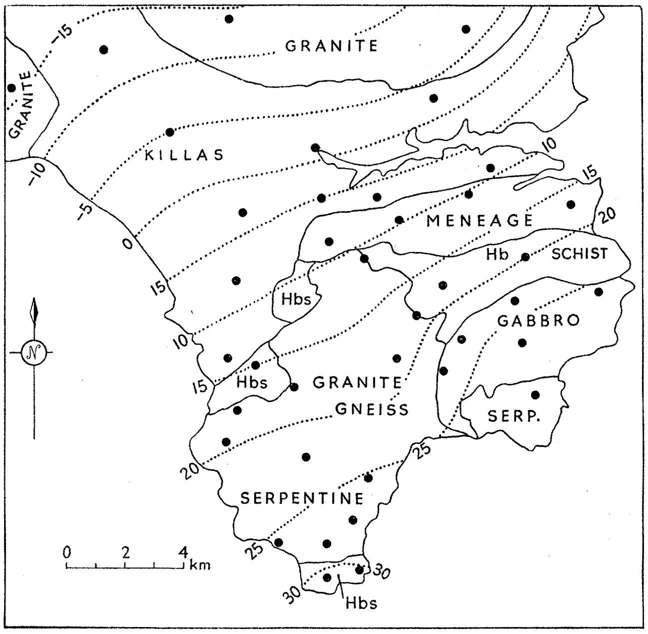


FIGURE 9. The Lizard peninsula showing the Bouguer anomalies and the simplified geology. Hbs stands for hornblende schist.

observation that the serpentinite is cut by gabbro dykes to suggest that the serpentinites and granitic rocks are of small thickness, and that the whole area is dominantly underlain by gabbro.

The positive anomaly of the Lizard can now be readily explained by a density contrast of about 0·2 g/cm^3 between the killas and a large mass of gabbroic rocks thickening southwards and perhaps underlain by a thrust. The Start and Lizard anomalies seem to belong to the same structural line to which the southern margin of the granites appears also to be related.

8. North Devon

8·1. *Lundy Island*

Lundy Island consists mainly of granite which is in contact with a small outcrop of supposed Devonian slates at the southern end. A minimum Bouguer anomaly of 35 mgal lies near the centre of the island. The anomaly rises gently to 36 mgal at the extreme north end and increases more rapidly over the contact (at 3·7 mgal/km for 0·4 km) to 39 mgal in the south. An enlarged gravity anomaly map of the island is included in figure 2. Although there is insufficient information to delineate the intrusion accurately the shape of both the gravity and submarine contours suggest a roughly circular mass which has a diameter only slightly greater than the length of the island. The granite outcrop probably extends below the sea to west, east and north, but the greatest extension is likely to be to the west.

Measurements on rock samples (table 1) show that the granite at the surface is about 0·13 g/cm^3 less dense than the slates. However, the granite at the surface is slightly weathered and the samples of slate were necessarily taken from close to the contact, so that the actual contrast in density may be lower at depth. We take it that this density contrast is the cause of the change of anomalies on the island.

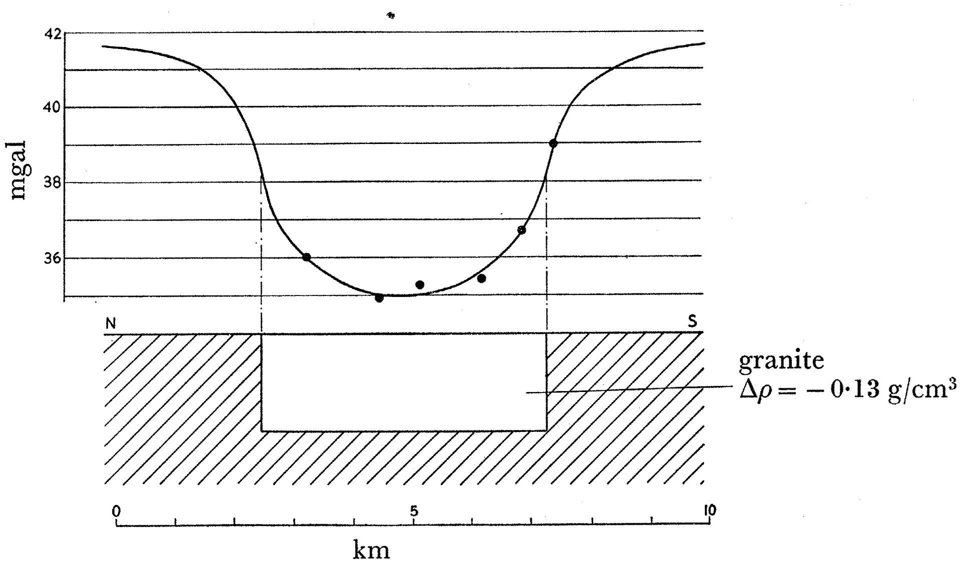


FIGURE 10. The observed Bouguer anomalies (●) over Lundy Island compared with the anomalies calculated for the model shown (—).

An impression of the thickness of the granite can be gained by assuming it to be in the form of a vertical cylinder. The observed profile is most accurately reproduced by a cylinder of density contrast 0·13 g/cm^3, diameter 4·8 km and depth to base 1·6 km (as shown in figure 10). The observed marginal gradient and change of anomaly between the contact and a station 3·2 km within also fit a cylinder of contrast 0·11 g/cm^3, diameter 7·1 km and depth 1·8 km, although the general agreement is not so good. These estimates would not be greatly altered for considerable departures from cylindrical shape provided the contact was steep, as seems likely from geological observations made by Dollar. The most satisfactory geological interpretation seems to us to be that the granite is a sheet or laccolith of thickness about 1·6 km. This is in agreement with Dollar's conclusion that the granite is formed of four separate intrusions of which the first consolidated as a sheet, possibly laccolithic in form.

Extrapolation of the gravity anomaly caused by the granite suggests that the local regional value of the Bouguer anomaly is at least 42 mgal, implying that there is a body of dense rocks within the area. It is not possible to tell whether this is a regional or local structure from the present measurements.

The Lundy gravity anomaly bears small resemblance to the anomalies so far observed over British post-tectonic granites. There is clearly little similarity to the gravity field of the large Cornubian batholith (§ 6). Perhaps the closest parallel is with the Mourne granite of Tertiary age which has been covered in a gravity survey made by Cook & Murphy (1952). They found that the anomalies are at the most only slightly lower over the granite and they consider that it is less than 4000 ft. (1·2 km) thick. A high anomaly to the south of the Mournes is attributed to an unexposed basic mass with which the granite is genetically connected. On the basis of the gravitational comparison we favour a Tertiary age for the Lundy granite although we should not be justified in unduly pressing this argument. Blundell (1957) has recently suggested a Tertiary age for the Lundy dyke swarm from a palaeomagnetic study.

Dollar considers the Lundy granite to be more closely related to the Armorican granites of the south-west than to the Tertiary granites of Ireland and Scotland. Perhaps the chemical and mineralogical similarities suggesting this interpretation are an indication of similar chemical conditions at depth in the crust rather than of identical age and petrogenesis.

8·2. *Exmoor*

Over Exmoor the Bouguer anomalies fall from about 25 mgal along the northern boundary of the Culm rocks to 3 mgal on the north coast between Porlock and Dunster (figure 11). The gradient is moderately uniform and has an average value of about 1·3 mgal/km. North of Bampton slightly steeper gradients of about 1·7 mgal/km form the southern half of the anomaly.

Throughout most of the region where we have traced this anomaly the gravity contours strike constantly slightly north of west, being clearly related to the strike of the Devonian rocks. At Ilfracombe they swing round towards the north-west before leaving the coast. The position of the eastern end of the anomaly is not known although the British Petroleum Company found it at Bridgwater which is about 30 km east of Dunster.

The interpretation of the anomaly is simplified by its two-dimensional character. An estimate of the maximum possible depth to the top of the structure responsible can be obtained by taking the anomalous mass to be concentrated uniformly along a horizontal line (Bott & Smith 1958). The depth of the line is then given by the following formula:

$$\text{depth} = 0{\cdot}65 \times \frac{\text{maximum change of anomaly}}{\text{maximum gradient}}.$$

The anomaly appears to continue into the Bristol Channel and so its total extent is unknown. If it is taken as 30 mgal a depth estimate of 11·4 km is obtained by applying the formula. Alternatively, the structure may have the form of a step, in which case an analogous formula gives a maximum depth of about 6 km. The maximum possible depth to bodies of a finite density contrast is bound to be less than these estimates: it is concluded that the structure is moderately shallow.

The negative anomalies of Exmoor mean that a body of rocks of relatively lower density underlies the region. An impression of the total thickness of these lower density rocks can be obtained by calculating the thickness of an infinite sheet of material giving the observed change of anomaly (22 mgal). If the rocks are 0·20 g/cm³ lower in density their thickness is calculated as 2·6 km and if 0·10 g/cm³ lower as 5·2 km. However, as the structure cannot be an infinite slab and as the gradient is likely to extend into the Bristol Channel these values are certainly underestimates of the necessary thicknesses.

Some various geological hypotheses which might account for the Exmoor gravity gradient are as follows:

(1) Certain two-dimensional gravity anomalies of large size are interpreted as **crustal** rather than geological structures; the depth of the Mohorovičić discontinuity may change or alternatively the individual crustal layers may vary in thickness at the expense of each other. An interpretation of this kind would not be satisfactory for the Exmoor gradients because of the relatively shallow depth already established for the density contrast.

(2) An **unexposed granite** might account for an anomaly of the observed size. The shape of the contours and the steady gradients, however, are not characteristic of typical anomalies over granite masses. The anomaly, then, seems to require a thick body of relatively low-density sedimentary rocks below Exmoor.

(3) It does not seem reasonable to suppose that **low-density rocks of Lower Devonian age** stratigraphically underlie the Foreland Grit in great enough thickness to give rise to the anomaly; at least a further 4 km thickness of sandstone would be needed, and it would have to thin out rapidly to the south in step with the rise of anomalies.

Nor does it seem feasible for the underlying **pre-Devonian rocks** to undergo a sufficient change in bulk density since they are practically non-porous. Also in general experience their density is rather higher than the measured density of the Devonian rocks of Exmoor.

(4) A more satisfactory hypothesis accounts tectonically for the lower density sedimentary rocks. In this way, **the Devonian rocks of Exmoor may form a large thrust mass** overriding a great thickness of Carboniferous and Devonian rocks of relatively low density.

We consider that the last hypothesis of a major thrust beneath Exmoor provides the most reasonable explanation of the anomalies. On the evidence of the British Petroleum gravity traverse Falcon (in Cook, Hospers & Parasnis 1952) has already suggested a major overthrust beneath the Quantock Hills, the Devonian having overridden the Carboniferous.

The first requirement of the 'thrust hypothesis' is an adequate density contrast. A contrast of 0·10 g/cm³ or more seems possible if the authochthonous Carboniferous and Old Red Sandstone rocks are of a more northerly facies and contain a good proportion of arenaceous rock, while the grit intercalations within the exposed Devonian formations dwindle southwards. It is also possible that the anomaly partly arises from a density contrast between the lower density Carboniferous and Old Red Sandstone rocks and denser rocks (metamorphics?) beneath, provided that the interface rises southwards: there is some evidence from the magnetic survey (§8·3) for the possibility of metamorphic rocks beneath the Culm synclinorium, and the resulting density contrast could be as great as 0·15 to 0·20 g/cm³.

From a study of the development of the Old Red Sandstone and Carboniferous thicknesses known in the neighbouring regions of South Wales and Bristol it would appear that an adequate thickness of lower density rocks are available to account for the anomaly, even without tectonic thickening. Two-dimensional models which satisfactorily represent the observed gravity profiles are shown in figure 11, assuming the anomalies cease to fall rapidly just beyond the coast. A notable feature of both models is the apparent southward steepening of the thrust planes, necessitated by the southerly position of the steepest gradients. Alternative explanations of these steep gradients may come either from the disposition of the low-density grits within the exposed Devonian, or from an abrupt southward rise of the rocks forming the floor of the lower density autochthonous rock mass. An interesting consequence of the models is that the horizontal tectonic transport of the suspected thrust is at least 14 km.

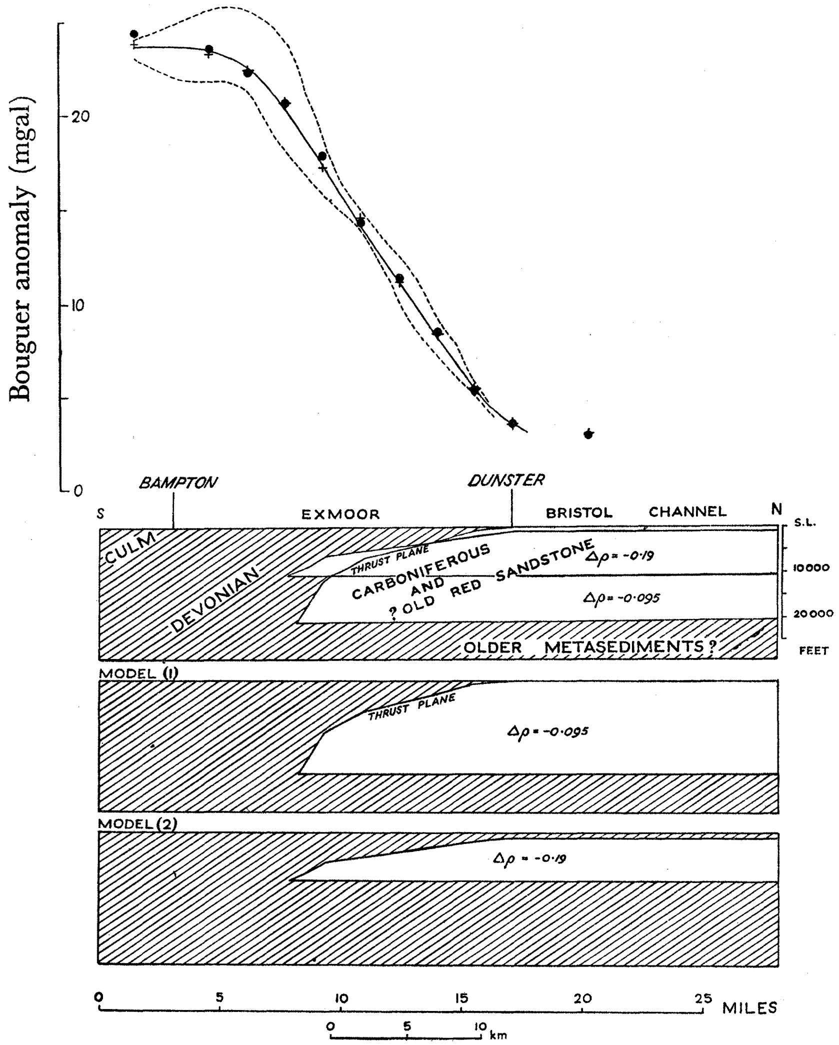


FIGURE 11. The envelope and average of five profiles of the Bouguer anomalies across Exmoor compared with the anomalies calculated for two theoretical models based on the thrust hypothesis. Both models are shown in the upper geological section and are separated for clarity below. —, average of five profiles at 5-mile intervals; grid bearing, 17° (east profile through Bampton). - - -, envelope of profiles. Theoretical anomaly models 1 (●) and 2 (+).

The main geological evidence supporting the idea of a major overthrust comes from the Cannington inlier which lies about 6 km north-west of Bridgwater (figure 1): described by Wallis (1924) who gives a full summary of earlier work. The main inlier of 'tremendously disturbed' Carboniferous limestone (S_1 age), surrounded by Triassic strata, dips to the south as if to *underlie* an inlying belt of Middle Devonian rocks outcropping less than 200 m to the south. Wallis thinks these relations are best explained by a major pre-Triassic fault between the Lower Carboniferous and Middle Devonian outcrops. If this fault is a thrust, as was suggested over 60 years ago by Ussher (1891), the disturbed character of the limestone is readily understood.

There seems to be no real tectonic objection to a major overthrust beneath Exmoor and the Quantock Hills. A thrust occupying a comparable position in the Hercynian chain is found in Belgium and France. This is the 'Charriage du Condroz', by which Devonian rocks have been transported at least 30 km northwards (as estimated by Foumarier (1933)) over the autochthonous Carboniferous rocks. It may even be suggested that the proposed thrust beneath Exmoor is the westward continuation of the 'Charriage du Condroz'.

The supposed thrust plane is to be expected to outcrop beneath the Trias and Bristol Channel along a line stretching from the Cannington inlier and continuing westwards on the seaward side of the coast line almost to Porlock. It is then presumed to diverge from the coast.

Coal Measures strata may underlie the overthrust in the Dunster and Porlock district. Whether these would be sufficiently undisturbed for economic use is open to question.

The two magnetic traverses across north Devon show that the anomalies decrease by about 150 γ in a northerly direction towards Exmoor and in a position well to the south of the gravity gradient just discussed. The lack of correspondence suggests that the two effects may not have a directly common origin. The positive magnetic anomaly is to be discussed in the following section (§ 8·3).

8·3. *The Culm synclinorium*

There are no pronounced changes in the gravity anomalies over the Culm synclinorium. The main features are three east-west ridges of relatively higher anomalies superimposed on the westerly regional gradient of 0·15 to 0·19 mgal/km. The ridges are roughly parallel to the Culm structures in contrast with the more north-westerly trend of both anomalies and structures over the Devonian rocks to the north.

The regional gradient may be caused by a layer of rocks of low density at depth which becomes thinner in a westerly direction, or by a similar westerly thickening of a higher density layer. If the density contrast between this layer and the rocks which enclose it is 0·10 g/cm^3, then the rate of change of its thickness is calculated as 0·037 to 0·042 km/km, giving a total change in thickness of the layer of 2·8 km between Tiverton and Bude. This steady regional change may possibly be a variation in thickness of the crustal layers themselves such as a slight westward rise of the Mohorovičić and Conrad discontinuities.

Little has been published about the structure of the Culm rocks. Owen (1950) described the coastal section between Bude and Hartland Point and Ussher (1892) has given a general description of the Culm Measures inland but no information about the structure in detail. Lithologically the Lower Culm is less arenaceous than the Upper Culm and should therefore have a higher average density. The Culm appears to have a similar bulk density to the Devonian of north Devon, but may be up to about 0·05 g/cm^3 lower than the Devonian of south Devon (see table 1).

The known structure would be expected to produce small gravity undulations striking east-west superimposed on a broad east-west trough. This roughly corresponds to the observed anomalies after they have been corrected for the effect of the granite chain to the south and the Exmoor anomaly to the north. The depths of the horizontal line mass distributions which could reproduce the observed total anomalies and maximum gradients of the three east-west ridges at points north of Okehampton are 1·9 km for the north ridge, 2·9 for the central and 3·2 km for the southern ridge. Hence, the origin of these anomalies certainly lies close to the surface. The ridges could be attributed to local upwarping of the underlying rocks or to a preponderance of less arenaceous Culm in these areas. In the first case the depth of the base of the Culm might be between 1·5 and 3·0 km and in the second case perhaps two or three times as deep.

North of Dartmoor there is a belt of high positive anomalies which reaches a maximum of about 5 mgal above the expected regional value at Exeter, and would be larger if full allowance were made for the effect of the Dartmoor granite. It is possible that the high anomalies may be related to the Permian vulcanism (Tidmarsh 1932). Alternatively, this may merely be the termination of the southern ridges of higher anomalies while the rapid decrease to the east reflects the incoming of the New Red Sandstone.

The high magnetic anomalies of the southern part of the synclinorium mean that there are more highly polarized rocks beneath. It has already been suggested that these magnetic rocks are truncated to the south by the granite belt (§ 6·1) and disappear northwards as Exmoor is approached (§ 8·2). One interpretation is that these anomalies may originate from basic igneous rocks within the Culm and Devonian formations which dwindle northwards. Another suggestion is that metamorphic rocks may be closer to the surface beneath the southern part of the synclinorium as a result of Hercynian thrust structures.

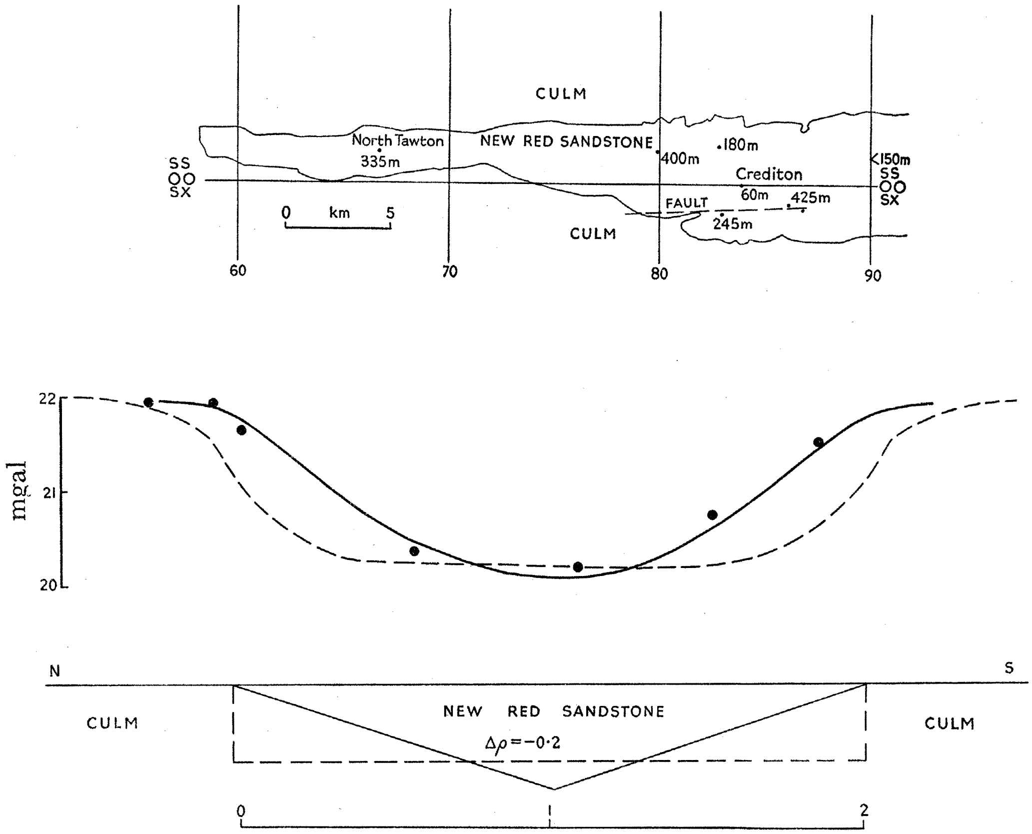
9. The sedimentary basins

9·1. *The Crediton New Red Sandstone trough*

The Crediton New Red Sandstone trough is followed for most of its length by a corresponding belt of relatively low Bouguer anomalies which can be attributed directly to the density contrast with the surrounding Culm rocks. The late Dr P. F. Hutchins (1954) carried out a detailed geological survey of the trough and found that the New Red rocks consist of about 60 % of conglomerates and 40 % of sandstones. These proportions suggest an average density of about 2·50 g/cm³ which is about 0·20 g/cm³ less than the Culm rocks.

At North Tawton there is a gravity traverse with closely spaced stations across the trough (figure 12). Two calculated profiles are compared with the observed traverse in figure 12. The poor correspondence of the profile for the rectangular model shows that the trough is not steep-sided at North Tawton. The anomaly is much better represented by the V-shaped trough which is 2 km wide and 340 m deep.

Elsewhere the stations are not sufficiently closely spaced to give information about the cross-section, but estimates of the depth of the New Red rocks below other gravity stations as calculated for a rectangular section are shown in the inset of figure 12. These estimates agree well with independent estimates of Dr Hutchins based on geological observations, except for the area east of Crediton where he considers the depth to be greater than 500 ft. (153 m). The accuracy of these estimates depends to some extent on the correction for the effect of the Dartmoor anomalies to the south. This was obtained by extrapolating the field of a model which fitted the Dartmoor anomaly. The source of error will be most serious near the centre of the trough where the probable error in depth is about 60 m.



kilometre scale (horizontal and vertical)

FIGURE 12. The observed Bouguer anomalies (●) across the New Red Sandstone trough at North Tawton compared with anomalies calculated for rectangular (- - -) and V-shaped (—) troughs. The inset shows the remaining depth estimates of the New Red Sandstone rocks. A density contrast of 0·2 g/cm^3 has been assumed.

9·2. *The Bovey Tracey basin*

South-east of Bovey Tracey there is a conspicuous kink in the closely spaced gravity contours along the eastern margin of Dartmoor (figure 2). If the Dartmoor anomaly is assumed to fall off monotonically eastwards beyond the granite contact, it is found that the kink is formed by a closed residual negative anomaly of about 6 mgal superimposed on the Dartmoor anomaly. This residual anomaly overlies the Bovey Tracey basin of Tertiary sediments and can best be attributed directly to their low density.

As the depth of the basin is likely to be small compared with its width, the depth below sea level at any place should be nearly proportional to the residual anomaly. There are not sufficient stations over the basin to construct a contour map of its floor, but the values we have do tend to confirm the basin-like shape. A depth of about 200 m below sea level corresponds with the lowest observed residual anomaly of −6 mgal if the density contrast is assumed to be 0·7 g/cm^3. A borehole at Teigngrace (near the centre of the basin) reaches a depth of 194 m below sea level; presumably the floor was nearly reached.

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9·3. *The Petrockstow basin*

The small china-clay basin near Petrockstow is 8 km in length from north-west to south-east and about 1·2 km wide on average. Two gravity stations were observed over the basin. The lower measured anomaly is 7 mgal below the local background field.

The clay density is assumed to be 0·7 g/cm^3 lower than the surrounding Culm Measures. The depth of the basin is then calculated as 245 m for a rectangular cross-section or 367 m for a V-shaped cross-section.

There are a few gravity stations to the east of the basin but none for 6 miles to the west, so that the behaviour of the regional anomaly is incompletely known. The estimates of depth should therefore be taken as tentative until further gravity stations have been observed and the density directly measured.

10. Conclusions

The exposed Armorican granite masses of the south-west have been shown to be cupolas of a large batholith whose floor lies at a depth of between 8 and 20 km; on the mainland the batholith can be divided into three main bodies (Dartmoor, Bodmin Moor–Hensbarrow and Carnmenellis–Land's End) connected by narrow ridges. The floors of the Dartmoor, Bodmin Moor and Hensbarrow granites may be deeper in the south, reflecting the general asymmetry. The granite contacts slope outwards in general and it has been possible to distinguish the roof and walls in many parts. The general spatial shape is consistent with a mechanism of emplacement combining forcible intrusion with stoping, the magma rising in the south.

It has been shown that the negative anomalies are caused by the relatively low density of the granite. The estimate of the mass deficiency below sea level appears to be greater than the total mass of the land above sea level along the granite belt, suggesting that the high ground is slightly overcompensated. The proposed compensation lies within the top 20 km of the crust and is distributed in a manner widely differing from the form usually envisaged for isostatic hypotheses.

The Lundy granite is thought to be a sheet slightly thicker than $1\frac{1}{2}$ km. The petrology and tectonics of this granite remain problematical, although the closest gravitational comparison is with the Mourne granite of Tertiary age.

The southward positive Bouguer gradients of the Start and Lizard peninsulas are thought to be related to a major thrust which may underlie these regions. The underlying denser rocks at Start, however, extend 3 or 4 km north of the position of the 'Start Boundary'.

The main decrease of the anomalies across Exmoor is also attributed to a large over-thrust beneath which it is thought that a thickness of at least 3 km of low-density Carboniferous and Old Red Sandstone rocks is present.

Over the Culm synclinorium three east-west ridges of high Bouguer anomalies are superimposed on a westerly regional gradient. These ridges can only be caused by shallow structures within or immediately below the Culm rocks. A high magnetic anomaly along the southern flank implies the presence of magnetic rocks extending to considerable depths.

The relatively low gravity anomalies over the Crediton New Red Sandstone trough suggest a V-shaped profile at North Tawton with a maximum depth of about 340 m. Negative residual anomalies also coincide with the Bovey Tracey and Petrockstow sedimentary basins and provide respective minimum estimates of 194 and 245 m for their depths.

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