

RECENT GEOPHYSICAL STUDIES IN SOUTH-WEST ENGLAND

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I. INTRODUCTION

Although a detailed knowledge of the surface geology of South-west England has been obtained from more than a century of research, it is only during the last fifteen years that knowledge of the deeper structure has become known through the use of geophysical methods. The methods which have been most profitably used are gravity survey (on land and at sea), magnetic survey (land and sea) and seismic refraction survey (at sea). Surface geology has also recently benefited from the results of radioactive age dating and palaeomagnetism.

It is the object of this paper to summarize these geophysical investigations and their interpretation; and to present new gravity results at sea and more sophisticated interpretations of some of the gravity anomalies than have hitherto been published.

It will be assumed that the reader is familiar with the stratigraphy and structure of South-west England. If not, reference may be made to the Regional Guide (Dewey 1948) or to the short summary in the gravity paper by Bott, Day and Masson-Smith (1958) with further references.

The seabed geology of the western approaches to the English Channel has been summarised by Whittard (1962). Donovan and others (1961) have given a map of the seabed geology of the Bristol Channel. This seabed geology, taken from these papers, is shown on Fig. 1.

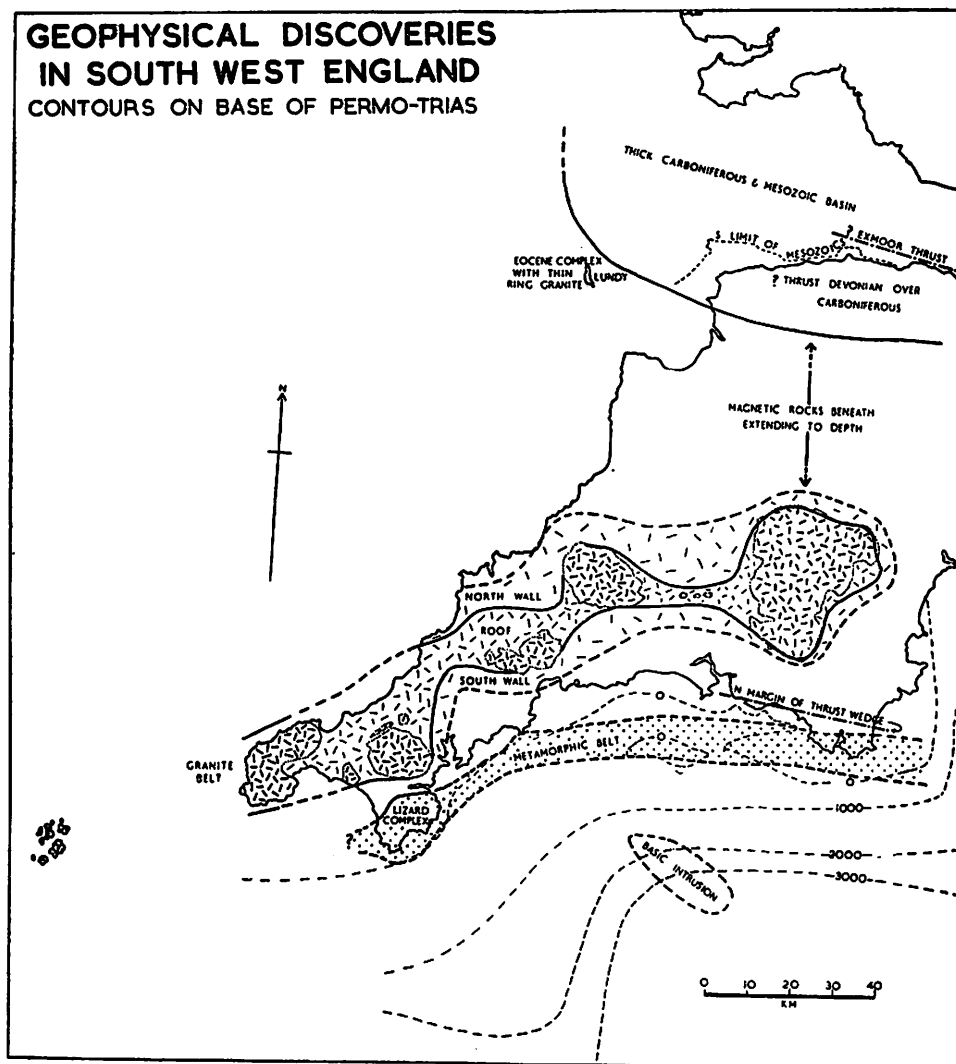


Fig. 10. Summary map showing the main findings of recent geophysical work in the South-west. The various boundaries are not meant to be accurate in position.

- (iii) Gravity, magnetic and seismic evidence is consistent with the concept of a Lizard-Dodman-Start thrust. In the Start peninsula the gravity anomalies require the denser rocks to extend north of the Start Boundary as an unexposed thrust wedge.
- (iv) The Devonian rocks of north Devon are underlain by a large thickness of relatively low density rocks. In explanation these Devonian rocks may have been thrust northwards over a basin containing thick Carboniferous rocks. The postulated autochthonous Carboniferous basin

extends beneath the Bristol Channel to South Wales. In the Bristol Channel it is overlain by synclinal Mesozoic sediments. This composite basin thins westwards at the longitude of Lundy Island.

- (v) The exposed granites (age about 270 My) form cupolas on a large inter-connecting granite batholith, which extends downwards at least 10 km and has well defined roof and outwards sloping wall regions. The granite has a tendency to be denser in the north flank of the batholith.
- (vi) The Cu-Sn-Pb-Zn mineralization (which is approximately the same age as the granite) is geometrically related to the granite batholith, but the relations may arise *either* due to late stage magmatic origin of the ore fluids *or* due to structural control by the batholith of the ore fluids rising from greater depths.
- (vii) The Exeter traps are not significantly different in age from the Dartmoor granite, suggesting a possible genetic connection.
- (viii) Past and present topographic uplift of the granite belt may be an isostatic response to the granite mass deficiency.
- (ix) South of Plymouth, there is an offshore Triassic basin reaching a thickness of at least 1,000 m and possibly controlling the position of the coastline. South of Eddystone there is seismic evidence for a metamorphic basement beneath thick Palaeozoic strata underlying the Triassic basin.
- (x) Magnetic anomalies suggest the presence of a plutonic intrusion, possibly basic, situated about 25 km south of Eddystone.
- (xi) The Lundy granite and dyke swarm are probably Eocene in age. The space form of the granite is consistent with a ring intrusion with the top of the sunken block about 2 km deep.
- (xii) A slight westward thinning of the crust, or increase in mean crustal density, is observed.

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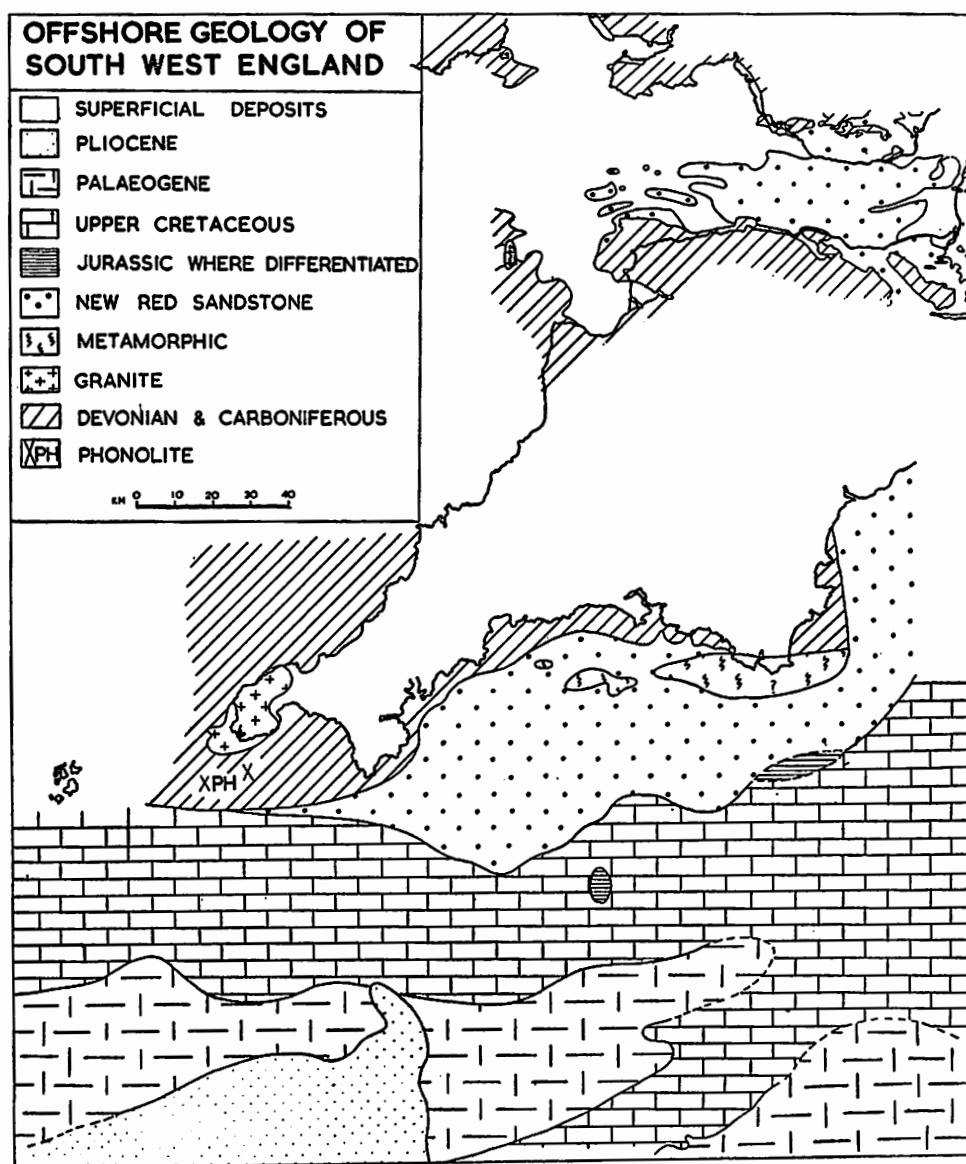


Fig. 1. Geological map of the coastal regions around the South-West after Donovan and others (1961) for the Bristol Channel and Whittard (1962) for the English Channel.

II. GRAVITY ANOMALIES AND THEIR INTERPRETATION

1. Description

The earliest gravity measurement in South-west England is reported to have been made by Adam Sedgwick in a mine; subsequently pendulum measurements have been made by Bullard and Jolly (1936) on land, and by Browne and Cooper (1950 and 1952) at sea.

More recently a regional gravity survey of South-west England (west of the line joining Dunster and Exmouth) was made by Bott, Day and Masson-Smith (1958). The main gravity features discovered were as follows:—

- (i) A belt of large negative gravity anomalies of up to 50 mgal amplitude follows the granite belt, the minimum gravity values corresponding with the outcropping granites.
- (ii) The Bouguer anomaly falls in a N.N.E. direction across Exmoor by about 20 mgal.
- (iii) The Bouguer anomaly rises southwards by about 10-15 mgal along the Start and Lizard peninsulas.
- (iv) A westerly regional gradient is observed over the Culm synclorium.

The latest gravity surveys include a detailed survey of the Carnmenellis and Land's End region by Scott (unpublished) and 20 underwater gravity measurements off the western most Cornish coast and in the Bristol Channel made by Bott and Scott in 1961 from H.M.S. Shackleton.

The gravity map (Fig. 2) shows the Bouguer anomalies on land and at sea.

2. Interpretation of the negative anomalies over the granite belt

The belt of negative anomalies over the granites is attributed to the low density of the granite in relation to the country rocks, for the following reasons. First, the high values of gravity gradient and second derivative require a density contrast which closely approaches the ground surface; second, there is almost perfect correlation between the individual gravity minima and the exposed granites; third, samples of granite give densities of 2.58—2.64 g/cm³ while the Devonian rocks of south Devon give values of 2.61—2.86 g/cm³ (Bott, Day and Masson-Smith, 1958) and the killas gives 2.71 ± 0.05 g/cm³ (Scott, unpublished).

The Dartmoor anomaly itself requires a minimum possible density contrast of -0.055 g/cm³ (Bott, Day and Masson-Smith, 1958), while mineralogical considerations would place an upper limit of about -0.20 g/cm³. If metamorphic rocks underlie the Devonian etc. as seismic results at sea to the south (Hill and King, 1953) suggest, the density contrast at depth is probably -0.15 ± 0.03 g/cm³. This value will be used in the following interpretation where quantitative results are required.

On the assumption that relatively low density granite is the cause of the low anomalies, it follows from the continuity of the anomalies that the exposed granites form cupolas on a large batholith of considerable depth. In regions between the exposed granites the roof is probably not more than 2 to 3 km beneath the ground surface along the axis of the batholith. On the basis of the gravity anomalies, the

contact of the granite may be divided into a relatively flat lying (but undulating) roof region and walls which normally slope steeply outwards.

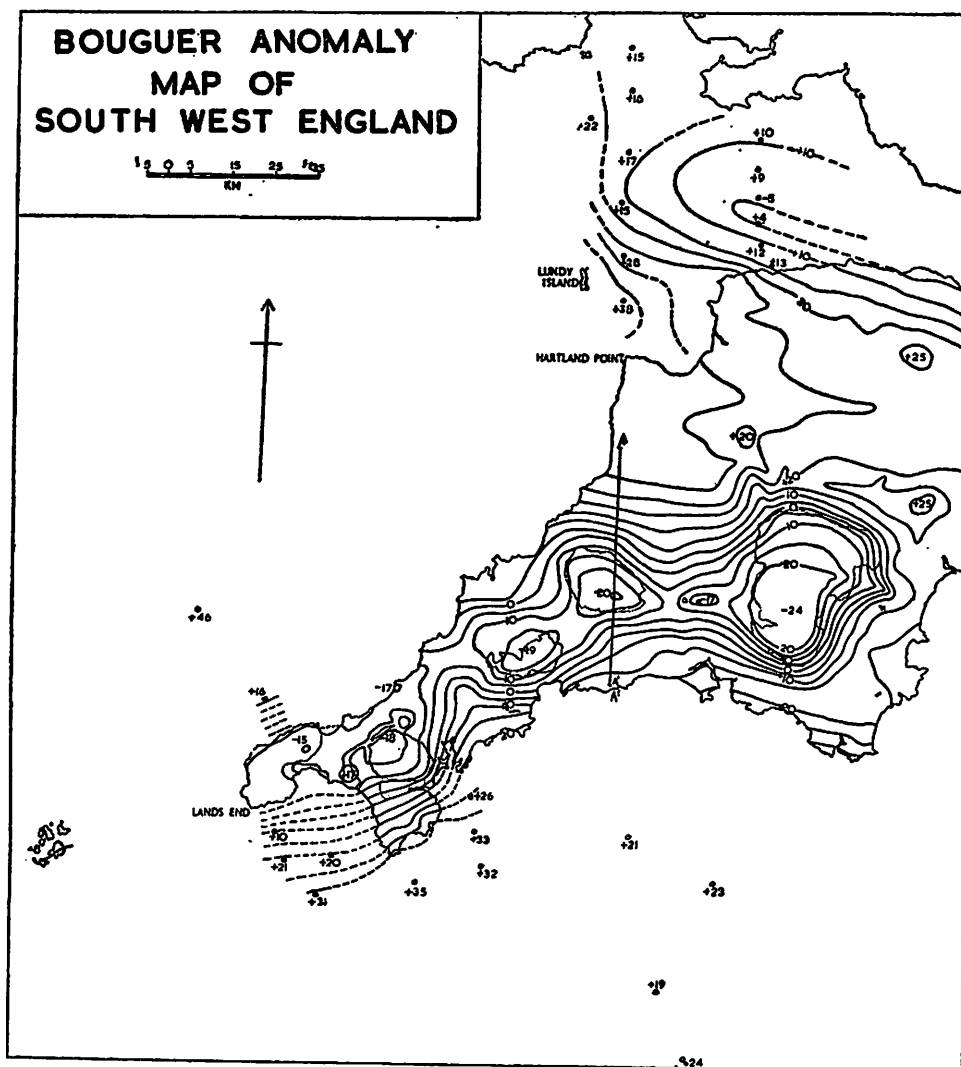


Fig. 2. Bouguer anomaly map of South-west England and the surrounding coastal regions. Measured sampled densities have been used for the Bouguer correction on land, while 2.50 g/cm^3 has been used at sea. Sources of information: *on land* Bott, Day and Masson-Smith (1958) supplemented by Scott (unpublished) for the Carnmenellis-Land's End region; *at sea*, pendulum stations shown as open circles (Browne and Cooper 1950, 1952), gravity meter stations shown as solid circles (Bott and Scott, unpublished). The Bouguer anomalies are based on an assumed value of g of 981.26500 cm/s^2 at Pendulum House, Cambridge, and are contoured at five milligal intervals.

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With the advent of computer methods, a more sophisticated approach to gravity interpretation is possible than in 1958. Using computer methods of calculating two-dimensional profiles across ideal shapes, an interpretation of a north-south profile across Bodmin Moor (AA' Fig. 2) has been attempted. A two-dimensional interpretation is approximately valid for Bodmin Moor which is distant from the ends of the negative belt. Fig. 3 is the best fit of observed with calculated anomalies after a number of attempts with the surface contacts fixed and under the assumption of uniform density contrast. This model shows that (1) the granite extends to a depth of the order of 10 km, and (2) the granite walls normally slope steeply outwards.

These two conclusions are independent of the actual density contrast and other assumptions; and may be legitimately extended to the whole granite belt on the basis of similar amplitudes and marginal profiles. Fig. 3, however, still provides a misfit over the northern part of the granite. The misfit can only be remedied by *either* allowing a shallower floor in the north (Fig. 4) *or* permitting the granite density to increase northwards (Fig. 5). Two factors suggest that density variation

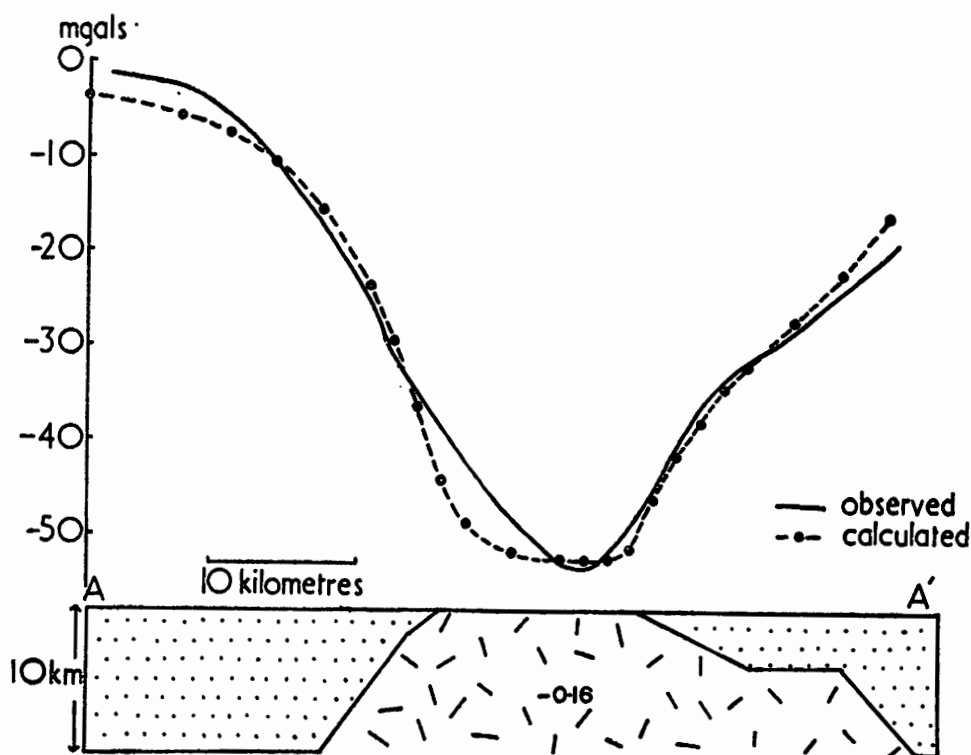


Fig. 3. Two dimensional interpretation of a profile along AA' (Fig. 1) across the Bodmin Moor granite on the assumption of a uniform density contrast between granite and country rocks. The fit is reasonable, except over the northern flank of the outcropping granite, where agreement cannot be obtained on this hypothesis.

within the granite is the more likely hypothesis: (1) sample measurements made by Scott show variations in granite density which correlate with such residual anomalies; and (2) the residual anomalies are sharp enough to suggest relatively shallow origin.

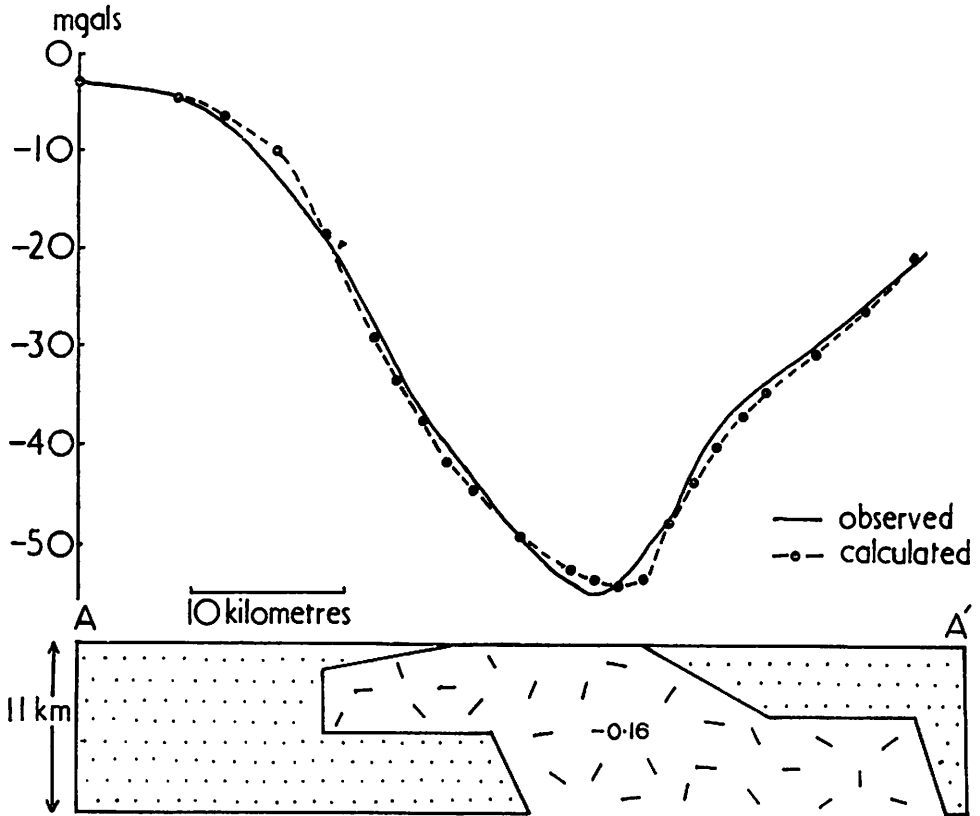


Fig. 4. As Fig. 2, but allowing a shallower floor beneath the northern flank of the granite, giving improved agreement between observed and calculated profiles.

3. The gravity anomalies and the Sn-Cu-Pb-Zn mineralization

The belt of intense Sn-Cu-Pb-Zn mineralization of South-west England follows closely the belt of minimum gravity anomalies associated with the granites (Bott, Day and Masson-Smith, 1958). For the three eastern granites both belts are displaced south of the centre line of the batholith. A more detailed gravity survey has been made by Scott (previously unpublished) of the Carnmenellis and Land's End part of the peninsula to investigate the topography of the roof of the batholith between and to the north of the granites; and to test whether the strips of most intense mineralization are related to 'ridges' in the granite roof, as postulated by Hosking (1950). This survey confirmed that some, but not all, of the postulated rises in the granite roof do exist.

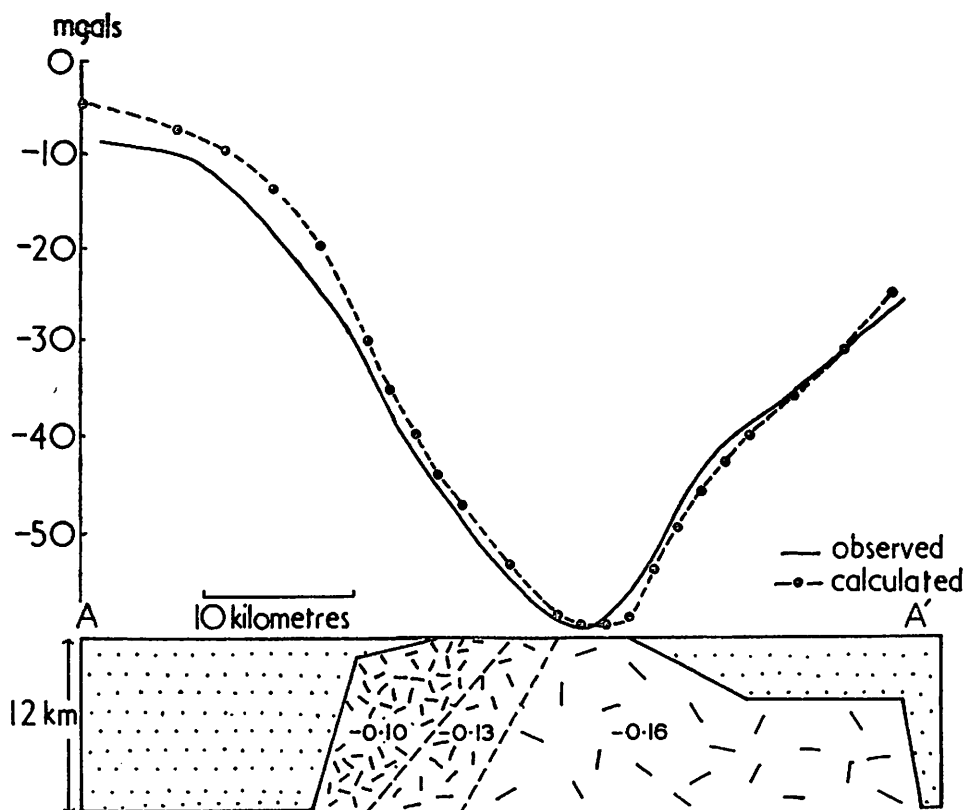


Fig. 5. As Fig. 2, but allowing density of granite to increase towards the northern margin, giving the best fit of the three attempts.

Thus the gravity anomalies show that the distribution of the mineralization on a broad scale is related to the presence of granite below and also to the asymmetry within the batholith which is revealed by the anomalies. On a local scale, Scott has shown that strips of intense mineralization may sometimes, but not always, be related to local rises ('ridges') in the roof of the granite in the main mining district of west Cornwall.

It has generally been assumed that the mineralization of South-west England originated as a late stage fraction of the consolidating granite magma. In fact South-west England has become a 'type' area in this respect. However, the close correlation between gravity anomalies due to the Weardale granite (Bott and Masson-Smith 1957) and the Pb-Zn mineralization of the Alston Block (Dunham 1934) combined with the results from the Rookhope borehole (Dunham *et al.* 1961) has demonstrated that a post-Carboniferous mineralization has very close geometrical correlation with a pre-Carboniferous granite; and similar but less clear cut relations appear to hold for the supposed Hercynian mineralization of the

Lake District and the Isle of Man. Furthermore, the post Carboniferous mineralization of the Derbyshire dome occurs where the gravity evidence (Geological Survey gravity overlay to quarter inch sheet 11) is against the presence of a large granite beneath. Thus, barring the unlikely possibility of younger granites intruding the older, the Hercynian mineralization of Northern England appears to have originated beneath the level of the floor of granites and possibly from the upper mantle; and to have risen through the upper crust by way of relatively easy passages such as are provided by faults, domes and granite batholiths. Thus for Northern England the magmatic origin of the Pb-Zn mineralization of supposed Hercynian age has been thrown in considerable doubt in favour of a hypothesis involving deeper origin of the ore fluids combined with structural control of their rise. These results also cast doubt on the magmatic origin of the similar deposits in South-west England, and perhaps we are left with the following two allowable hypotheses:—

- (i) The mineralization arises as a late stage product of a consolidating granite magma. In this case the South-west mineralization would probably have a quite distinct genesis from similar mineralization of similar age in North England.
- (ii) The mineralization is of deeper origin (possibly upper mantle) and has risen through the consolidating granite batholith as the easiest passage towards the surface. In this case, the close similarity of age between granite and mineralization need have no special significance, although some contamination of the mineralizing fluids by the granite magma is to be expected (e.g. tourmaline).

4. Isostasy and the granite belt.

From the gravity anomalies over the granite belt, an estimate (albeit low) of the mass deficiency associated with the low density granite can be made. It was found by Bott, Day and Masson-Smith (1958) that this is of the same order of magnitude as the mass of the relatively high topography associated with the belt, although the granite mass deficiency is relatively larger towards the west end of the belt. This correlation led to the suggestion that the relatively high ground of the belt is not necessarily due to resistance to erosion but may be isostatically compensated by the granite mass deficiency. This type of isostasy differs from the normally accepted hypotheses in that the compensation takes place within the upper part of the crust. It is perhaps of wider significance than has been recognised.

Thus it is considered that an isostatic mechanism could be the cause of the high ground associated with the granite belt. Such a mechanism can also account for the positive character of the granite belt in Mesozoic and Tertiary time.

5. The gravity anomalies associated with the Lundy granite.

A fall in the Bouguer anomalies of between 4 and 10 mgal is associated with the Lundy granite (Bott, Day and Masson-Smith 1958). This suggests that the granite is relatively thin in marked contrast to the Armorican granites of the mainland. It is perhaps about 2 km thick on the basis of the measured density contrast

of -0.13 g/cm^3 . Its gravity anomaly is comparable to that observed over the Mourne granite (Cook and Murphy 1952) of Tertiary age. The gravity anomalies would be consistent *either* with a laccolithic space form *or* with a ring complex involving cauldron subsidence in which the central sunken block has only dropped about 2 km. The latter suggestion would probably be in better agreement with the geological evidence (Dollar 1942).

6. The Start and Lizard gravity anomalies.

A gravity gradient of about 1.5 mgal/km , rising southwards along the Start peninsula, commences abruptly near Kingsbridge four miles north of the Start boundary. This abrupt commencement (i.e. high second derivative) shows that the source of the anomaly is shallow; it also shows that a wedge of relatively dense rocks commence to thicken southwards at the latitude of Kingsbridge. Thus the character of the gravity profile requires the dense rocks to extend about 4 km north

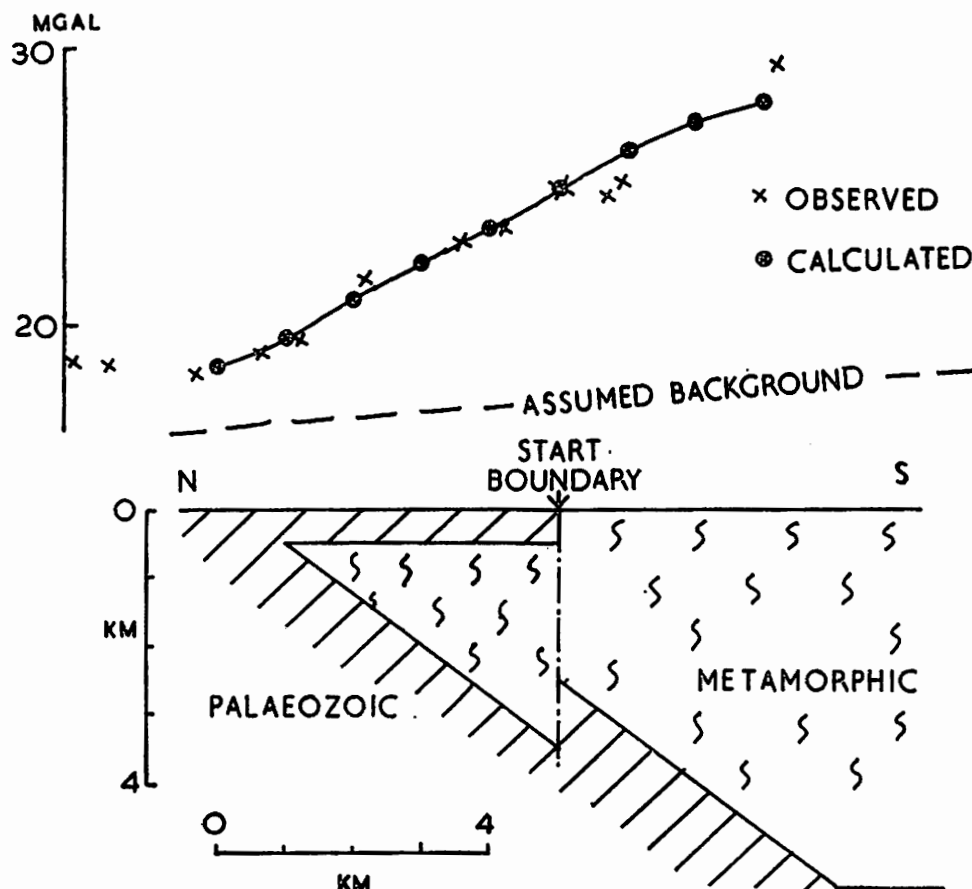


Fig. 6. A possible interpretation of the gravity gradient along the Start peninsula.

of the Start Boundary. The simplest geological explanation is to identify the denser wedge with the metamorphic rocks cropping out on the peninsula. Sample measurements (Bott, Day and Masson-Smith 1958) would allow a contrast of 0.60 g/cm^3 with the Devonian rocks of south Devon.

A model which satisfied both surface geology and accounts for the gravity features is shown in Fig. 6. A possible geological interpretation of the model is that the metamorphic rocks form a thrust wedge, which has later been downfaulted to the north at the Start Boundary.

The southward gravity gradient along the Lizard peninsula appears to be similar in character to the Start anomaly, but is less easy to interpret owing to the confusion with the marginal gravity gradients associated with the southern wall of the Carnmenellis granite. Nevertheless, this gradient is consistent with a mass of dense gabbroic rock thickening southwards from the Lizard boundary; it is also consistent with a southward dipping thrust plane beneath the Lizard Complex.

7. The Exmoor anomalies

In a N.N.E. direction across Exmoor the Bouguer anomalies fall by about 22 mgal. The gradient is fairly uniform but it does reach a maximum observed value near the southern margin. Gravity gradients and second derivatives require a shallow source; thus low density rocks within the upper part of the crust must thicken northwards beneath Exmoor. For a density contrast of -0.10 g/cm^3 these low density rocks must reach a thickness of at least 6 km (20,000 ft.) beneath the north-east Devon coast to account for the observed gravity change.

The position of the steepest gravity gradient and other features on the profile are not consistent with the type of anomaly expected for an unexposed granite beneath Exmoor (Bott 1962). The remaining possible geological explanations (Fig. 7) seem to be restricted to the following two:—

- (i) Exmoor is underlain by a major thrust which has carried the outcropping Devonian rocks northwards across a large basin of Carboniferous and Devonian rocks.
- (ii) Low density arenaceous rocks of Lower Devonian or earlier age thicken northwards by more than 6 km across Exmoor.

The writers prefer hypothesis (i) on the grounds that O.R.S. and earlier rocks in Great Britain have a relatively high density; and that over thick O.R.S. or Lower Palaeozoic basins in Great Britain there is a conspicuous absence of anomalies of comparable size. By contrast, Carboniferous basins do sometimes give rise to gravity anomalies of this magnitude.

8. Gravity anomalies of the Culm synclorium.

The Culm synclorium is a region of high positive Bouguer anomalies in contrast to the granite belt to the south and Exmoor to the north.

A westward regional rise in the Bouguer anomalies of about 0.17 mgal/km is observed along the axis of the Culm synclorium. This is unrelated to surface geology and is thought to be due to either a westward thinning of the crust or a westward increase in the average density of the crust. Comparable regional increases

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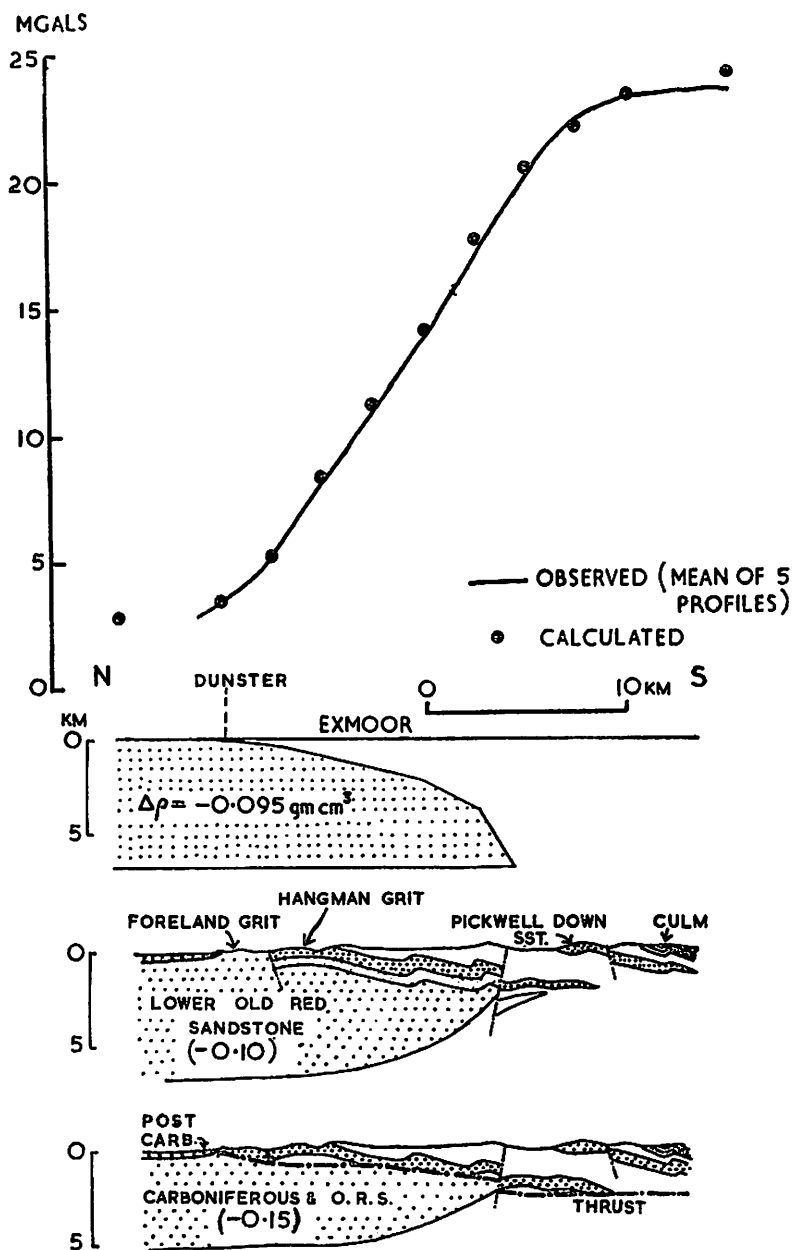


Fig. 7. Comparison between observed and calculated anomalies across the Exmoor gravity gradient for one satisfactory density model (after Bott, Day and Masson-Smith 1958, Fig. 11). Beneath are shown two geological hypotheses which would be consistent with the model: *Upper*, a major northward thickening of Lower O.R.S.; *Lower*, Exmoor is underlain by a major thrust.

in the Bouguer anomalies towards the Irish Sea are observed in Wales and North-west England (see Bott (1964) for a fuller discussion of the possible cause of such gradients).

This regional gradient may account for the westward rise in the minimum values of the Bouguer anomalies associated with the individual major granites, although other explanations are possible. It is certainly likely to influence the major gravity anomalies already discussed, but it is not likely to prejudice any of the major conclusions which have been reached.

Superimposed on the regional gradient of the Culm Synclinorium are local ridges of relatively high gravity approaching 5 mgal in amplitude. These run parallel to the Culm structures and are attributed to belts of relatively dense (less arenaceous) rocks within the Culm, possibly controlled by thrusting and/or folding.

9. Local gravity anomalies over post Carboniferous sediments.

Small local negative gravity anomalies are observed over the Crediton New Red Sandstone trough and over the Tertiary deposits of Bovey Tracey and Petrockstowe. These are caused by the relatively low density of the sedimentary infill and are treated in detail by Bott, Day and Masson-Smith (1958).

10. Interpretation of gravity anomalies at sea.

All gravity anomalies at sea (including those of Browne and Cooper) are given on figure 2 as normal Bouguer anomalies reduced for an assumed density of 2.50 g/cm³ for the rocks immediately beneath the seabed.

A line of six submarine pendulum stations extending southwards from Plymouth across the Channel (Brown and Cooper 1952) show that the Bouguer anomalies along the seismic line of Hill and King (1954) range between 19 and 24 mgal. After correction for the Mesozoic sediments, the background Bouguer anomaly is found to be within the range of 35 to 45 mgal, which is comparable to the Bouguer values in the vicinity of Lundy Island.

Underwater gravity stations (Bott and Scott, unpublished) in the neighbourhood of West Cornwall are chiefly important for showing that the margins of the roof of the Land's End granite lie close to the north and south coasts of the peninsula.

Underwater gravity measurements also reveal a gravity low in the middle of the Bristol Channel north of Exmoor. This would be consistent with northward extension of the low density rocks beneath Exmoor (postulated as Carboniferous) beneath the Channel to South Wales; together with an overlying thickness of the order of 500 m or more of Mesozoic sediments. The combined Bristol Channel—Exmoor gravity low appears to close to the west at the approximate longitude of Lundy Island, suggesting that the composite Upper Palaeozoic—Mesozoic basin thins or disappears westwards at about this longitude.

III. MAGNETIC ANOMALIES AND THEIR INTERPRETATION

A few vertical field magnetometer traverses were made by Bott, Day and Masson-Smith (1958) in the neighbourhood of the Dartmoor and Bodminmoor

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granites, and northwards across Exmoor. The magnetic field (corrected for latitude) appears to be relatively uniform and featureless over the granites and to the south of them. But directly to the north of the granites the vertical field anomaly rises steeply and abruptly by about 150 gamma towards a magnetic 'high' which dominates the southern flank of the Culm synclinorium (Fig. 8). The anomalies then fall northwards by 250 gamma towards the north Devon coast.

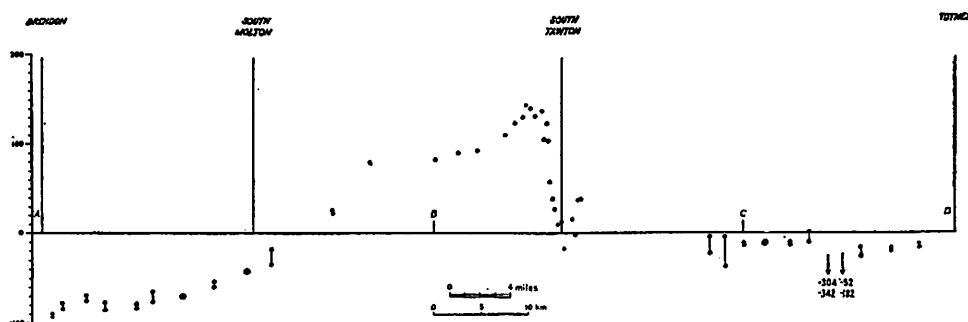


Fig. 8. Profile of the vertical field magnetic anomalies across Devon from north to south (reproduced from Bott, Day and Masson-Smith 1958, Fig. 4, by kind permission of the Royal Society).

This pattern of anomalies implies that the granites and southern country rocks have relatively low and uniform magnetization in contrast to rocks of higher polarisation within or beneath the Culm synclinorium. The abrupt gradient suggests that the granite contact forms the boundary and that the upper part of the northern magnetic rocks is close to the surface. The width of the high demonstrates that the magnetic rocks extend to considerable depth. The belt of steep gradients is continuous between Dartmoor and Bodmin Moor (but embayed to the south) and this is interpreted as demonstrating the shallow sub-surface connection between the two granites with a southern embayment between them. The northward fall of the magnetic anomaly across Exmoor may be attributed either to deepening or disappearance of the magnetic rocks towards the north.

A seaborne total field magnetic survey in the western English Channel (Allan 1961) discloses an oval magnetic anomaly of over 300 gamma amplitude, with a north-westerly elongation and a real extent of $50 \times 20 \text{ km}^2$ with its peak situated 25 km south of Eddystone. Allan showed that a S.W.—N.E. profile across the centre of the anomaly could approximately be simulated by induced magnetization of a rectangular body of infinite depth, $8 \times 13 \text{ km}^2$ in areal extent with depth to top surface of 1.3 to 2.5 km and susceptibility of 1.7×10^{-3} c.g.s. units. This would be consistent with geological interpretation as a gabbro intrusion. (Fig. 9).

Allan's survey showed sharp anomalies of N.W.—S.E. trend off the south-east coast of the Lizard peninsula, which rapidly die out seawards and to the east. In the discussion after Allan's paper, Bullerwell stated that the aeromagnetic survey of south-west England which was flown for the Geological Survey by Hunting

Geophysics confirmed that similar strong anomalies of N.W.—S.E. trend are found over the Lizard Complex; he also noted that the anomalous area is sharply terminated at the north margin of the Complex. These observations over land and at sea show that the Lizard Complex does not extend (at least as a near surface body) far beyond the outcrop on the Lizard peninsula. The present writers would add that the sharp termination at the northern margin is suggestive of a floor to the magnetic rocks dipping at a relatively shallow angle southwards from the northern contact. If the 'magnetic floor' is equivalent to the floor of the Complex, this would be fully consistent with the concept of an underlying thrust plane. On the other hand Allan considered the restricted areal extent of the Lizard anomalies as evidence against the Lizard—Dodman—Start thrust. The writers regard this as an invalid deduction from the magnetic anomalies, in that the rocks overlying (or underlying) a thrust plane do not necessarily have the same magnetic and lithological characteristics along the length of the structure.

Allan's survey also revealed sharp local anomalies south-east of Plymouth Sound, which are probably related to local variations in magnetization of underlying metamorphic rocks.

In 1961 Bott and Scott made four magnetic traverses towards Lundy from H.M.S. Shackleton to test whether magnetic rocks underlay the Island. These traverses failed to give any indication of an underlying basic intrusion of large size.

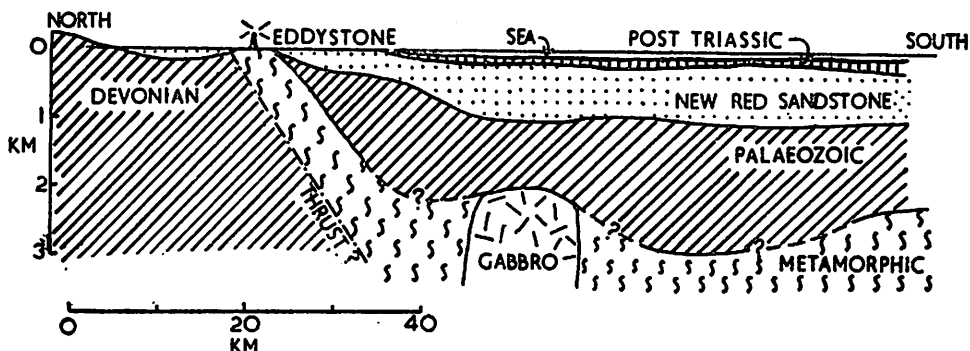


Fig. 9. Interpretation of seismic refraction and magnetic data along a line extending south from Plymouth (after Hill and King 1954; Allan 1962).

IV. MARINE SEISMIC REFRACTION SURVEYS

Seismic refraction studies at sea to the south of Devon and Cornwall by Bullard, Hill and co-workers have added greatly to our knowledge of the offshore deep structure. The earliest survey (Bullard and Gaskell 1941) revealed 60 m (200 ft.) of Class 2 strata (see below) overlying a Class 3 basement at a station about 5 km south of Lizard Point; and 400 m (1,320 ft.) at a station about 50 km south-east of Lizard Point.

Correlation of seismic velocity with strata outcropping of the seabed (Hill and King, 1954) and laboratory velocity measurements on rock samples from the main-

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land (Day and others, 1956) lead to the following classes of velocity, with postulated identifications shown in parentheses:—

- Class 1: 1.7-2.5 km/s (Mesozoic)
- Class 2: 2.7-3.6 km/s (Permo-Triassic)
- Class 3: 3.65-4.85 km/s (Palaeozoic)
- Class 4: 5.2-7.4 km/s (metamorphic and igneous)

Hill (Hill and King 1954) observed a traverse of seven refraction stations extending southwards from Plymouth to about the centre of the Channel. The lines were shot in an east-west direction and were largely unreversed, thus requiring the assumption of uniform horizontal layering for interpretation. The main conclusions (Fig. 9) were (1) that there is an offshore basin of New Red Sandstone, interrupted by the Eddystone metamorphic ridge, extending from a few km offshore to a point south of the centre of the channel and reaching thicknesses greater than 900 m (3,000 ft.); and (2) that a class 4 basement was detected at three stations south of Eddystone at depths of about 2,000 m (7,000 ft.).

Merriweather (1958) reported four lines of shots at sea to a hydrophone situated about 3 km offshore near Perranporth, north Cornwall. This survey suggests that Palaeozoic rocks extend northwards under only a thin cover of superficial deposits to a distance of about 20 km offshore; and that these are underlain by higher velocity rocks (Class 4) at a depth of about 400 m assuming uniform horizontal layering.

V. RADIOACTIVE AGE DATING

Dating in the Lizard area by Miller and Green (1961a) using the potassium-argon total volume method on biotite and muscovite give ages of 391 My for the Kennack Gneiss (the youngest intrusive) and 356 My for the supposedly earlier Old Lizard Head Series. Measurements by Dodson (1961) using the isotope dilution method give 350 My years for muscovite from the Old Lizard Head Series and 368 My for the Kennack Gneiss and Landewednack Hornblende Schist. Later potassium-argon measurements on the hornblendes (Miller and Green, 1961b) give ages of 366 ± 20 My for the Kennack Gneiss, 371 ± 20 and 442 ± 24 My for the Landewednack Hornblende Schists, 357 ± 20 My for hornblende amphibolite and 492 ± 26 My for hornblende granulite (both from the aureole for the peridotite). The suggested interpretation of these results is that the true age of the Kennack Gneiss is 360–390 My but that the other rocks are older than Caledonian giving low values owing to argon loss etc. during the Caledonian orogenies. Biotite from Eddystone gives 375 ± 17 My.

Kulp and others (1960) obtained potassium-argon ages of 271 ± 5 My for Dartmoor granite from Haytor rocks and 250 ± 15 My for the Land's End granite, Lamorna Cove; and a rubidium-strontium age of 277 ± 5 My for the Dartmoor granite. Dodson, Miller and York (1961) obtained a mean age of 265 ± 5 My for the Dartmoor granite using the total volume and isotope dilution methods of argon measurement.

Miller, Shibata and Munro (1962) obtained an age of 279 ± 6 My for the Killerton Park lava (Exeter traps) based on biotite measured by both total volume and isotope dilution methods. This is not significantly different from the age of the Dartmoor granite which may suggest a genetic relationship.

Miller and Fitch (1962) obtained ages of 50 ± 3 and 55 ± 3 My on biotite and feldspar respectively from the earlier G1 intrusion of the Lundy granite, using the isotope dilution technique. Dodson and Long (1962) gave a value of 52 ± 2 My for the G1 granite based on a mean of potassium-argon and rubidium-strontium methods, and obtained a whole-rock maximum age of 66 ± 3 My. Thus the Lundy granite appears to be mid-Eocene in age and is certainly not pre-Tertiary.

Lead isotope measurements (Moorbath 1962) on galena samples from the mineral zone associated with the Hercynian granites give ages ranging from 260 ± 70 to 300 ± 60 My based on the Holmes-Houtermans model. Samples from the earlier E.-W. veins and from the later N.-S. set do not differ significantly in age. Nor are the ages significantly different from that of the granites (see above).

VI. PALAEOMAGNETIC STUDIES

Creer (1957) published results of a palaeomagnetic study on five of the Exeter Volcanic traps from the vicinity of Exeter. He obtained directions of magnetization giving declinations ranging from $S6^\circ W$ to $S12^\circ W$ and dips ranging from $+25^\circ$ to -27° (mean value -11°).

Blundell (1957) measured the direction of natural remanent magnetization from the Lundy dyke swarm. The stable samples showed reverse magnetization. The mean direction obtained gave a declination of 197° and a dip of -59° , which differs highly significantly from the figure for Permian rocks (see Creer, above) but resembles closely the direction for the Tertiary Antrim lavas, thought to be of Eocene age. The results of this study thus demonstrate that the Lundy dyke swarm is Tertiary, and possibly Eocene, in age. It may be noted that this is the same age as suggested by radioactive methods for the Lundy granite G1. Thus the granite and dyke swarm appear to belong to the same igneous episode.

VII. CONCLUSIONS

The principal conclusions emerging from recent geophysical studies in South-west England (Fig. 10) stated with geological emphasis, are enumerated below in approximate sequence of age:—

- (i) Age dates show that the metamorphism of the Lizard schists and the intrusion of the Lizard peridotite are of pre-Caledonian age, but suggest that these rocks have been affected by Caledonian as well as Hercynian movements. Magnetic anomalies at sea suggest a N.W.—S.E. pre-Caledonian strike direction which has affected the Lizard rocks.
- (ii) The Culm synclorium contains magnetic rocks which extend considerably in depth and are now sharply terminated to the south by the granite contact.

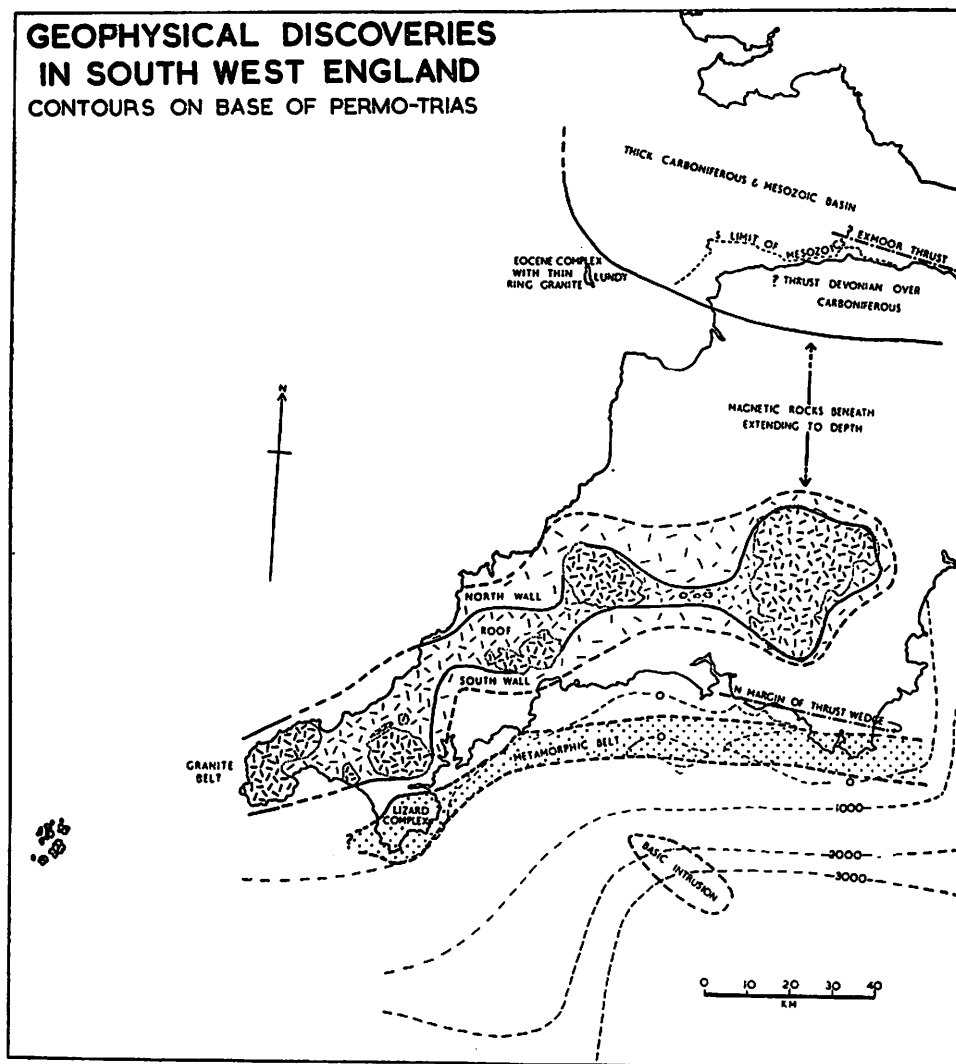


Fig. 10. Summary map showing the main findings of recent geophysical work in the South-west. The various boundaries are not meant to be accurate in position.

- (iii) Gravity, magnetic and seismic evidence is consistent with the concept of a Lizard-Dodman-Start thrust. In the Start peninsula the gravity anomalies require the denser rocks to extend north of the Start Boundary as an unexposed thrust wedge.
- (iv) The Devonian rocks of north Devon are underlain by a large thickness of relatively low density rocks. In explanation these Devonian rocks may have been thrust northwards over a basin containing thick Carboniferous rocks. The postulated autochthonous Carboniferous basin

extends beneath the Bristol Channel to South Wales. In the Bristol Channel it is overlain by synclinal Mesozoic sediments. This composite basin thins westwards at the longitude of Lundy Island.

- (v) The exposed granites (age about 270 My) form cupolas on a large inter-connecting granite batholith, which extends downwards at least 10 km and has well defined roof and outwards sloping wall regions. The granite has a tendency to be denser in the north flank of the batholith.
- (vi) The Cu-Sn-Pb-Zn mineralization (which is approximately the same age as the granite) is geometrically related to the granite batholith, but the relations may arise *either* due to late stage magmatic origin of the ore fluids *or* due to structural control by the batholith of the ore fluids rising from greater depths.
- (vii) The Exeter traps are not significantly different in age from the Dartmoor granite, suggesting a possible genetic connection.
- (viii) Past and present topographic uplift of the granite belt may be an isostatic response to the granite mass deficiency.
- (ix) South of Plymouth, there is an offshore Triassic basin reaching a thickness of at least 1,000 m and possibly controlling the position of the coastline. South of Eddystone there is seismic evidence for a metamorphic basement beneath thick Palaeozoic strata underlying the Triassic basin.
- (x) Magnetic anomalies suggest the presence of a plutonic intrusion, possibly basic, situated about 25 km south of Eddystone.
- (xi) The Lundy granite and dyke swarm are probably Eocene in age. The space form of the granite is consistent with a ring intrusion with the top of the sunken block about 2 km deep.
- (xii) A slight westward thinning of the crust, or increase in mean crustal density, is observed.

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