A GEOPHYSICAL APPROACH TO THE GEOLOGY OF SOUTH WEST CORNWALL

A thesis submitted

by

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ABSTRACT

The study area comprised an offshore region, Mount's Bay, as well as a terrestrial region, the area north of Mount's Bay. New data presented ~~is~~ are obtained from (1) a "Sparker" and Echometer survey of Mount's Bay, (2) Petrological examination of rock samples collected from the sea-bottom in the bay, (3) a detailed magnetic survey in the bay, (4) palaeomagnetic measurements on some of the Lizard igneous and metamorphic rocks and (5) a detailed gravity survey between the three granite bosses of South West Cornwall.

The interpretation of the data reveals the presence of several areas of unexposed granite, two of which may be of particular economic significance. The role of tension in the country rocks caused by the granite intrusions is stressed as a factor in the formation of the Cornish mineral lodes. Cross-folding on a small scale is inferred in the area north of the Godolphin granite, and cross-folding on a large scale is postulated in the area west of the Carnmenellis granite. It is likely that in Mount's Bay there are near surface basic-ultrabasic complexes

similar to the one on the Lizard. An entirely new hypothesis of emplacement and formation of the Lizard igneous suite is suggested. Contrary to orthodox opinion, it is argued that the origin of folding in South West England is due to vertical block uplift rather than to horizontal compression.

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INTRODUCTION

One of nature's gifts to Cornwall has been a rich endowment in tin and copper. This has been exploited so successfully that the known reserves are almost exhausted. Of the plethora of mines which once existed, only two still survive. Nowadays, tin continues to command a high price and there is great incentive to discover new lodes. But a careful inspection of the surface of Cornwall has failed to reveal more deposits. Fortunately, there remain the less direct methods of exploration to which the enterprising prospector may resort.

He may choose to drill at various points or he may use geophysics or geochemistry. In fact, all three are being applied to the problem and before long some tangible result may be forthcoming. This thesis is concerned with the geophysical side of the approach.

The treasure is concentrated in a well recognised belt which runs north-east through Cornwall. Within this belt itself the mineralisation is particularly dense in

the south-western region. This zone naturally attracts the most attention and it offers an alluring target for further exploration. Fig. 1 shows that the zone is cut off by the shores of Mount's Bay. This gives rise to the expectation that the mineralisation continues into the bay, but the exploration of the underwater areas presents unusual problems. However, with the advent of modern techniques a successful assault becomes feasible.

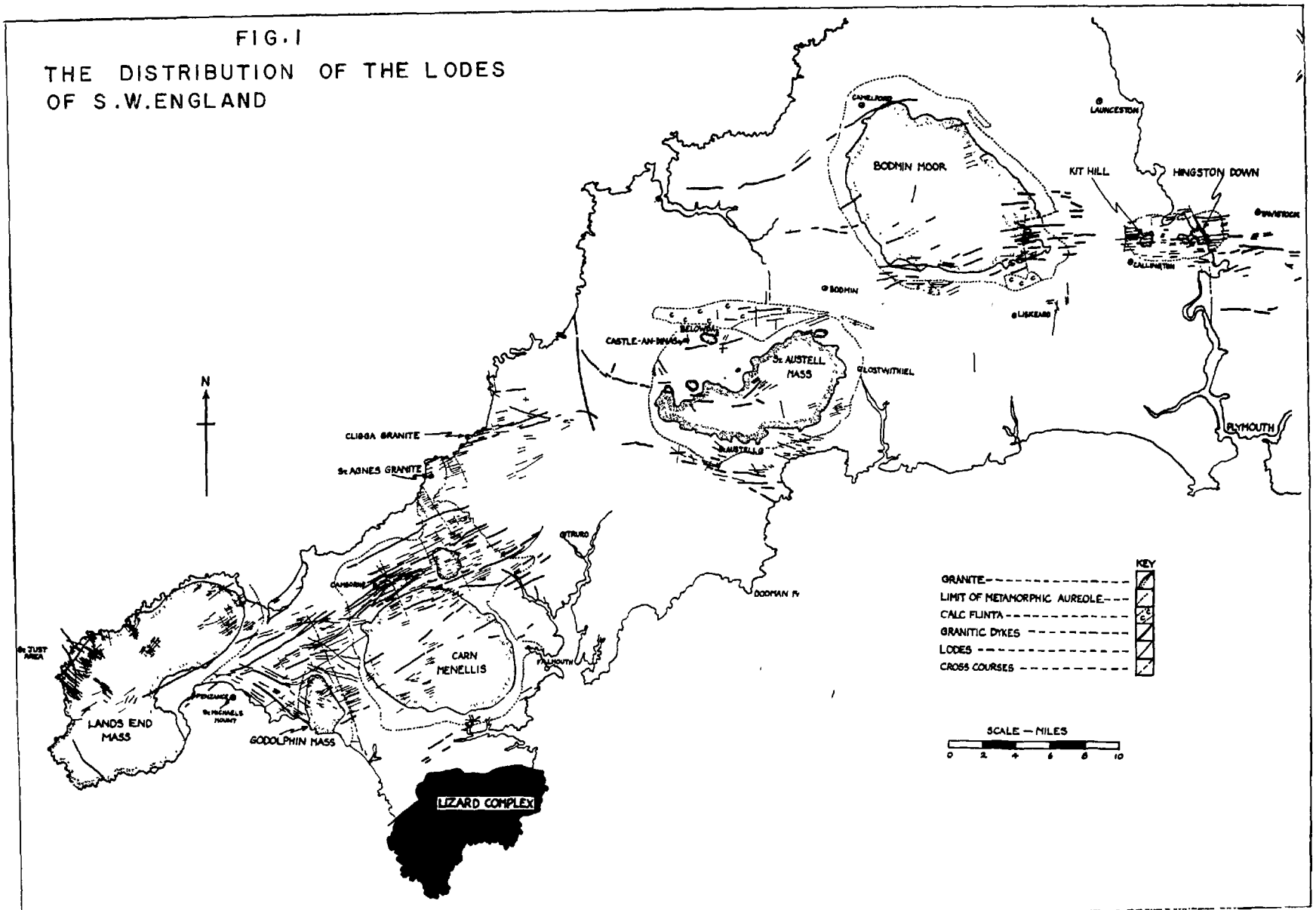
The campaign opened in 1963 with continuous seismic profiling as the main objective. Supporting action came from rock-sampling of the sea-bed and the execution of some magnetometer traverses. The writer was not involved in this opening phase of the operation but the data and specimens were given to him for interpretation.

Though the seismic records turned out to be disappointing, the magnetometer traverses showed unexpected anomalies. They were followed up by a systematic magnetic survey of the bay in 1964. During that summer, a combined geophysical/geochemical attack was launched in the bay. It was supplemented by more rock sampling of the sea-bed.

The scope of the investigations was also widened to embrace the land area as well. Accordingly, the region between the three granite masses north of Mount's Bay (Fig. 1.1) was surveyed by the gravitational and magnetic

FIG. 1

THE DISTRIBUTION OF THE LODES OF S.W.ENGLAND



methods. This was done partly from a desire to extrapolate the results seawards and partly because of the great geological interest of that region.

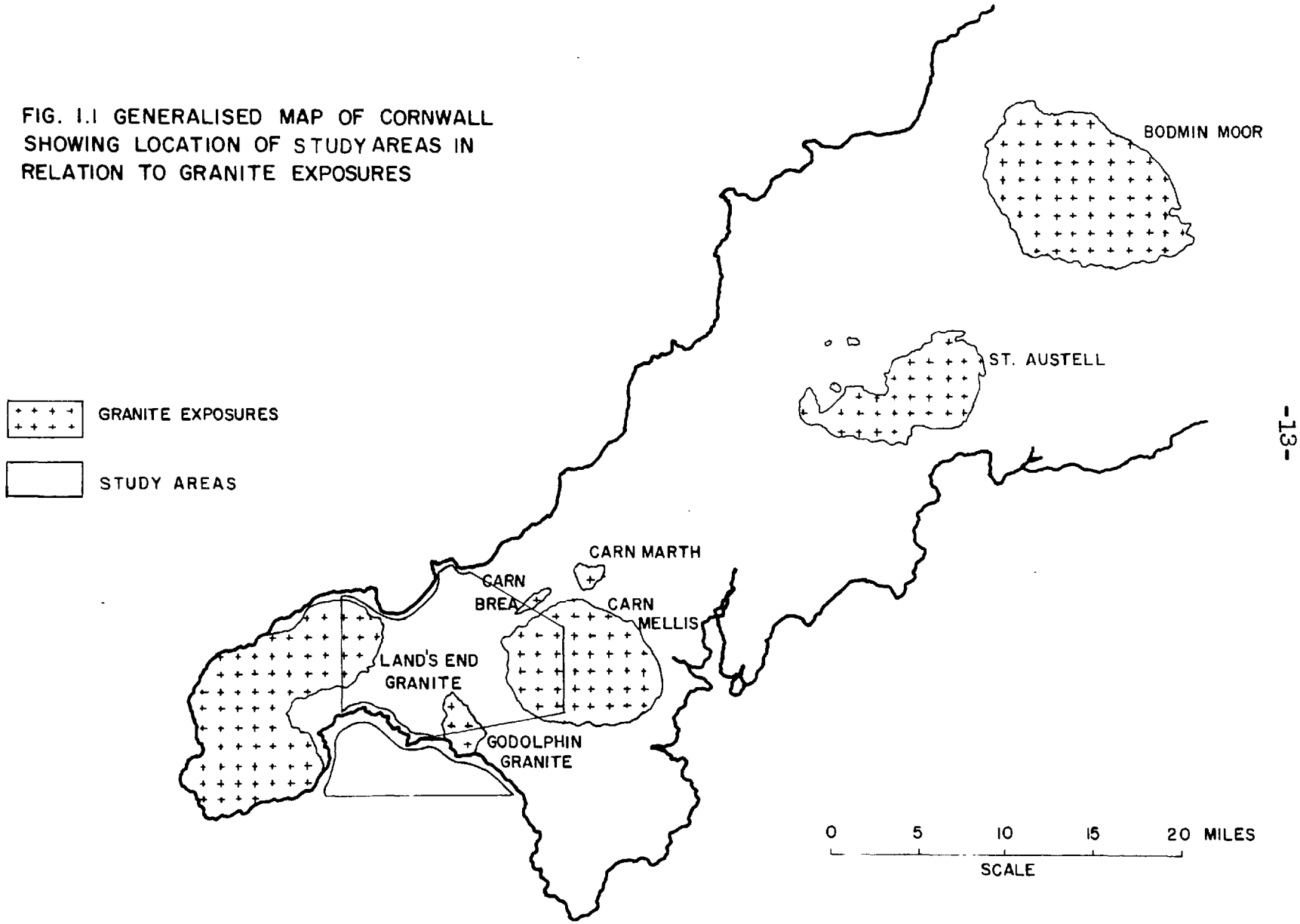
The gravitational results were particularly encouraging but since the area had been covered by a limited number of traverses there were some large blank spaces in which no readings had been taken. An attempt was made to rectify this unsatisfactory state of affairs by occupying some additional stations in April 1965.

The final visit to the area was made later that year when a number of oriented specimens were collected from the Lizard peninsula for magnetic determinations. Some more gravity work was also done. The study areas are shown in Fig. 1.1

Plan of the Thesis.

The thesis is presented in four sections. The first begins in customary fashion with a short summary of the regional geology. The review of previous geophysical work which follows, reveals the fundamental importance of the geophysical results. An appraisal is made of the local geology to define the problems and to decide on a suitable approach. This leads to the inevitable conclusion that a geophysical approach to the geology of South West Cornwall is mandatory.

FIG. 1.1 GENERALISED MAP OF CORNWALL SHOWING LOCATION OF STUDY AREAS IN RELATION TO GRANITE EXPOSURES



Section 2 gives the results obtained by the various surveys during the period 1963-1965. Geophysical as well as petrological results are given, the geochemical data having been processed and interpreted by Mr. P.M. Ong. On the terrestrial area, the most important results came from the gravity survey. In the offshore area the significance of the results was only apparent after combining the data from the seismic and magnetic surveys with that from the rock sampling program.

In section 3 the known geology is discussed in the light of the foregoing results. New information must be taken into account and certain modifications of the accepted version become necessary. The appropriate amendments and additions are incorporated into the previous body of knowledge leading to a revised geology of South West Cornwall. The contributions have economic as well as purely geological implications.

In the fourth section the discussion moves to the wider area of South West England. The local area is examined in its regional setting and the broader connotations of the local results are considered.

PART 1

The setting, the problem and the solution

THE GEOLOGY OF SOUTH WEST ENGLAND

Contributions to the geology of South West England began more than 200 years ago and since then a formidable literature has accumulated on the subject. This is impressive not only for its sheer weight, but also for its high quality in parts. Yet, despite this, unresolved controversies still persist and the unknown blankets many parts of the story.

A truly objective account must include various arguments put forward in support of conflicting opinions. But this would be tedious, and the writer has rejected such a pedantic approach. Instead, an attempt is made to show South West England in its geotectonic setting. By injecting a small amount of reasonable deduction into the account an enhanced cohesion is achieved.

We may begin at the Devonian period, since older rocks are not exposed. The Silurian period closed with the

paroxysmal phase of the Caledonian orogeny but its effect on Devon and Cornwall is unknown. During the Devonian and for much of the Carboniferous, South West England formed part of the Rheno-Hercynian geosyncline, which was crumpled and subsequently elevated towards the close of the Carboniferous by the Hercynian orogeny. Because of the paucity of the outcrops, little can be known of the history of the area after this episode.

In Permian times, the region was a landmass, when New Red Sandstone rocks were formed under desert conditions. During the Jurassic the area was tilted eastwards and late Cretaceous deposits were laid down on the upturned edges of the older strata. These were in turn buried under the Chalk sea, and by Tertiary gravels. In the late Tertiary, the re-emergence of the land took place in stages, marked by platforms cut at various heights above the present sea level. Renewed uplift in the Pleistocene is shown by present day raised beaches and by the presence of two more shelves. Within very recent times there has been a slight submergence giving rise to drowned valleys.

Thus, it is seen that the pre-Devonian geology is inaccessible to direct view and the post-Hercynian record is mostly obliterated. Attention can therefore be focussed onto the events of the Devonian and Carboniferous.

Spanning this part of the record is the Hercynian geotectonic cycle. We must look to this cycle for the origin of the significant geological features.

The cycle had two stages. In both, the geosyncline was divided into zones of subsidence and uplift, but subsidence predominated in the first stage and uplift in the second. The transition from stage one to stage two involved a general inversion of the geotectonic conditions. The first stage occupied the greater part of the cycle; the second came in pulses which culminated in general uplift towards the end of the cycle.

The study of the cycle falls naturally into two sections, sedimentation and structure. To these two facets must be added a third which is concerned with the igneous activity at various stages of the geotectonic cycle.

Sedimentation

In the closing stages of Ludlow times, the sea retreated southwards from Britain, and the Devonian period opened with a geosyncline stretching from Cornwall to the Ardennes. It formed a broadly subsiding area, divided into secondary troughs and geanticlinal ridges. The evolution of the geosyncline gave rise to four sedimentary sequences.

During the early part of the cycle a lower terrigenous sequence was deposited. In the troughs a uniform series of shales and mudstones was laid down under a reducing environment giving colours that are monotonously grey. Few fossils are to be found in these sediments. By contrast, the sediments of the geanticlinal areas are purple, red or green and they show a varied lithology.

At the time of greatest subsidence of the geosyncline a limestone sequence succeeded the lower terrigenous rocks. With its deposition the first stage of the geotectonic cycle came to an end.

The beginning of the second stage of the cycle ushered in the upper terrigenous sequence. This was closely linked to renewed central uplifts in the geosyncline. The upper terrigenous sequence recorded the erosion of the uplifted regions, and therefore displayed a wide variety of rocks.

The molasse deposits completed the succession of geosynclinal sedimentary sequences. They occurred in the final stage of the geosyncline when high mountain ranges were formed. At this time uplift achieved its greatest dominance over subsidence.

Devonian

The Devonian rocks of South West England have two principal areas of outcrop, which are characterised by different facies development.

1. South Devon and Cornwall.

The lowest Devonian strata consist of extensive marine deposits of mud. These are typical of the lower terrigenous sequence and they show that bathyal conditions were already established in the lower Devonian in South Cornwall. They were followed by greywackes, spilites, tuffs and cherts.

The lower terrigenous sequence continued into the middle Devonian with the development of more slates and mudstones. The limestone series began to appear and was of great importance locally. This was especially true between Torquay and Plymouth where massive limestones were developed. Further north, in the Padstow region, the shaly facies of the bathyal areas was more characteristic, from which it may be concluded that there was a northward movement of the geosynclinal axis from South Cornwall to South Devon.

The upper Devonian shows a large variety of rock types. There are calcareous shales of different colours interstratified with lavas, tuffs and breccias. This is

the result of a changing environment associated with the migration of the geosynclinal axis. The northward advance which began in the middle Devonian accelerated in the upper Devonian.

2. North Devon.

The facies of North Devon is of intermediate type belonging partly to the Old Red Sandstone of the region north of the Bristol Channel and partly to the true Devonian of the south. These rocks were laid down not far from the fluctuating shoreline which marked the northern margin of the geosyncline. In the lower and middle Devonian, shales and sandstones are predominant. In the upper Devonian, the strata show a deepening sea, and the youngest beds are neritic fossilferous sandstones and shales.

Carboniferous

In Devon the Carboniferous rocks follow the Devonian without a break. Elsewhere in Britain the sea invaded the Old Red Sandstone continent and deposited a marine calcareous facies. The lower Carboniferous saw the greatest development of the limestone sequence, but within the geosyncline itself the sediments were of the Flysch type, and they have been given the name Culm.

The lower Culm rocks show the overlap of the upper terrigenous and the limestone sequences. The sediments were fed by erosion of the south Cornish massif, elevated at the end of the Devonian. This deposition took place in a calcareous environment, so that the lowest Culm beds consist of radiolarian cherts, calcareous shales and black limestones. The presence of the south Cornish massif is shown in the earliest beds by a small increase in coarse clastic material from north-east to south-west. Towards the end of the lower Culm there was a sharp lithological change, marked in South Devon by the appearance of greywackes deposited by turbidity currents. The greywackes spread from the south and west across Devon and continued through the lower Westphalian. This deposition is indicative of a mountain building episode to the south, the duration and extent of which show that the Sudetic phase was both wide and prolonged.

The beginning of the middle Culm sedimentation is marked by the abrupt cessation of the turbidite deposition. The succeeding sediments are predominantly coarse mudstones and fine siltstones, deposited by currents coming from west of north. This direction contrasts strongly with that of the underlying greywackes sequence, in which the sediments have a south-westerly derivation. The nature

and source of supply of the middle Culm rocks show that they are a southward extension of the coal measure deltas lying north of the Bristol Channel. The deltaic sedimentation reflects an uplift and rejuvenation of the craton to the north.

The slow retreat of the deltas was followed by renewed turbidite deposition, which continued into the upper Culm, when it was abruptly terminated by the Asturic folding.

The molasse sequence following the creation of the mountain ranges was formed under desert conditions. It is of only minor importance in South West England and will not be given further consideration.

Structure

The inversion of geotectonic conditions was accomplished in a series of phases, each phase having its greatest impact on a particular zone of the geosyncline (see Fig. 1.2). Within the Hercynian chain of fold mountains three main zones have been differentiated because of their separate structural styles and their different times of formation.

1. In the Moldanubian zone (South Brittany, Central Plateau of France, Black Forest, Inner Bohemia) Pre-Cambrian gneisses can be recognised. This zone was

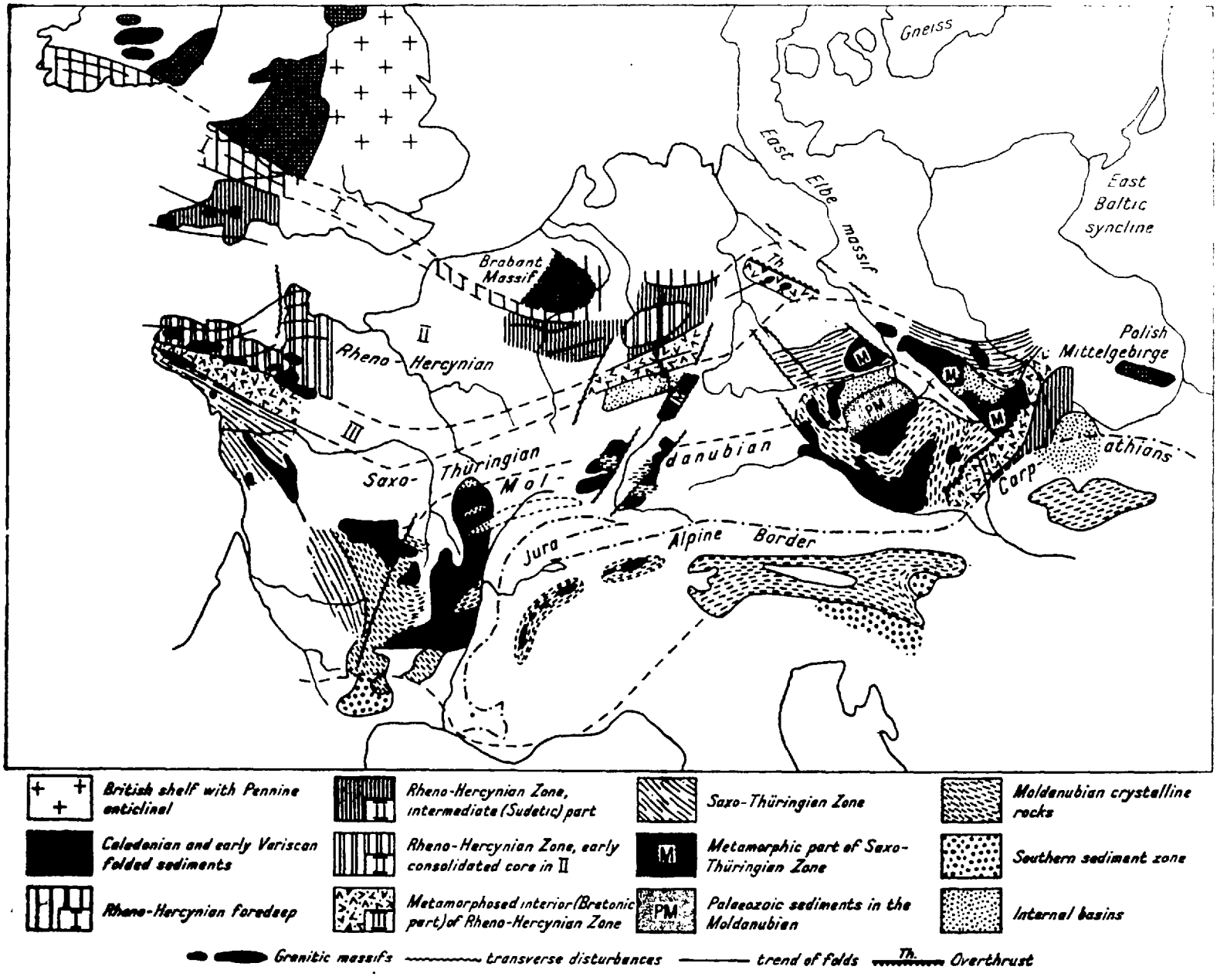


Fig 1 2 Divisions of the Variscan mountains. *After von Bubnoff and Kossmat.*

overthrust en bloc without actually being folded. The movement occurred at the end of the Devonian.

2. In the Saxo-Thuringen zone (Brittany, Odenwald, Erzgebirge, West Sudetes) a uniform penetrative deformation of the sediments and crystalline rocks is characteristic. The folding occurred at the end of the Dinantian.

3. In the Rheno-Hercynian zone (South West England, Harz, Rhenish Schiefergebirge) crystalline schists do not participate in the structure. The folds are tightly compressed and inversions occur. The deformation took place after the Westphalian.

Thus, in proceeding from South Brittany in a north east direction the time of the main folding becomes progressively later with the variation in the type of deformation also following this direction.

In South West England, the stratigraphy shows clear signs of the changing physical environment arising from the evolution of the orogeny. But the unconformities are of insufficient lateral continuity to permit a differentiation into distinct structural zones. Nevertheless, the south-south-west to north-north-east gradation of the Hercynian fold belt is also apparent on the more local scale.

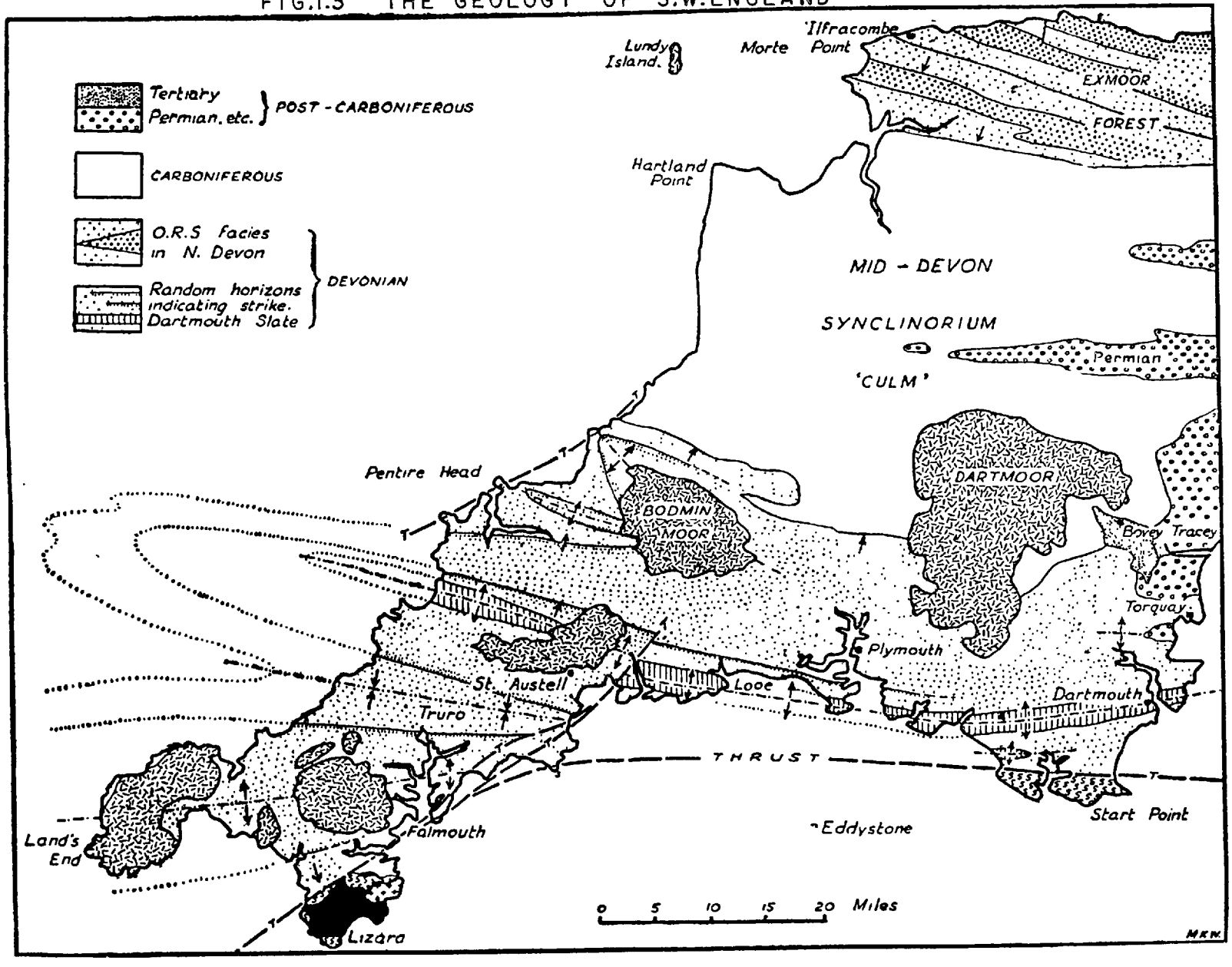
Uplift (and presumably folding) began in the south-south-west and is successively later towards the north-north-east. In addition, the intensity of folding is greatest in the south-south-west with a steady decrease towards the north-north-east. A closely related phenomenon was the persistent northward advance of the geosynclinal axis in the middle Devonian and lower Carboniferous.

As we have already seen the paroxysmal folding in South West England has been ascribed to the Asturic phase. The preceding phases also left their imprint on the region, but they may be regarded as the preliminary shudders leading up to a grand climax after Westphalian times.

The large scale structures consist of two anticlinoria (Fig. 1.3) separated by a broad synclinorium, all striking approximately east-west. The northern anticlinorium in North Devon is succeeded in the south by the synclinorium of Carboniferous strata. South of this synclinorium are more Devonian rocks which become progressively older until the English Channel is reached. They form the northern limb of a huge anticline whose southern limb is not seen but which probably lies beneath the English Channel.

The structure in the southern anticlinorium is complicated by second order anticlines and synclines, which

FIG.I.3 THE GEOLOGY OF S.W.ENGLAND



are in turn modified by third order anticlines and synclines. The cores of the second order anticlines are occupied by large granite masses. Of the five main granite bosses in South West England, four are to be found in the cores of the anticlines. Evidence for a similar setting of the Dartmoor granite is not so clear, but there is some indication that this granite also occupies the core of an anticline. The axes of these four anticlines show a gradual change in strike from east-west to north-west - south-east, thereby exhibiting a fan-shaped spread. The third order structures are tight isoclinal folds broken by strike thrusts which cause repetitions of the sequence.

The Culm synclinorium trends east-west and its axis passes through Crediton. Both its northern and southern margins have been broken by thrusting. On the northern margin younger rocks are thrust over successively older rocks so that in some places a portion of the succession is missing. On the southern margin the thrusts bring older Devonian rocks over the Carboniferous in many places. Minor anticlines and synclines appear as ripples on the limbs of the main anticlinorium. Proceeding from south to north the folds are in turn recumbent, inclined to the north, vertical, and eventually inclined to the south.

In North Devon the strata dip uniformly at 35° to the south, but in the extreme north-east they bend over into an anticlinorium. Second order anticlines are usually developed with an associated syncline to the north. Isoclinal folding is a local phenomenon.

Throughout the region, the softer argillaceous sediments gave way freely and developed slaty cleavage dipping parallel to the axial planes of the minor folds. The harder beds reacted differently and were fractured and broken by innumerable thrusts and strike faults. Thrusting is most severe in the southern anticlinorium, where many repetitions of the sequence give rise to imbricate structure. In the Culm synclinorium the southern limb is horizontally elongated in the Dartmoor region by a series of strike faults but as the northern limb is approached the thrusts become fewer and less powerful. Eventually in North Devon, though overthrusts do occur on a small scale, older strata are never thrust for any appreciable distance over the newer strata.

In addition to strike faults and thrusts there are three sets of cross-faults. Two of them strike west-north-west and east of north respectively. These are regarded as complementary wrench faults genetically related to the regional folding. The third set strikes

north-north-west and these are probably tension fractures forming at right angles to the fold axes.

The structural features of South West England were nearly all caused by the Hercynian orogeny and since that time there has been little modification. During the Alpine orogeny dextral wrench faulting occurred with a strong preference for a north-north-west strike.

Igneous History

Within the small area of Devon and Cornwall, there is a large variety of igneous rocks. They represent the magmatic activity associated with particular phases of the Hercynian orogeny. The pattern of igneous activity conforms closely to that of the typical geotectonic cycle.

During the subsidence of the geosyncline, basic magma was extruded as flows or intruded as sills. Sometime before inversion, the igneous activity ceased. Later, in the period of uplift, granitic magma was intruded as batholiths, and these were followed by fissure intrusives and then by the formation of ore veins. After a considerable time, the whole cycle ended with a renewal of extensive outpouring of lava having a peculiar composition. Thus each phase shows a characteristic chemical composition and form of activity.

Phase 1a.

From the early part of the middle Devonian until the lower Carboniferous, there was sporadic eruption of spilitic lavas. The contemporaneous sinking of the geosyncline resulted in an interbedding of lavas with mudstones and radiolarian cherts. In addition to the abundant flows of spilite, others of acid composition occurred. These are quartz keratophyres and are the acid members of the spilitic suite. All the extrusives show an abundance of soda.

With the extrusives are associated a number of intrusives. These range in composition from basic to ultrabasic and are for the most part sills, though there may be a few dykes. The basic types are also abnormally rich in soda.

The rocks of this phase are therefore linked by their marked chemical affinity and by their spatial and temporal association.

Phase 1b.

During the Bretonic phase of folding, before the spilitic extrusions had ceased, there was an injection of ultrabasic bodies. Their arrival brought to completion Steinmann's Trinity. This constant association of spilite, radiolarian chert and serpentine, in the early stage of geotectonic cycles shows that they are genetically related.

The most famous ultrabasic intrusive in South West England is the Lizard serpentine. It is alleged to have been intruded along a thrust - the Lizard thrust, which supposedly passes through Dodman Head and the Start Peninsula.

There were originally three types of peridotite but they have all been completely converted to serpentine. The three types grade perfectly into one another, indicating that they consolidated within a short period of each other.

All the serpentines show a conspicuous fluxion banding which reflects a layering of the constituent minerals. Microscopically, a foliation is also seen as an alignment of the diallage crystals. The fluxion banding and foliation are always parallel and concordant and they are the effects of pressure acting on the still viscous rock. In general, the fluxion structures are parallel to the edge of the intrusion. Away from the margins their orientation is northerly or to the west of north, and the dip is always nearly vertical. The inference is that the pressure acting on the viscous mass was from east-north-east to west-south-west.

There are three sets of mutually perpendicular joints. One is horizontal, and the other two are vertical. Of the

latter, one is parallel to the fluxion structure while the other is at right angles to it.

Phase 2.

The extrusion of spilite continued into the lower Culm, but from then on until the Stephanian, there was a pause in the igneous activity. The main deformation occurred after the Westphalian and towards the end of the folding a series of granite plutons were intruded. During the deformation, conditions had become favourable for the local mobilisation of the basement. A granite series was born and some magma was squeezed out into the synorogenic sediments of South West England.

The various granite outcrops show marked mineralogical and chemical similarities. Each of the bosses consist of different types of granite, each type being of a different age. In some instances the time interval between successive intrusions was very short. Later members are generally similar in mineralogy to the earlier ones, but there is an overall decrease in basicity with time. The composition of the original magma was in all probability sodipotassic, though there is uncertainty on this point because of the operation of differentiation and assimilation.

Regional pressures acting at the time of intrusion dictated a common flow direction to the magma of the bosses. The orientation of felspar phenocrysts show that the flow was northerly in the eastern part of the area. From there it gradually swung round to the west, so that in the most westerly granites of the Scilly Isles, the flow is north-west.

Related to the flow lines are three sets of mutually perpendicular joints. One is horizontal and of the vertical joints, one is parallel to the flow direction while the other is at right angles to it. The orientation of flow lines and joints is remarkably similar to the corresponding structures of the Lizard serpentine.

After the granite bosses, dykes of aplite, pegmatite and quartz porphyry were formed. These were followed by quartz-tourmaline veins and the final differentiates were the ore bearing solutions.

Phase 3

After a considerable period of time (15 million years by radioactive dating) there was eruption of a wide variety of lavas. Before the occurrence of this phase, the folding had completely finished and the uplift of the region had taken place. The lavas were laid down on a very irregular surface from which rose hills of

Carboniferous rocks. They were extruded under desert conditions with a consequent rapid disintegration of iron bearing constituents.

The actual centres of eruption have been located in some cases while in others the lavas are of the Puy type. The centre from which many eruptions came, was located in the neighbourhood of the Dartmoor granite. This explains the decrease in size away from Dartmoor of blocks of acid and intermediate lavas found in the Permian breccias.

The lavas may be divided into ten types grouped into three series. Each type also exhibits several facies. Most of the rocks are of quite exceptional mineral and chemical composition, though there are some lavas of normal type. Most are trachytic and some others are allied to basalt. Among the features of special interest are the association of basic plagioclase with quartz and of orthoclase felspar with olivine. These peculiarities are understandable if the lavas result from an interaction between the depth residuum of the Dartmoor granite and a late acid residuum.

PREVIOUS GEOPHYSICAL SURVEYS

Devon and Cornwall comprise a relatively narrow strip of land bordered on three sides by water. For this reason most of the relevant geophysical results have been a by-product of investigations of the English Channel and the Continental Shelf. Fundamental data to which the geophysical results could be related has been provided by cores taken from the sea-bottom. By combining the geophysical and coring data it has become possible to draw a provisional geological map of the western approaches. On the terrestrial area, the most striking feature is the rarity of previous surveys. Recently, there has been aeromagnetic and aero-electromagnetic coverage of the region.

a. Previous Marine Surveys

Of the four available geophysical methods - magnetic, gravitational, seismic and electrical - only the last has failed to find an application in the offshore exploration. This is hardly surprising since the sea effectively prevents the passage of electrical energy into the sea-bottom. Nevertheless, even the electrical approach has recently been attempted, but without much success. The

interpretation of the early geophysical results could only be tentative because of the inadequate geological control. However, with fairly extensive coring, a more reliable elucidation has emerged.

1. Gravity Surveys.

In the application of the gravitational method to the offshore areas, the leading role has been played by Brown and Cooper. Prior to their surveys, the gravitational work was of a sporadic nature and of doubtful accuracy.

In 1948, Brown and Cooper made measurements of the gravity field at 43 stations in the English Channel. For this purpose they used a Vening-Meinesz 3 pendulum apparatus and the entire programme was carried out in a submarine. Five stations in the area at which measurements had been made in 1946 were included in the final results. The accuracy of the observations was estimated to be better than $\pm$ 2.0 mgals.

After correcting for the Mesozoic sediments, the values were plotted at the various stations and partial isogams drawn at intervals of 10 mgals. A closer spacing of contours was deemed impractical since any anomaly less than 10 mgals could be explained by a local variation in the Mesozoic strata.

There was an area of strong negative anomalies off the French coast in the Cherbourg-Le Havre area, extending about halfway across the Channel. This was thought to consist of at least two separate anomalies close together, with an east-north-east to west-south-west trend. These features represented intracrustal masses and could not be subcrustal roots.

In the Western Channel there was a positive anomaly. Whether this was due to very deep masses or to a locally high density could not be determined.

2. Seismic Surveys

Bullard and Gaskell began seismic work in the English Channel in 1941. They were followed in 1953 by Hill and King. In 1956 Hill returned with Day and combined his data with that from the previous surveys. To aid the interpretation of the results, the compressional wave velocities in a wide range of rocks from South West England and the Channel Islands were measured in the laboratory.

Three layers were differentiated according to their seismic velocities. They correspond to a metamorphic basement, palaeozoic strata, and post-palaeozoic strata. All the available seismic data was combined with the gravitational results to give the depths and thicknesses of the three layers.

The metamorphic basement approaches the surface in the region of the Lizard, Dodman, Eddystone and Start (Map A). From this line it slopes southwards under the Channel. Between Eddystone and the Rutts a channel of New Red Sandstone rocks cuts through the metamorphic outcrop.

The structure contours of the palaeozoic rocks show a semi-isolated basin lying between Devon and Brittany, connected with a long trough-like feature to the west. A postulated outcrop of metamorphic basement within the palaeozoic floor passes through Start, Eddystone and the Lizard and continues in a south-west direction.

The isopach map of the post-palaeozoic deposits closely resembles the contour map of the palaeozoic rocks. In both, there is a suggestion that a slight ridge runs from the Lizard to Morlaix.

3. Magnetic Surveys

From 1956-59 Allan covered 1500 square miles of the western English Channel with magnetometer traverses. In all there were 14 north-south profiles (average spacing 5 to 6 kms), one east-west, and five others in various directions. Profiles were planned to pass close to the Lizard, the Eddystone and the South Devon coast.

The magnetic contour map shows :

1. A large anomaly 30 miles south of Plymouth. This has a north west-south-east strike and a peak value of 280 gamma. The anomaly is caused by a body approximately five miles by eight miles and its top surface lies at a depth of 1.0 to 1.5 miles. It is thought to be a basic rock brought up by another thrust plane to the south of the Eddystone thrust.

2. A number of very large anomalies to the east of the Lizard which die out quickly eastward, and are closely related to the geology of the Lizard. Their eastern extent coincides with the New Red Sandstone boundary. The New Red Sandstone is known to occur in troughs and valleys of the Hercynian mountains, and in this area it had banked up against cliffs of older rocks.

3. A number of smaller anomalies south-east of Plymouth Sound. These can be related to the known geology. They occur at the assumed boundary of the New Red Sandstone and the Start metamorphics. Allan believes that the latter rocks have a higher magnetic susceptibility because of their derivation from basalts and dolerites.

4. An area south of the main anomaly which is remarkably smooth magnetically. The palaeozoic floor and the metamorphic basement must here be very regular.

5. No indication of the supposed thrust passing through the Lizard, Dodman and Start.

Allan's work was followed up by Hill and Vine (1965). Their magnetic map of the western approaches showed a well marked elongation of anomalies in a west-south-west to east-north-east direction. From the known geology, the only formation above the metamorphic basement that is capable of producing an appreciable magnetic contrast is the New Red Sandstone. But calculations based on possible configurations of the NRS revealed that it could not give the anomalies. It was therefore concluded that the relief of the basement was responsible for the general magnetic features. The authors' opinion is that the basement was thrown into a series of ridges and valleys by the Hercynian orogeny.

A general correlation between the gravity and magnetic highs and lows was noticed, but the pronounced magnetic high south of Plymouth is not accompanied by a gravity high. Allan had previously encountered this anomaly and had postulated the presence of gabbroic material at comparatively shallow depths. However, it is difficult to see why such a body does not give a gravity anomaly.

b. The Provisional Geological Map of the Western Approaches

In order to produce this map Whittard made in 1963 a synthesis of all the geophysical and coring results. From the map, the main features of the area could be picked out.

Adjacent to South West England are Devonian beds, mostly slates. Their distribution indicates that either the Lizard thrust swings out to sea unexpectedly on a southerly course, or that the Devonian rocks overlie the Lizard mass on its southern side, the contact lying out to sea.

Three discrete phonolitic masses occur in the Devonian slates. They rise from the sea-bed as rugged peaks with exceedingly steep slopes.

Metamorphic rocks resembling those of the Start appear westwards from their terrestrial outcrop. At sea, they are surrounded unconformably by the New Red Sandstone.

A granite mass approximately five miles by two miles has been found 20 miles north of Roscoff which is on the north coast of Brittany. Its chemical affinities lie with the granites of Brittany rather than with those of South West England.

The New Red Sandstone occupies a large area of the sea-bed and extends southwards from the coast between Start Point and the Lizard. Westwards it wedges out (in surface outcrop) to the south of Mount's Bay.

c. Previous Terrestrial Surveys

In 1936 Bullard and Jolly made a pendulum gravity survey, but no interpretation of the results was published. In the decades that followed, several gravity surveys were conducted in southern England, but Devon and Cornwall appear to have been ostracised by succeeding investigators. It was not until 1958 that a publication by Bott, Day and Masson-Smith appeared, giving the geological interpretation of gravity and magnetic surveys in Devon and Cornwall. This accomplished in one step a major leap forward, and made some reparation for the years of neglect.

1. Gravity Survey

As part of the survey, the densities of 400 rock samples were determined, these samples being representative of the various rock types of the region. The gravity measurements were made with a Worden gravimeter and corrected values at the gravity stations were presented as a Bouguer anomaly map. This shows :

1. A belt of negative anomalies closely related to the Cornubian granites. This relationship arises from the lower density of the granites with respect to the country rocks. The authors suggest that the granites are cupolas of a large batholith whose floor lies at a depth of eight to ten kilometres. The main exposures of granite were believed to be connected by narrow ridges below the surface. In general, the contacts of all the granites slope outwards at steep angles. The floors of the Dartmoor, Bodmin Moor and St. Austell granites may be deeper in the south.

2. A rapid increase of the gravity values southwards over the Lizard and Start peninsulas. This was thought to be related to a major thrust underlying the two regions. However, the denser rocks must extend for at least three to four kilometres north of the Start boundary. Thus the anomaly at the Start cannot be explained by the simple hypothesis that the metamorphics are thrust over the Devonian rocks.

3. A decrease of the gravity values across Exmoor. This is attributed to a large thrust mass of Devonian rocks overriding at least three kilometres of Carboniferous and Old Red Sandstone rocks.

4. Three east-west ridges of higher values over the Culm synclinorium. These are caused by shallow structures within or immediately below the Culm rocks.

5. Local decreases over the Crediton trough and the basins of Bovey Tracey and Petrockstow. The Crediton trough is probably V-shaped and has a maximum depth of 340 m. The Bovey Tracey and Petrockstow basins are at least 194 m and 245 m deep, respectively.

2. Magnetic Survey

A few traverses were carried out with two Watts field magnetometers. At many stations, readings were taken on both instruments set up about 100 yards apart. The magnetic values were not contoured, but the profiles show:

1. A steady decrease in the magnetic readings from Exmoor in North Devon to the southern part of the Culm synclinorium. At this boundary there is a remarkably abrupt drop in the field. Southwards the decrease continues but at a much reduced rate. The line marking the sudden change follows closely the northern margins of the Dartmoor and Bodmin Moor granites. In the area between the two granites the line makes a southern deflection to pass just north of the granites at Kit Hill and Hingston Down. Along the line large negative anomalies are found locally; north of it lies the belt

of largest positive anomalies; south of it the magnetic field shows little variation.

2. A stable field over the granites themselves, with greater variations over the country rocks to the north. At the southern margins of the granite, there does not appear to be a significant change.

The results show the presence of highly polarised rocks beneath the southern part of the Culm synclinorium. These are truncated on the south by the granites. The contrast between the granites and the highly magnetic rocks extends to considerable depths. The authors suggest that the strong polarisation arises from basic igneous rocks which dwindle northwards in the Culm and the Devonian. An alternative hypothesis is that they are metamorphics brought closer to the surface by Hercynian thrusts.

d. Previous Airborne Surveys

Aeromagnetic Survey

In 1964 the Geological Survey of Great Britain published on a scale of 1:250,000, an aeromagnetic map of South West England (Map B). The north-south flight traverses were spaced at two kilometres or less and there were east-west tie-lines every ten kilometres or closer.

The mean terrain clearance was 500 feet. The interpretation of this sheet has not been published and the follow up ground surveys are now being carried out.

In discussing Allan's paper, Bullerwell gave a preliminary interpretation of that part of the map covering the Lizard. Thirty flight traverses had passed over the peninsula. The sharp anomalies there had a conspicuous grain in a north-west to south-east direction, and they were dissimilar to those over the Dodman and Start. The sharp termination of the anomalies at the northern margin of the Lizard complex and at sea shows that the Lizard rocks have a restricted areal distribution. The anomalies could be correlated with the basic intrusive rocks exposed on the peninsula. The serpentine was strongly polarised, the hornblende schists less so, and the granite gneiss least of all.

Aero-electromagnetic Survey

South West England has also been surveyed from the air by the electromagnetic method. The results of this survey have not yet been published.

CONCLUSIONS

The success of seismic exploration has been demonstrated at sea. The method is capable of differentiating between metamorphic basement, palaeozoic strata, and post-palaeozoic strata. On land, such a primitive division of the geological column would be of little value.

The gravity map is dominated by the presence of granites. We have already seen that the granites were intruded in one episode during phase two of the geotectonic cycle. Their emplacement was largely guided by the pre-existing structures. Thus, the extent and the shape of the granites indicate the structure of the country rock at the time of the intrusion and the essential structure of the area has remained almost unchanged since then. A gravity survey is likely to reveal the distribution and form of the granites. Useful results may be obtained on land and at sea.

The magnetic anomalies are caused by the presence of basic rocks, while the background magnetic field is related to the attitude of the underlying basement. The basic rocks are products of phases 1a, 1b and 3 of the magnetic cycle. Thus a magnetic anomaly may arise from any one of a large number of basic rocks. However, the

composition of the magma varied during the course of the cycle and if some magnetic anomalies can be correlated with particular types of magma it may be possible to map different types of basic rock by their attendant anomalies. The method is applicable to both land and sea.

THE GEOLOGY OF SOUTH WEST CORNWALL

The area consists of disturbed sedimentary strata intruded by basic and acid rocks. The sediments, known locally as killas, were deposited while the crust was generally mobile. Extensive fissuring allowed basic magma to ascend freely and be deposited as submarine lavas. Where the fissures and vents were plugged by congealed lava and by newly deposited sediments, the most convenient paths for the magma became the planes of separation between the sedimentary layers. Basic rocks therefore formed within the killas as intruded sills. These comprise the second group of rocks in the area, and are known as greenstones.

The thick accumulation of sediments and basic rocks within the geosyncline caused a gradual decrease in the penetrability of the crust. During the preliminary folding phases there was considerable compression resulting in further solidification of the sediments. The crust became impenetrable to magma but allowed the passage of granitising agents. Thus granitic magma was generated and the main folding phase created new fissures and weaknesses, permitting granite plutons to approach the surface. These granites are the third great group of rocks of South West England.

Killas (or Mylor Beds)

The Mylor beds consist of dark shales containing thin bands of pale sandy sediment. The shaly material is dark grey or blue-black. The sandy bands are repeated in great numbers an inch or so apart.

The shales are the characteristic Mylor rocks. They have a distinct cleavage which dips at a different angle from that of the arenaceous bands. Most exposures of the Mylor beds are permeated by quartz veins in vast numbers, which are of later origin than the main folding and the brecciation of the shales.

The slates are fine-grained clay-slates of very uniform character, composed essentially of quartz, white mica and chlorite. Accessories present are iron oxide, rutile, pyrite cubes and occasional felspar. There are no fossils in the killas. This fact, together with their appearance and composition, show that they were deposited in bathyal conditions and under a reducing environment.

The Mylor rocks are everywhere much broken and folded. They have a steady dip to the south-south-east and an east-north-east strike. The angle of dip is variable but is often about 45°, though higher and lower inclinations are by no means uncommon. Evidence of folding is constantly present, the folding being nearly

isoclinal. The axial planes of all folds have a south-east dip and the folds are mostly narrow. The folds are seldom complete as they are usually cut by thrust planes. There are innumerable such faults which dip to the south-south-east at higher angles than the dip of the bedding. As a rule the throw is not great but the general effect is to repeat the same beds at short intervals. Hence, the impression is given that there is an immense thickness of uniform rocks, dipping in a constant direction. In reality, they are the same beds recurring. For this reason it is not possible to estimate the thickness of the Mylor beds.

No base is known for the series, nor are there fragments of older rocks which would give a clue to their relative age. Also, as stated before, no fossils have been found in them. The age of the Mylor rocks is therefore open to conjecture. Since they appear to pass up conformably into the Falmouth beds of the Gramscatho, they have been provisionally assigned to the lower Devonian.

Contact Alteration of the Killas by the Greenstones.

Where the killas have been intruded by greenstone, the two rocks have been converted into a greyish-green cherty looking hornstone. The alteration of the killas

is confined to a few inches from the margin of the intrusion. The typical minerals formed are alkali-felspar, quartz, small stout rutiles, granules of epidote and acicular prisms of green hornblende. Once the killas have been modified by the greenstone, they become immune to metamorphism by a later granite.

Contact Alteration of the Killas by the Granite.

Where the granites have come into contact with the killas, profound changes have been wrought in the invaded rocks. The changes depend on the nature of the rock affected and its proximity to the granites. Surrounding the granites are gradational zones which are characterised by distinctive mineral assemblages. The growth of new minerals in the killas has been effected by the addition of fluoric and basic emanations combined with the application of heat. The typical metamorphic minerals are muscovite, tourmaline, biotite, andalusite and cordierite. These give an assemblage easily distinguishable from that formed during the metamorphism by the greenstones.

The Greenstones

The term greenstone is applied to a group of dark green basic rocks which have been much altered and more or less sheared. The term is essentially a means of field

classification and it includes a variety of rock types. The range in composition of the group embraces albite-dolerite, dolerite, picrite, minverite and amphibolite. Apart from the disparity in mineralogical composition, there is also a difference arising from their manner of formation. Thus a greenstone may be an intrusive sill, an interbedded lava, or even a metamorphosed rock.

The chief component of the greenstones is felspar. Chemical and optical examination both show that it is often rich in soda and comparatively poor in lime. As already seen, this abundance in soda is characteristic of stage 1a of the magmatic cycle. Taken as a whole the felspar is in the range oligoclase-(albite-oligoclase).

The next most important constituent is hornblende. This is of the green actinolitic variety and with chlorite imparts to the rock its characteristic green appearance. The hornblende is a secondary product, resulting from the alteration of pyroxene or olivine.

Pyrites and iron oxide (altered to sphene) are always present, and there is usually some chlorite in varying amounts. Yellow grains of epidote are not infrequent.

The greenstones were injected and extruded before the folding of the region, as they participate in the distortions of the killas. On account of their massive

character they are less twisted and contorted than the slates, which seem to have yielded and flowed around them. Shearing in the greenstones is sometimes severe but tends to be localised, and there are usually other parts of a sheared greenstone which have escaped crushing. The unsheared portions acted as resistant phacoids obliging the adjacent rock to flow around them.

The greenstones tend to be found around the granites, but there are also two diverging belts, much broken and disturbed, which are apparently unrelated to any granites. The northern belt strikes north-east and passes through Ludgvan, St. Erth and Gwinear (Fig. 2.11). The southern belt strikes east-south-east and runs through Marazion and Perranuthnoe to Cudden Point, where it appears to pass out to sea. It may be noted that the strike of the northern belt parallels the general strike of the killas in the region, while the southern belt is nearly at right angles to the normal trend.

Contact Alteration of the Greenstones by the Granite.

At the contact with the granites, new minerals were formed in place of the decomposed minerals of the normal greenstones, thereby enhancing their toughness. The growth of fresh felspar and hornblende crystals is typical. Where fluoric and boric vapours have acted on the greenstone, axinite and fluorspar were produced.

The Granites

There are several granite bodies in the area of which the Carnmenellis, the Godolphin and the Lands End masses are the most important. They invariably occupy the high ground and so dominate the topography. Their dominance of the region extends over the geology as well, and the main interest of the geology stems from their presence. They have attracted a great deal of attention not only for their own sakes, but also for their associated mineral veins and for the metamorphism which follows their margins.

The granites are of the usual type found in Devon and Cornwall, but close examination reveals slight differences between the isolated masses. There are even more striking differences between earlier and later intrusives within the same mass. They may be described as muscovite-biotote granites with large crystals of orthoclase. There are many accessory minerals including tourmaline, cordierite, apatite and zircon. The amount of muscovite and tourmaline increases greatly in certain areas, and in the neighbourhood of some lines of fissure. All the granites are now generally accepted as being intrusive into the surrounding rocks.

The Land's End Granite

The surface plan of the granite shows an L-shape with two main axes trending north-east to south-west and north-west to south-east. The dip of the granite surface is indicated by the width of the metamorphic aureole. The aureole is particularly wide near Penzance where it attains a thickness of more than one and a half miles, and in the north-east where a width of one mile is the average. In general the dip of the granite margin is low in the east and south, but steep or very steep towards the north-west and north.

Within the granite, flow structures are expressed by the orientation of the felspar phenocrysts. They are best observed on vertical joints or occasionally on exfoliation planes, and are best developed near the margins of the intrusion. When the directions of the flow lines are plotted, the intrusion process of the granite is revealed. The magma was intruded from the south-east at a low angle (less than 30^{o}). During its flow to the north-west its movement was controlled by the pre-existing anticlinal arch in the country rocks, striking north-east to south-west. The flow became horizontal at the crest of the anticline, then plunged down at a steep angle to the north-west. West of a line from Mousehole to Cape

Cornwall, the magma flow shows a marked departure from the expected north-west direction, and is to the west instead.

Related to the flow lines are three sets of joints. The first set at right angles to the flow lines are the cross joints or Q-joints. Their dip varies from northerly in the southern portion of the granite, to southerly in the northern part giving a fan shaped arrangement. The second set are parallel to the flow lines, these are the longitudinal or S-joints and they are usually vertical. The third set, the flat lying or L-joints, have dips of the order of 10° to 20°.

The Land's End mass consists of an earlier porphyritic granite, the G1 granite, and about seven square miles of fine grained granite, called the G2 granite. The latter is extremely fine grained but is similar in composition to that of the coarse granite into which it was intruded. The G2 granite is a later differentiate of the contaminated G1 granite. G1 was formed from a potassic magma and G2 shows that the trend of differentiation was from dominantly potassic-- less potassic-- sodic. On the other hand the original magma was probably sodic but became more potassic by assimilation of the shales.

The Godolphin Granite

The Godolphin granite occupies about eight square miles. It is vaguely pear shaped in outline with an elongation in a north-north-west to south-south-east direction. A ridge of granite hills runs parallel to the length of the mass. The metamorphic aureole surrounding the granite is a quarter of a mile wide on the average, but towards Tremearne and Porthleven widens to fully three quarters of a mile. North of Godolphin hill there are isolated metamorphic areas extending to Gwithian.

The Godolphin granite is composed of three separate intrusions. The first, the G1 granite, is a medium grained porphyritic granite, which appears at the northern end of the mass. The remainder of the pluton is nearly all occupied by the second type, the G2 granite, which is a medium grained lithonite granite. There are no porphyritic crystals in the G2 granite. The G3 granite is a leuco-granite with aplitic and pegmatitic facies. It occurs along the coast as a relatively thin layer capping the G2 granite.

Flow lines are confined to the G1 granite. In general the flow is aligned north-west to south-east with some minor local variation. Initially, the G1 magma was intruded at the present day southern margin of the

Godolphin mass. It entered at a high angle and flowed northwards to form a small dome-shaped body on Godolphin warren. The G2 magma followed, rising once again in the south and following the path of the earlier flow. However, it did not reach as far north, and part of the G1 granite escaped concealment. G3 was intruded once more in the south as a relatively thin sheet between the G2 and the adjacent sediments.

As in the Land's End mass there are three sets of joints related to the flow direction. The cross joints strike east-north-east to west-south-west and dip at steep angles. The longitudinal joints strike north-north-west to south-south-east and dip vertically. The third set are the flat-lying joints. At the contacts with the killas the joints are often continuous with those in the adjacent killas.

The Carnmenellis Granite

The Carnmenellis granite has a nearly circular shape and covers an area of about 51 square miles. It is attended by two satellite bodies, the Carn Brea and Carn Marth granites. The metamorphic aureole is narrowest on the eastern side of the intrusion and is widest to the north. In this direction the aureole extends to the coast, some four miles away.

The Carnmenellis boss is made up of four separate intrusions. The first of these is the Type 1 granite which is essentially the outer or marginal facies. This is a coarse granite with abundant porphyritic crystals of orthoclase. It occupies the lower reaches of the boss.

The fine granite is a fine grained tourmaline granite with porphyritic crystals of perthitic orthoclase. It was intruded while the Type 1 granite was still plastic. The semi-solid cover was cracked by the new intrusion and the fissures sealed by vein injections of quartz-tourmaline.

Next in time came the Type 2 granite which is medium grained, but has less conspicuous porphyritic felspars than Type 1. The Type 2 granite occurs in an arcuate zone, concave towards the centre of the boss, and concentric with the belt of Type 1.

The Type 3 granite occurs in the central part of the whole intrusion and forms the highest ground in the area. It is medium grained but its average grain size is below that of either Type 1 or Type 2.

Flow structure is seen in all three types. In Type 1 the flow is aligned in a north-north-west to south-south-east direction, with some less persistent and less definite minor flows. In the eastern part of the outcrop the flow axes pitch to the east, and in the west the pitch

is to the west. The magma was injected from the south into a pre-existing anticline at a high angle. In its northward advance the flow became horizontal in the central part of the anticline, then plunged northwards and spread beneath the sediments to the north. In the Type 2 granite the flow was east-west with minor flows striking north-south. The magma entered from the eastern border of the intrusion, flowed westward until it reached the barrier formed by the Type 1 granite then it spread horizontally in a north-south direction. Flow structures in the Type 3 granite show that it followed a course similar to that of the Type 2 granite.

The force of the intrusions caused a deviation of strike and dip in the enclosing sediments, and a corresponding deflection in strike of the greenstone masses around the periphery. The normal cleavages in the killas were also obliterated by the granite and in their place new cleavages were imposed parallel to the margins of the granite.

Four joint systems traverse the granite mass. The Q-joints strike east-north-east to west-south-west. The variation in their dips shows a fan shaped spread. The S-joints strike north-north-west to south-south-east and they are nearly vertical. The third set are the horizontal

joints. There are two sets of diagonal joints, one set dipping vertically and the other subhorizontally.

Minor Intrusions

Each granite mass is accompanied by several dyke and vein phases which range in age from pre-granite to post-granite. The pre-granite veins include quartz, quartz-felspar and quartz-tourmaline. Contemporaneous with the granite are granite veins, aplites and pegmatites. Post-dating the granite are the quartz porphyries (elvans), quartz-tourmaline veins and the mineral lodes. The genesis and time relations of these have stimulated much activity and argument in the pase, but it is not proposed to dwell further on such problems. Of more relevance will be the recognition of certain features of the lode system.

The mineral lodes are essentially fissure veins which were originally joint planes along which movement has occurred. Those faults which do happen to be mineralised are usually normal faults. The veins were formed by the infilling of open fissures together with impregnation of the country rocks. The lodes of major economic importance are exceedingly complex and show the effects of repeated re-opening, brecciation and shearing. Both a hypothermal and mesothermal suite of minerals are present. Usually

the earlier lodes are hypothermal and these strike parallel to the north-east to south-west granite joints. The mesothermal lodes strike parallel to the north-west to south-east granite joints and frequently fault the earlier lodes. The two sets of lodes therefore cross each other at right angles.

Several factors controlled the deposition of the lode minerals, all of them pointing to an intimate relation between the granites and the lodes. In general, the temperature has determined the chemical nature of the deposits, while the form of the granite has determined the distribution of the lodes. Primary zoning, dependent on distance from the granite is evident in several areas. The typical arrangement shows a tin bearing region surrounded by concentric zones in which copper and then lead/zinc is predominant.

The trend of the lodes is remarkably uniform, reflecting the similarity in trend of the joints in the various bosses. This north-east to south-west strike parallels the regional strike of the killas, and therefore represents the dominant structural trend of the region. There are, however, some significant departures from this direction which occur in the districts of St. Just, St. Hilary and Nancegollan, where the lodes have

a definite tendency to strike north-west to south-east. In every area the lodes and elvans are parallel and this holds even in regions where the lodes show an anomalous strike. But they do not occupy the same fracture system, as the dykes dip at a lower angle than the lodes, and the latter usually form a conjugate system whereas the dykes favour one dip direction only. The lodes are more or less restricted to areas known to be underlain by granite, but in this respect there is a glaring exception in the lodes at Gwinear. Though the spatial relationship between the granites and the veins is apparent, there does not seem to be a correlation between the shape of the exposed granites and the trend of the lodes. The exception in this case is the lode system of Carn Brea which parallels the elongated granite mass.

Structure

Small scale structures recognised in the killas testify to the intense deformation which has affected the area. But in the absence of fossils or of markedly different beds it is difficult to unravel the geological structure. Furthermore, the area is bounded on three sides by the sea so that observations are limited to a narrow strip of land. The best indication of the larger

structures comes from the distribution of the greenstones. These were intruded as sills and lava flows concordant with the bedding and thereafter participated in the folding.

Greenstone is found around the Lands End granite at Penzance, St. Ives, Zennor, St. Just and Tater du, though between Carbis Bay and Ludgvan it is notably absent (Fig. 2.11). On the assumption that these greenstones are parts of one thick sill, the outcrops may be explained by postulating an anticlinal axis passing through Gwithian, Hayle and between Carbis Bay and Ludgvan.

More greenstones, having north-east to south-west strike, occur to the north-west of the Godolphin and Carnmenellis granites, while another belt with a north-west to south-east strike passes through Marazion, Perranuthnoe and Cudden Point. It has been suggested that these indicate an anticline near Ludgvan, running north of St. Hilary, to Binner Downs and Truro, and that there is another direction of folding at right angles to this trend.

The deposition of the greenstones undoubtedly show the existence of some anticlinal structures. However, it is not so obvious that these were pre-granite, since they may equally well have arisen by the forceful thrusting aside of the country rocks by the invading granite magma. Any pre-granite structures would be greatly modified by

these diapiric intrusions, and it is not possible to know the extent of the modification. Thus, there can be no direct evidence of pre-granite anticlines, but on general grounds their existence is a reasonable assumption. It is accepted that the region had been subjected to intense deformation before the arrival of the granites, and it would be rash to contend that no large scale anticlines and synclines were formed. The marked similarity in orientation of the flow structures and joints in the various bosses is a further indication that there was regional control guiding the emplacement of the granites.

As previously noted, numerous small faults and thrusts traverse the killas causing many repetitions of the sequence. Faults trending north-west to south-east are also common, and along them the movement is usually oblique to the right hand side. The motion is best shown where the mineral lodes are displaced. The most persistent of the cross-courses as they are called, strikes N 28^{o} W and passes to the north-east of the Godolphin granite.

CONCLUSIONS

South West Cornwall presents some exceptional features with regard to its ore deposits. In the first instance, the most intense mineralisation of South West England falls within this region. Secondly, there is the anomalous strike of the lodes around St. Just, St. Hilary and Nancegollan. Thirdly, the lodes of the Gwinear district occur at least three miles away from the nearest known granite. The solution of these problems is compounded by the general obscurity concerning the structure of the region, the age and the thickness of the killas. Such a parlous position stems from an inability to extract the necessary information from the sedimentary strata, and it therefore becomes necessary to make the fullest use of the other rocks available, i.e. the igneous intrusions.

As previously indicated, the granites are intimately related to the pre-existing structures and to to the mineralisation, while the basic intrusions are other indicators of structure. An investigation of the granites and greenstones may therefore throw light on the large scale structures and on the causes of the anomalous features in the mineralisation. Data from the exposed

granites and greenstones have been incorporated into previous interpretations of the area, and new information must now come from unexposed bodies. For this purpose geophysics would appear to be an effective and cheap tool.

PART 2

The Results

OFFSHORE SURVEYS

a. Seismic Survey

Mount's Bay was covered by some 260 miles of traverse using a Continuous Seismic Profiler in conjunction with a Marconi Graphette echo-meter. The positions of the traverse lines were given by Decca Navigator. Taking advantage of the suitable orientation of the Decca grid in relation to the known geological trends, the traverses were run parallel to the lines of the Decca grid. The east-west profiles were spaced at intervals of a quarter of a mile and the north-north-west to south-south-east profiles were one third of a mile apart. The southern edge of this pattern is defined by an east-west line from Kemyal Point, one and a half miles south of Mousehole, to Porthleven Sands.

The accuracy of the Decca fixes is adversely affected by several factors and the Decca Navigator Company provides

tables of standard errors for those effects amenable to computation. For the Mount's Bay area the position of any traverse line is accurate to 300 feet, while the distance between two nominally parallel lines may vary by 210 feet. In practice, discrepancies of this order were realised, but close inshore, the errors became more erratic, and sometimes exceeded three times the Standard Deviation. In such cases the Decca positions were adjusted by means of land fixes.

1. Bathymetry

The Marconi Graphette echo-meter was designed for relatively shallow work. It employs a magnetostrictive transducer which radiates short pulses at regular intervals and between pulses acts as a detector for incoming signals. In order to reduce unwanted reflections, the transducer is constructed to receive signals from a restricted area. With the transducer facing vertically downwards, the restricted area lies within 17^{o} in the direction of movement of the boat and 27^{o} in the perpendicular direction. The pitch and roll of the boat serve to increase this area. The instrument operates at 74 kc/s and with a stylus speed of 92.3 in/sec on 6 inch recording paper the record can be read to $\pm$ half a foot.

The instrument records the time taken for the radiated pulse to be reflected back to the receiver. If the velocity of sound in the sea-water is known, the depth to the reflecting surface may be calculated. Sound velocity in sea-water is itself dependent on a number of factors, the most important being the salinity, temperature and pressure. Salinity and temperature were measured at various times, at a large number of locations and the average values calculated, while the mean hydrostatic pressure was determined by taking the average depth of water parallel to the bathymetric contours. The velocity of sound was obtained from the formula

$$C = C_{0,\ 35,\ 0} + \Delta cs + \Delta ct + \Delta cp + \Delta stp,$$

where C is the velocity of sound at $0^{\circ}C$, 35‰ salinity, and atmospheric pressure, Δ cs, Δ ct and Δ cp are the correction terms for changes in salinity, temperature and pressure, respectively, and Δ stp takes into account the simultaneous changes in these factors. The corrections were obtained from Little's tables, and the value used was 4.92 ft/ms. The accuracy of the instrument was checked periodically by comparing its results with direct measurements of the depth carried out with an iron bar.

A profile representing the topography of the sea-bottom is obtained by plotting the water depths against

the corresponding boat positions. This gives, in fact, a distorted picture of the true topography whenever the surface is not horizontal. The relation between the observed dip ϕ on the record and the true dip θ of the sea-bottom is given by de Blavon's formula

$$\sin\theta = \tan\phi$$

A graph of θ plotted against ϕ reveals that if the reflecting surface dips at 90°, the record will only show a dip of 45°. For small values of θ, the distortion is very slight and is usually neglected.

A further consequence of a sloping sea-bottom is to displace each observed point on the slope horizontally down the dip. The amount of displacement is given by Krause's formula

$$D = \gamma \tan\phi$$

where D is the depth on the record and ϕ is the dip on the record.

A final correction was necessary to eliminate the effect of tidal variation, which raises and lowers the boat with respect to the sea-bottom. All computed depths were therefore related to Newlyn datum by applying the tidal corrections obtained from predicted tide-tables.

After the various corrections had been applied, a bathymetric chart of Mount's Bay was constructed (Fig. 2.1).

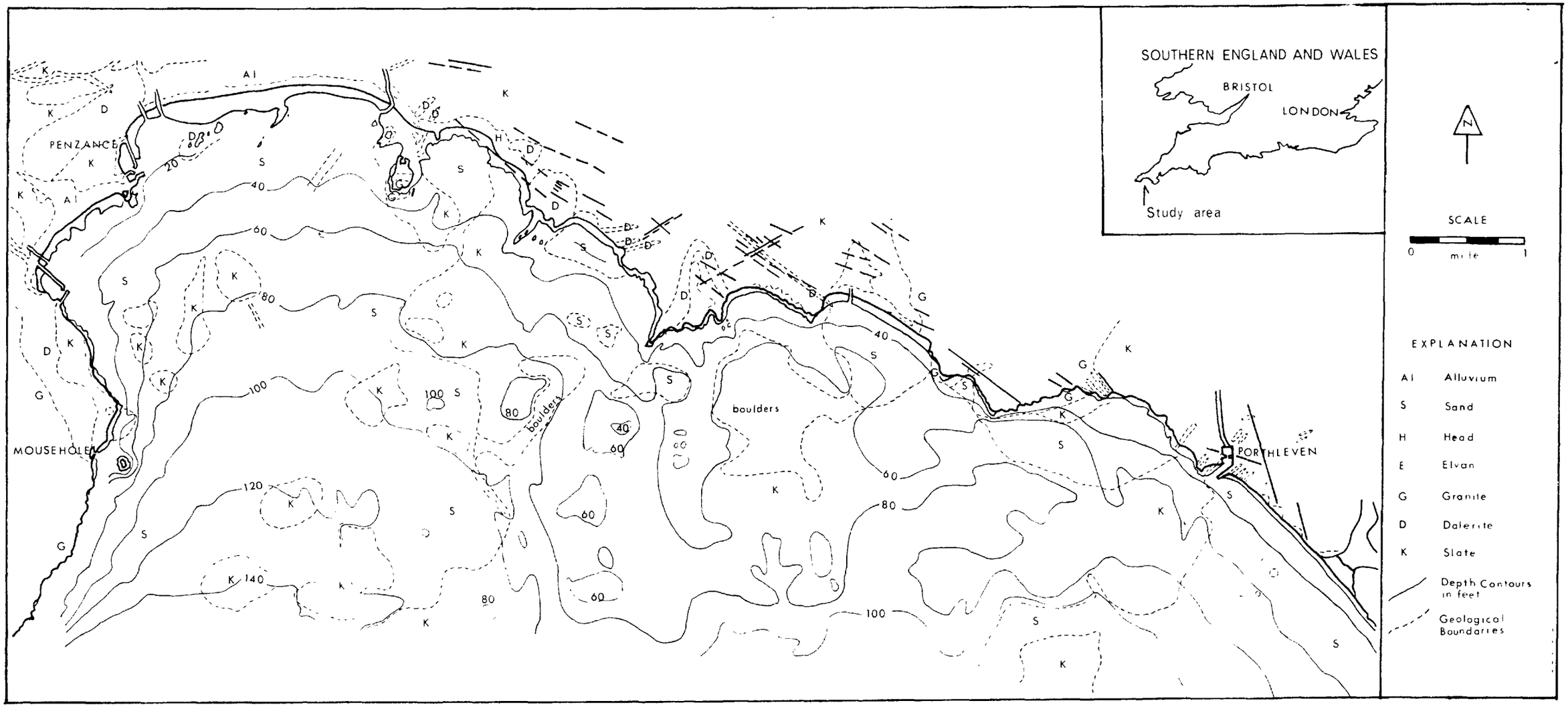


Figure 2.1 The bathymetry of Mount's Bay and the geology of the surrounding area.

The deepest area is about four miles south of Penzance where the depth exceeds 140 feet. The central part of the bay, south of the Marazion-Prah Sands coastal section, is the shallowest and the depth is generally less than 90 feet. Further east the depth shows a slight increase. The sea-bottom in the west of the bay and off Porthleven sands, slopes regularly outwards to sea with little relief. In the central area of the bay, there are minor variations in the direction of slope, but these do not appear to follow a clearly defined pattern.

2. Continuous Seismic Profiler.

In this system the acoustic energy is provided by a spark discharge in water. The spark electrode was towed 150 feet astern of the survey boat and maintained about five feet below the water surface. This was done by attaching floats at suitable points to the cable. The pulse is made by discharging at regular intervals two large condensers connected in parallel. The energy stored in the condensers was about 100 Joules, of which about 0.5-10% was converted into acoustic energy (Hersey).

With such a sound source a continuous range of frequencies from 0 c/s to 15 kc/s is produced. This is particularly desirable since the sound absorption by sediments is dependent on frequency. Lower frequencies

give better penetration but are themselves subject to the disadvantage that they give less definition. On the other hand, the higher frequencies give better definition at the expense of penetration. Hence a continuous frequency range is well suited to deal with a variety of conditions.

The reflected pulses were detected by a magnetostrictive hydrophone. This was also towed 150 feet astern of the boat and maintained at five feet below the surface, but by leading the cables from opposite sides of the boat, it was separated from the spark source by about ten feet. The output from the hydrophone was fed into an Alden dual channel recorder. The block diagram of the recording system is shown in Fig. 2.2.

Pre-amplifier

The pre-amplifier was a two-stage fixed gain amplifier with linear frequency response. Its output was split into two and led into separate channels.

Filters

Variable band-pass filters were used. On channel one the filters were set to pass 150-600 c/s. On the other channel the setting was varied from time to time in an attempt to improve on the record from channel one. Such attempts were apparently unsuccessful and eventually the setting was maintained to pass 150-1200 c/s.

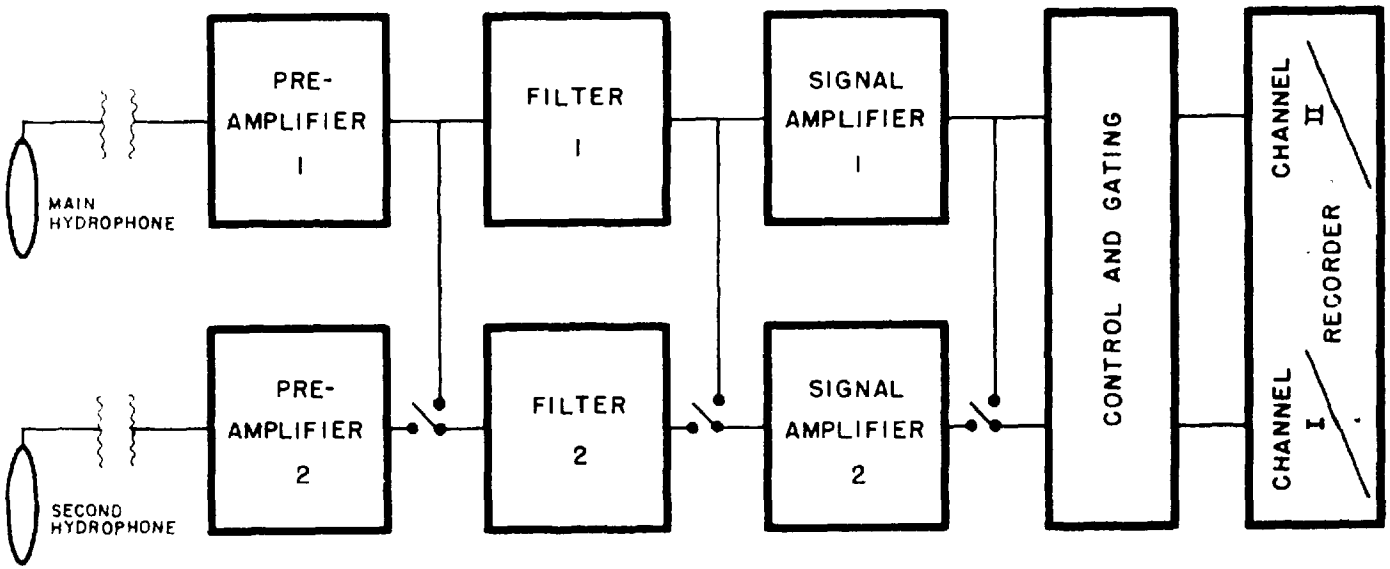


FIG 2.2

DUAL CHANNEL SPARKER RECEIVING AND RECORDING SYSTEM

Signal Amplification

This section carries three controls.

a. The attenuation dial was regulated to give a satisfactory level of signal.

b. The compression switch was switched off to render inoperative the automatic gain control. Thus the pick-up signals were recorded with intensities proportional to their strength.

c. On channel one, halfwave rectification was used and on channel two full wave rectification was used.

Control and Gating

This section does not affect the pick-up signals but controls the recording process. In the shallow conditions found in Mount's Bay, it was sufficient to record the reflections occurring within the first eighth of a second of each spark discharge. Accordingly, the phase setting was at one and the time sweep was left at one eighth. The spark was discharged four times per second, since this was the maximum rate consistent with full charging of the capacitor banks.

Interpretation

The Sparker is subject to the same errors as the echo-meter. The variations in salinity, temperature and pressure, the dip distortion and the horizontal offset

may be dealt with as in echo-meter interpretation. Additional complications are introduced by the greater power of the acoustic source and the non-directional properties of the hydrophone. Because of the latter factor, even if the sea-bottom is flat, there can be no certainty that a reflection appearing on the record lies vertically beneath the traverse line. In exceptional circumstances a reflection from a surface not vertically beneath the boat may be readily identified (Fig. 2.3a), but for the most part one must simply hope that the traverse has passed over the features seen on the record.

The greater power of the acoustic source gives multiple reflections of the bottom and of the sub-bottom. They may be easily recognised by two diagnostic features. Firstly, the surfaces giving multiples occur at fixed intervals on the record and secondly any dip in the first reflection is doubled in each succeeding reflection.

In order to calculate the penetration achieved in rock or unconsolidated sediment, some knowledge of the velocity in these media is required. For solid rocks the velocities used, were based on determinations made on similar rocks on land. These included a range of 10-14 ft/ms for the killas, 11-17 ft/ms for the granites, and a wide range of unsatisfactory determinations of greenstone

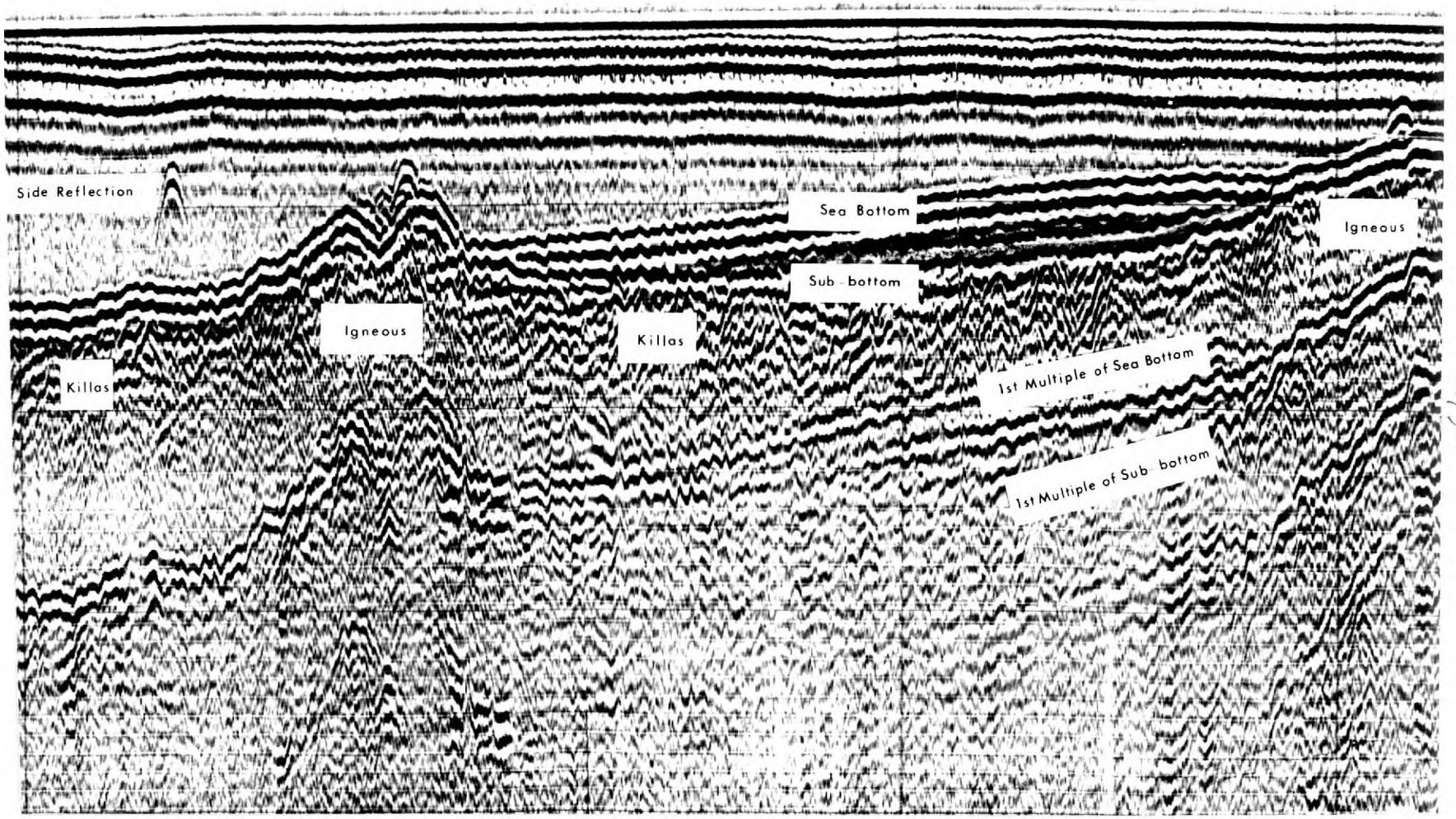


FIG. 2.3 a PART OF A SPARKER RECORD

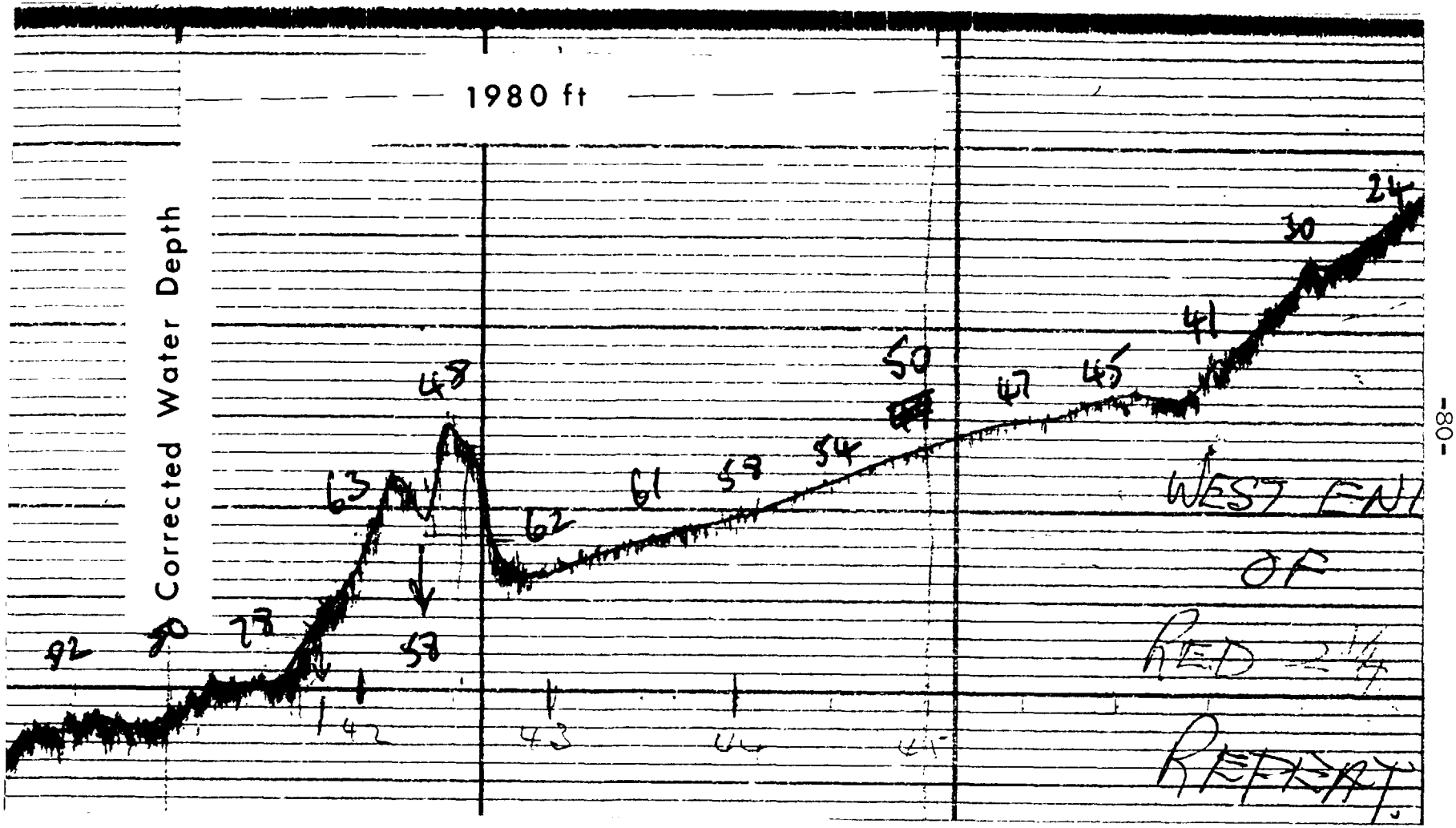


FIG. 2.3b ECHOMETER RECORD CORRESPONDING TO FIG. 2.3 a

velocities averaging 12 ft/ms. For the unconsolidated sediments a similar approach was clearly impossible, and it was necessary to indulge in some rough calculations. The velocity of sound in unconsolidated sediments is dependent on porosity, rigidity, pressure, temperature, mineralogy and grain aggregate compressibility. No information was available on the characteristics or the distribution of sediments in Mount's Bay, but Shumway had carried out some laboratory studies involving the various factors. Shumway's results were used and a velocity of 5000 ft/sec was employed for the unconsolidated sediments.

The corrections for sub-bottom dips and horizontal offsets are more complicated than in the case of the bottom slopes. The corrections are given by the following formulae (Fig. 2.4)

$$\frac{\Delta H}{h} = \frac{1}{\sec\alpha}\left(\frac{v_1}{v_0}[\sec\theta - 1] + \frac{H'}{h}[\sec\alpha - 1]\right)$$

and $$\frac{\Delta x}{h} = \tan\theta + \frac{h'}{h}\tan\alpha - \frac{\Delta h}{h}\tan\alpha$$

where ΔH = depth correction

Δx = horizontal offset

From the record H', α', h can be determined where h is the depth of the sea-bed and $H' = H + \Delta h$ with H being the depth of the point below the sea-bottom

Then $\alpha = \sin^{-1}(\tan\alpha')$

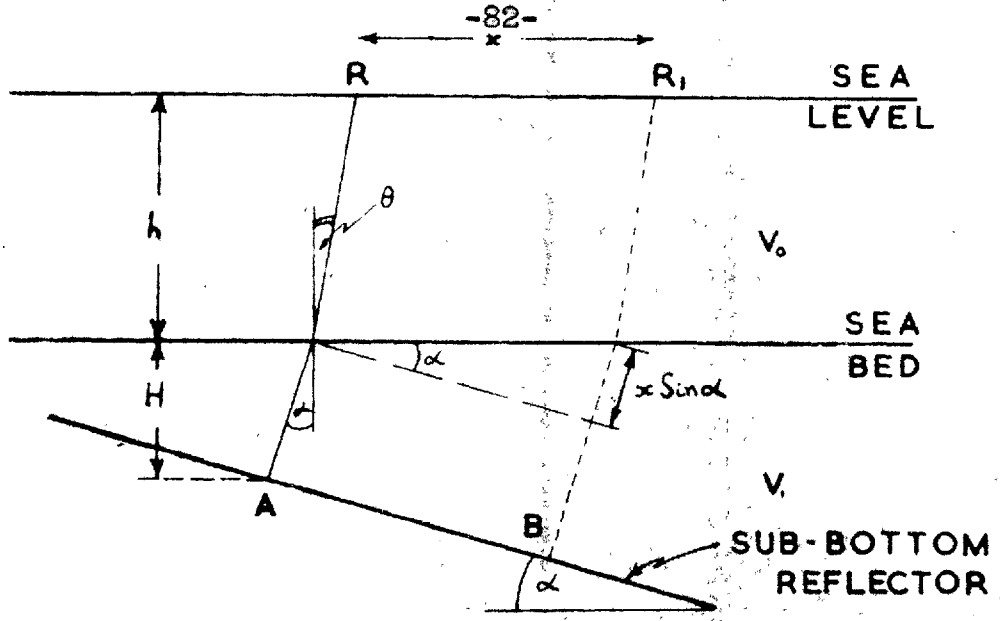


FIG. 2.4 a DIAGRAMMATIC REPRESENTATION OF REFLECTION PATHS FROM A DIPPING SUB-BOTTOM REFLECTOR.

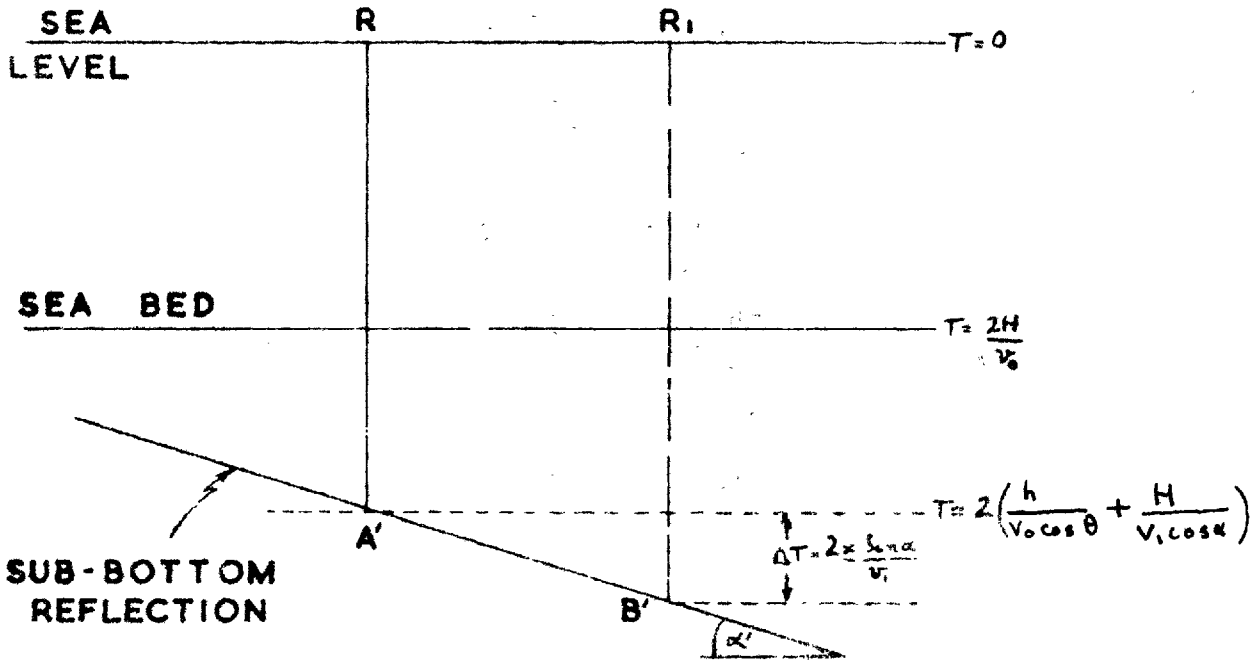


FIG. 2.4 b DIAGRAMMATIC REPRESENTATION OF RECORD PRODUCED BY CONDITIONS INDICATED BY FIG. 2.4 a

A curious pattern appearing on many parts of the records was interpreted as an indication of a rough bottom. It can be shown that the reflection from a boulder or of a surface irregularity, takes the form of a hyperbola. A large number of irregularities in a particular locality then give rise to intermingling hyperbolae and the total effect is that of a herring-bone pattern. On the records (Fig. 2.3a) the narrowness of the herring-bone ornament is a consequence of the small horizontal scale of the records.

The sound pulse generated by the spark discharge lasts for about three microseconds and a reflecting surface is therefore represented on the records not by a single line, but by a broad band occupying three microseconds of the vertical scale. With a velocity of 5.0 ft/ms this occupies 15 feet, and if two reflecting horizons are within this distance of each other it is impossible to separate them on the record. However, one may frequently deduce in such cases that two surfaces are present.

The records showed very strong bottom reflections and in certain areas strong sub-bottom reflections as well. From the Sparker results alone it was not possible to say whether the latter were due to a discontinuity between

rock and unconsolidated sediments or a discontinuity between rock A and rock B. The question was settled by appealing to the echometer records. These showed that in every instance of sub-bottom reflections the sea-bed was particularly smooth and in many cases there was an accompanying decrease in intensity of the reflected signal on the echometer record (Fig. 2.3b). Both these conditions point to a substantial thickness of unconsolidated sediments resting on bedrock. The smoothness of the sea-floor obviously occurs when unconsolidated sediment has completely submerged any protuberances of the bedrock surface, while the decrease in the reflectivity is due to the low specific impedance of the sediments. The reflectivity R is defined as the ratio of the reflected to the incident energies and is given by

$$R = \left[\frac{\rho_1 c_1 - \rho c}{\rho_1 c_1 + \rho c} \right]^2$$

where ρ and c are the density and velocity of sea-water and ρ_1 , c_1 those of the rock. In the case of killas/sea-water

$c_1 = 11.5$ ft/ms

$\rho' = 2.70$ gm/sec

$c = 4.95$ ft/ms

and $\rho = 1.03$ gm/cc

giving $R \simeq 51.5\%$

In the case of unconsolidated sediments/sea-water since there is little difference in velocity between them.

$$R = \left[\frac{\rho_2 - \rho}{\rho_2 + \rho} \right]^2$$

Hence $R \simeq 10.2\%$ if $\rho_2 = 2.00$ gm/cc.

Thus the reflectivity over rock, and this difference is shown up on the echometer records.

From the records the distribution and thickness of the unconsolidated sediments was determined. The results are shown in Fig. 2.5. More than one third of the area surveyed is covered by sediments having a thickness exceeding 15 feet. This sedimentary cover is most extensive in the western part of the bay, and is also appreciable off the Loe estuary. In the central part of the bay, sediments are either absent or too thin to be measured by the Sparker.

The thickness is extremely variable. A maximum, exceeding 60 feet, was recorded half a mile south of Mousehole. Elsewhere, there are some limited areas where the thickness reaches 40 feet, but for the most part it is between 20-30 feet. The thicker accumulations appear to have a haphazard distribution.

By subtracting the thickness of sediments from the sea-bottom contours, the topography of the bed-rock surface is shown. When this is done, some depressions in

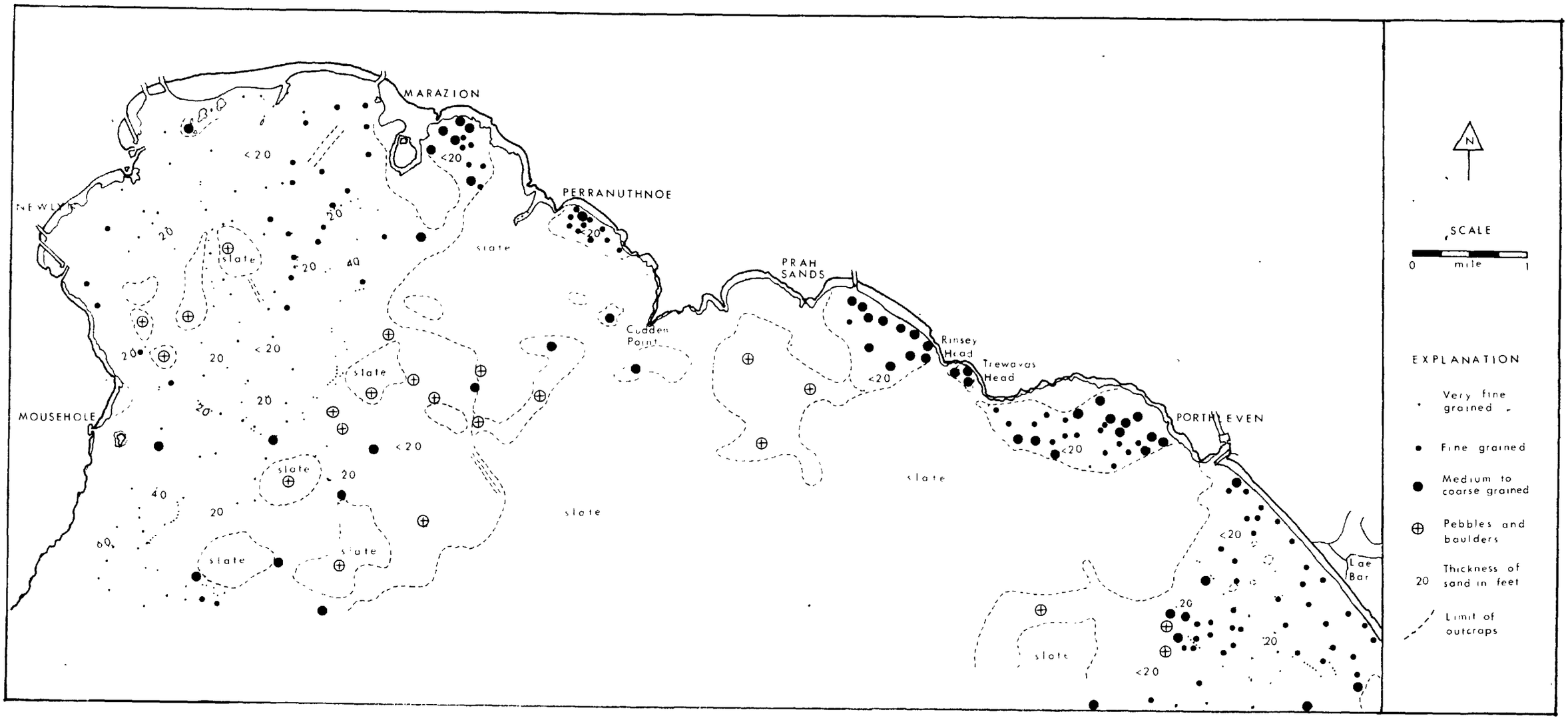


Figure 2.5 Thickness and character of the unconsolidated sediments in Mount's Bay.

the form of buried valleys become apparent (Fig. 2.6). The buried valleys appear opposite the streams at Loe, Porthleven, Marazion and Penzance. Taking into consideration the subsidence of the land within very recent times, it is most likely that the depressions are the old channels of the present day streams.

b. Petrology of Rocks Collected from Mount's Bay.

Rock samples from the sea-bottom were collected by a team of amateur divers using aqua-lung apparatus. The sampling sites were determined largely by the Sparker and Echometer results. From these records the distribution and thickness of the unconsolidated sediments was determined (Fig. 2.5). All areas covered by more than 15 feet of sediment were regarded as unlikely to yield rock samples, and these areas were geochemically sampled. The diving confirmed that the boundaries shown in Fig. 2.5 between rock and sediment were fairly accurate.

To collect the rock samples the divers used the traditional hammer and chisel, but in certain areas muscle power proved to be of no avail and a compressed air percussion hammer was employed. The location of the samples was determined by means of sextant charts.

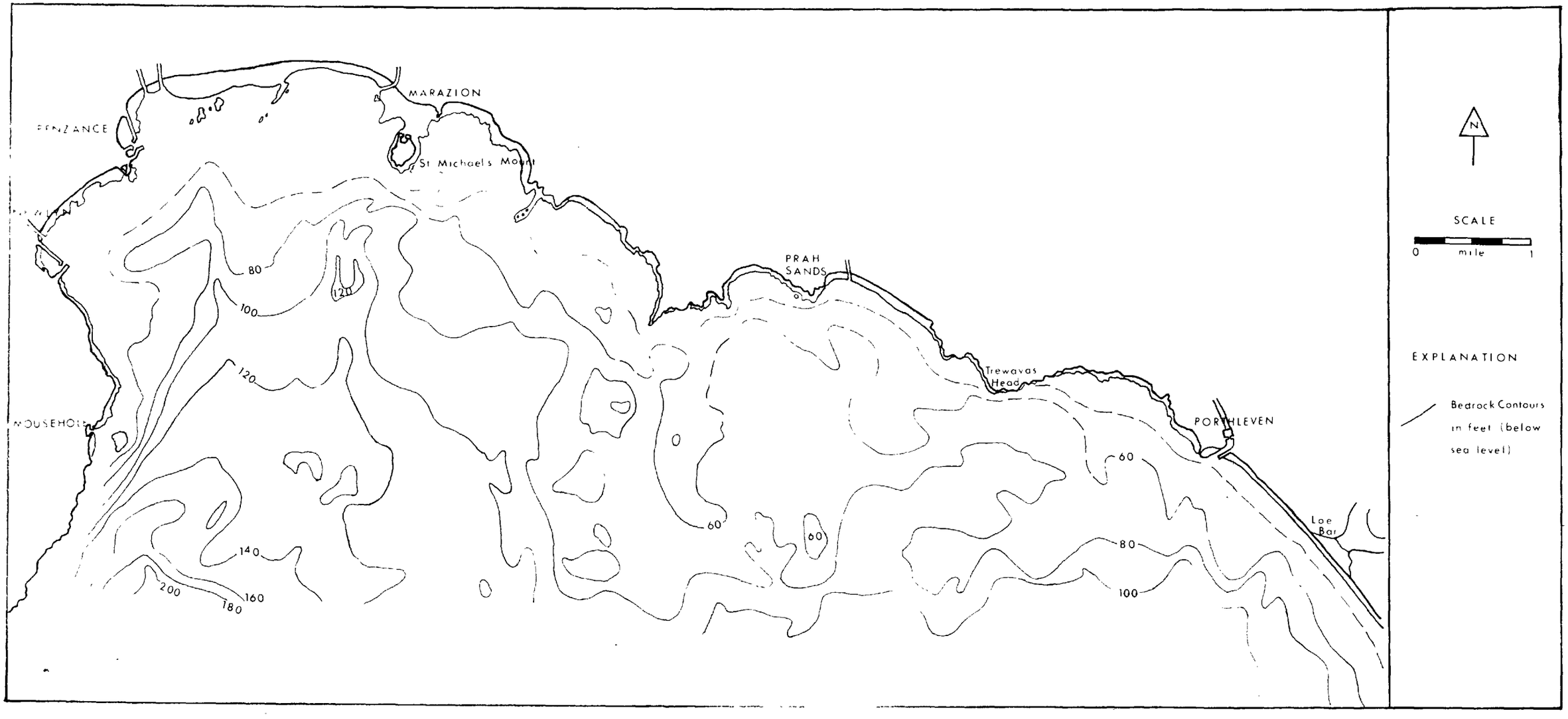


Figure 2.6 Bedrock topography of Mount's Bay calculated from the echometer and sparker charts.

The divers were not geologists, and so the only information gleaned from the outcrops consisted of the rock specimens themselves. It is probable that these did in fact come from outcrops, or at any rate from large blocks. This is surmised from the absence of smoothing and from the luxurious coating of moss and limpets on the specimens, these factors suggesting that the rocks had not been rolled about on the sea-bed. However, from the presence of quartz veining in several of the samples it is suspected that the most conspicuous lumps on the outcrops were singled out for demolition by the divers.

Inspection of hand specimens confirmed that the rocks on the terrestrial area continue into the bay. With the exception of some scattered areas of greenstone, the killas are the only rock type found in the bay. Close sampling near to the margins of the Godolphin and St. Michael's Mount granites showed that the coastline more or less corresponds to their sea-ward limit.

The Killas

Some of the samples showed unmistakable signs of contact alteration and these were duly sectioned. The West of England has long been famous for its development of typical contact alteration phenomena, superimposed on low grade regional metamorphism. The various zones of

metamorphism surrounding each granite boss have been well described, and from a recognition of such zones in the bay, it is possible to deduce the location of underlying granite.

Starting from unmetamorphosed Mylor slate, eleven zones of increasing metamorphism have been recognised by Bagchi, culminating in the development of muscovite schist at the contact with the granite. Unfortunately, the end products of the metamorphism are dependent not only on the nearness of the granite, but also on the original composition of the slates. For instance spotting is characteristic of the onset of thermal metamorphism but Reid and Flett have noted several localities at which spotting is not of thermal origin. Also, cordierite occurs as spots in the spotted slate, but may also be formed in the inner contact aureoles as irregular spots consisting of a mixture of white mica and chlorite. Again, muscovite is characteristic of the highest grade, but it may occur as a replacement of biotite in the biotite hornfels. In view of these uncertainties it was decided to employ a broader classificition of metamorphic zones, which would be accurate if not precise. Three categories of metamorphic grade were recognised and their distinguishing features are given below.

Tourmaline or muscovite schist

In this grade there are various gradational stages from an abundance of biotite (with a little tourmaline) to an abundance of tourmaline (with virtual disappearance of biotite). When alteration is complete the rock is converted into a banded schistose aggregate of tourmaline and quartz. The tourmaline schist is found at the granite margin or along certain lines of fissure.

The muscovite schist consists of large plates of muscovite arranged in parallel layers, alternating with quartz-rich layers. This rock is formed at the immediate contact with the granite.

Biotite and cordierite or andalusite hornfels

In hand specimens these are hard, splintery, dark brown or black. There is no sign of spotting and the original foliation of the rock is preserved.

In thin section they consist of quartz, biotite, fresh recrystallised felspar, rutile, iron oxide and a little tourmaline. The type of hornfels is decided by the prevalence of either biotite, cordierite or andalusite. When andalusite is present it is usually colourless and not well shaped. By rejection of biotite a dark border is found around white spots. Weathering causes the andalusite to be replaced by aggregates of sericite.

Cordierite is much less frequent than andalusite and it is usually represented by irregular spots of sericite and chlorite. In the biotite hornfels there are dark bands of biotite flakes elongated parallel to the bedding. The biotite rich bands alternate with quartz rich bands. The various hornfelses are to be found in the inner metamorphic aureole.

Spotted slate

The spots are seen even in hand specimen and are composed of chlorite, sericite, biotite and iron oxide. Chlorite and sericite in the spots often occur together forming felted aggregates, but in some rocks the sericite is the main ingredient. These two minerals may be from the alteration of cordierite while the sericite spots may be secondary after andalusite. The groundmass is a fine grained mixture of secondary mica, chlorite and granular quartz with a few grains of iron oxide and flakes of pale yellowish-brown biotite. The spotted slates are symptomatic of medium-low grade metamorphism.

Unaltered killas

In hand specimen the killas are soft, well-laminated dull black or dark grey. They contain quartz, white mica, and chlorite as essential constituents. Accessory minerals are iron oxide, rutile and pyrite.

The Greenstones

These were originally basic rocks emplaced during the sinking phase of the geosyncline and they have suffered the effects of the Asturic folding. All the greenstones were affected by the folding movements though some masses were more severely sheared than others. The intrusion of the granite after the folding superimposed a thermal metamorphism on the greenstones in certain localities. Because of their history subsequent to their emplacement, rocks which were originally different in composition have been brought to the same metamorphic facies, so that rocks of varying composition and texture are all classed as greenstones.

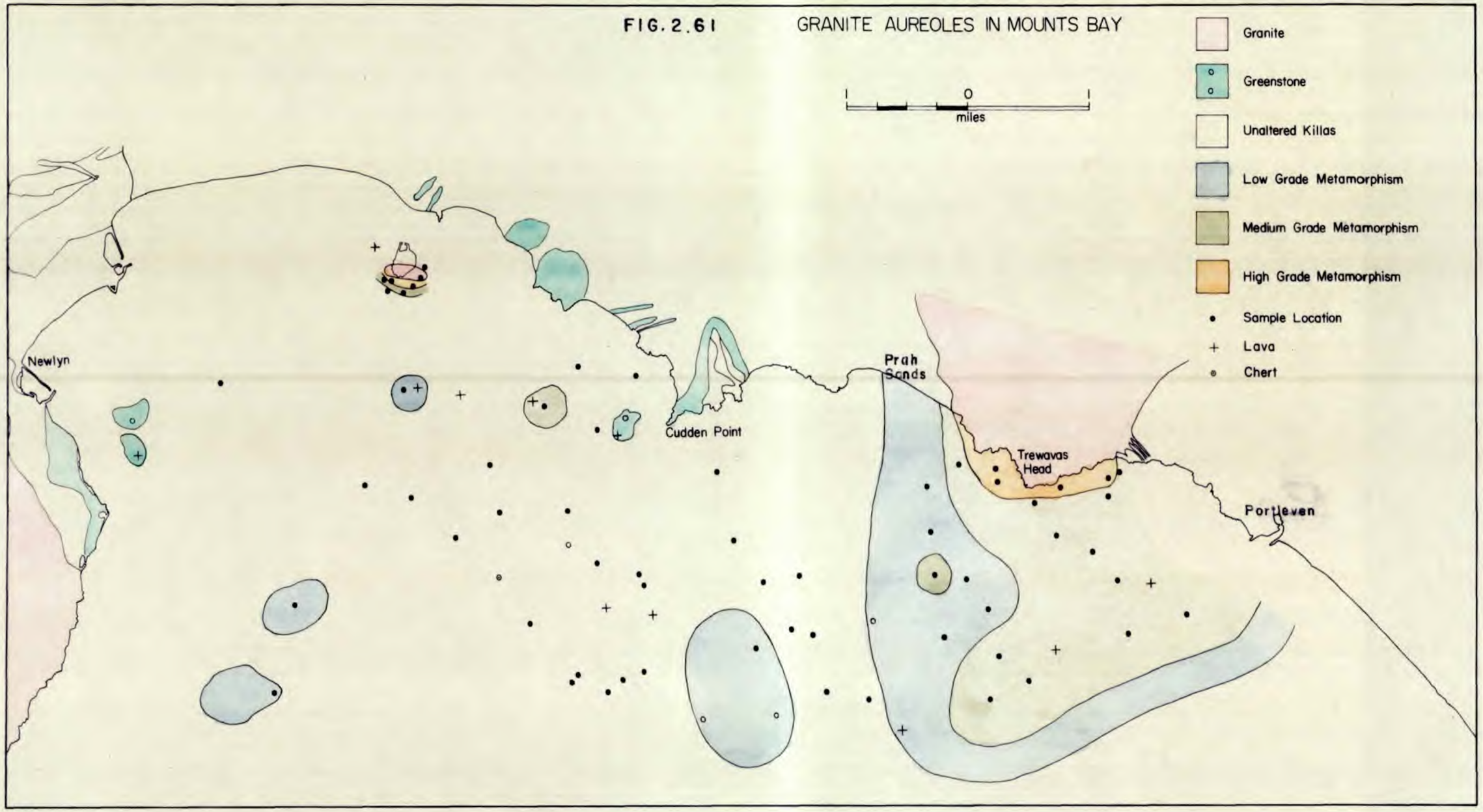
The green colour of the rocks comes from the abundance of chlorite, epidote and actinolite in various proportions. The other minerals present are plagioclase, zoisite, calcite, sphene and iron oxide. The plagioclase in the coarse rocks show low extinction angles and appears to be albite; in the finer grained samples the albite is often untwinned and exists as colourless grains. One specimen consisted almost exclusively of actinolitic hornblende, while another showed bands of epidote alternating with layers rich in albite. Similar features have been reported from the terrestrial region and they have been

explained as an effect of localised shearing. Some sections appeared to be extremely rich in calcium minerals; one rock in particular was made up largely of calcite while another was very rich in epidote and zoisite. The minerals found in the greenstones are typical of low grade regional metamorphism and could have been caused by deep burial; they are not notably schistose or laminated, and they are considered to be in the greenschist facies.

The fine-grained greenstones may be either tuffs or lavas, but in certain cases it is possible to decide that they were originally lavas. These may show vesicles, or phenocrysts, or just a vague alignment of the iron oxide. Judging from the relative abundance of calcium rich minerals in some of these lavas, it is considered that they were originally spilitic. The occurrence of chert at one locality shows that it is the sort of environment in which spilities may well occur.

Since the Sparker and Echometer results could not help in differentiating between the areas of greenstone and the areas of killas, the submarine area could not be separated into killas and greenstone. However, although there is no granite exposed in the bay, it was possible to locate areas of near-surface granite by the attendant metamorphic aureole. These are shown in Fig. 2.61.

FIG. 2.61 GRANITE AUREOLES IN MOUNTS BAY



The largest area of metamorphism occurs south-south-east of the Godolphin granite. The coastal exposures of this mass show a fairly gently sloping contact on the western margin of Prah sands, and a sharp, steeply dipping contact on the south between Trewavas Head and Porthleven. The moderate width of the metamorphic aureole at Prah sands and to the south of it is consistent with the gentle dip of the granite margin, but though the contact between Trewavas Head and Porthleven is steep, the aureole extends one and a half miles south of the coastline. Underwater sampling very close to the coast confirmed that the granite margin is nearly at the present coastline. Furthermore, the Sparker records showed that there is a depression immediately to the south-south-east of the granite, which is infilled with unconsolidated sediments. South of this depression the bedrock exhibits a fairly high grade of metamorphism showing that the granite is again close to the surface. Thus, the granite plunges steeply down at the coast, forming a syncline, rises up in an anticline and then presumably dips down to great depth further out to sea.

In the western part of the bay isolated patches push up through the unconsolidated sediments and in some cases there is evidence of thermal metamorphism in the

rocks of these protuberances. They cannot be related to larger granite masses and in this respect are similar to the granite body on St. Michael's Mount. Possibly, they are the tips of very narrow cupolas.

c. Magnetic Survey.

Although the land area was magnetically quiet, anomalies had been detected offshore by some preliminary traverses in 1963. Consequently, a magnetic survey of Mount's Bay was carried out the following year. A proton precession magnetometer was again used, but the bottle was encased in foam rubber and given a rough hydrodynamic shape. It was towed about 60 feet behind the survey boat by means of a cable specially designed to withstand the strain. The area was covered by running traverses parallel to the lines of the Decca grid. The north-south lines were 0.5 miles apart and there were three east-west tie lines 1.0 mile apart. The total length of traverses was 140 miles.

The magnetometer is incapable of continuous readings and discrete measurements were made at intervals of 15 seconds. With such a repetition rate and a boat speed of seven knots there were sufficient readings to define adequately any magnetic anomalies. An effort had been

made to fit a recorder to the instrument, but the attempt was unsuccessful and the readings were recorded manually. By changing the observer at intervals of about 40 minutes, mental fatigue was held in check and the accuracy of the readings enhanced. The absolute total field was given to an accuracy of one gamma by the equation

$$F \text{ (in gammas)} = \frac{24051}{\text{instrument reading}}$$

The traverse lines were plotted by means of Decca Navigator, and time marks put in along the traverses every minute to allow the magnetic values to be correlated with the boat position. The mean value around each time mark was plotted in order to smooth out minor fluctuations in the observations and also for greater ease in plotting the results.

The diurnal correction was obtained from the magnetic observatory at Hartland Point. There are two objections to this. Firstly, Hartland Point is 75 miles away from Mount's Bay and secondly the variation at sea is not the same as on land (Hill and Mason). Ideally a continuously recording magnetometer should have been moored in the bay to give the diurnal correction, but the available resources did not allow this.

After correcting the readings for the diurnal variation, certain discrepancies were apparent at the intersections of the traverses. Due allowances had to be made for the inaccuracies of the Decca position lines, but it was still found that the traverses from south to north were about 15 gammas greater than on those run east to west or vice versa. The north to south lines showed reasonable agreement with the east to west and west to east lines. In order to avoid a herring-bone pattern on the magnetic map 15 gammas was subtracted from the values on the south to north lines. According to Bullard and Mason the greatest heading error for these latitudes should be in the opposite direction. The theory may be reconciled with this awkward fact by assuming that the magnetisation of the boat used in Mount's Bay was opposite in direction to that used by Bullard and Mason.

Interpretation

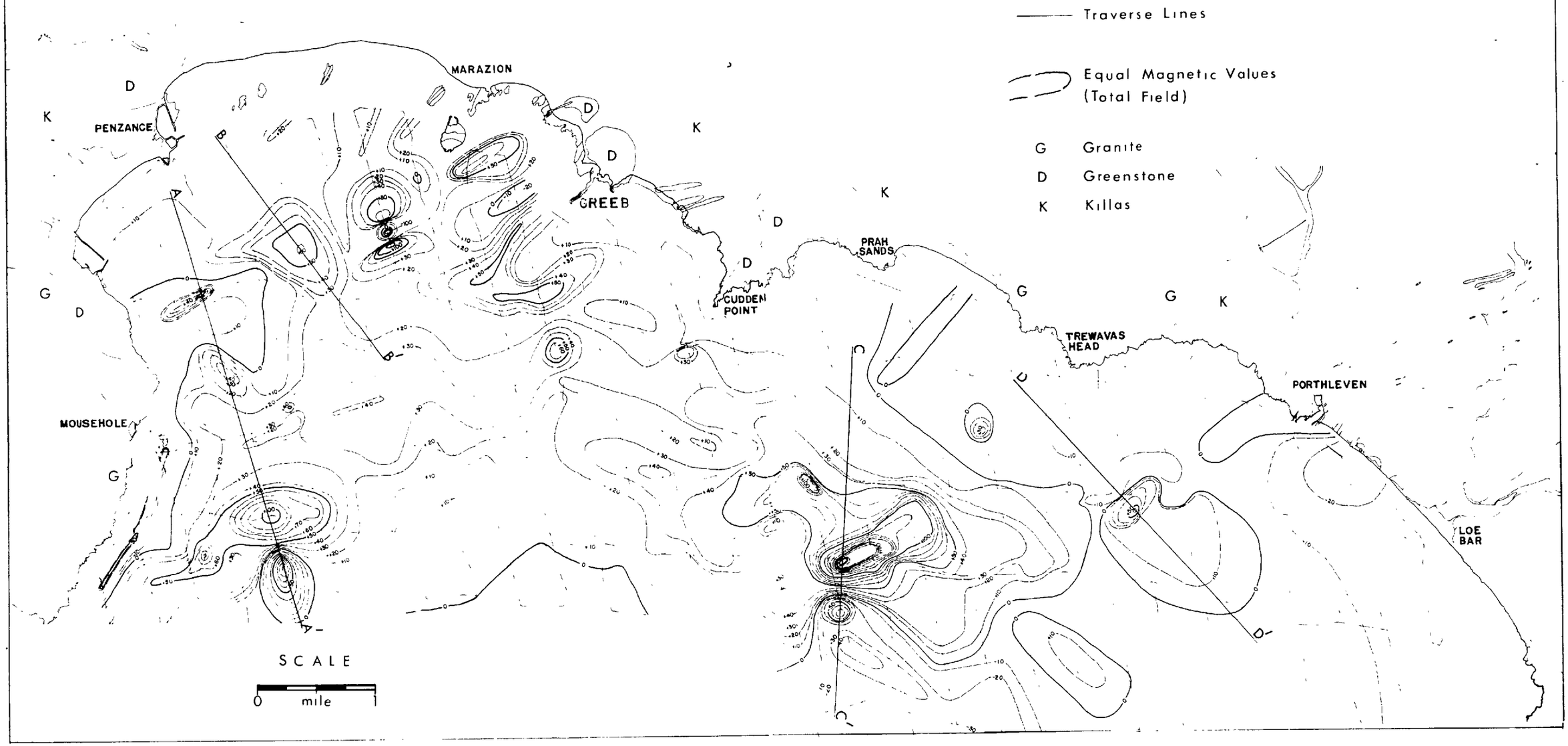
Values of the total magnetic field were plotted and contoured at intervals of ten gammas and the original map on six inches to one mile was reduced to one inch to one mile. Perusal of the aeromagnetic map of the region showed that the contours are very widely spaced and that the 160 gammas contour threads its way through the Mount's Bay

area in a meandering fashion (Map B). From this it is inferred that the regional gradient is small and that its value is reliably indicated by the 160 gammas contour. On the detailed magnetic map of Mount's Bay a contour showing similar characteristics was found, and its value was subtracted from all the readings to give the residual map shown in Fig. 2.7.

Several anomalies are present on the map and the first task was to distinguish if possible those not due to geological factors. The map was compared with Admiralty Chart No. 1267 on which the positions of known wrecks is indicated. There appeared to be no correlation between the positions of the wrecks and the magnetic anomalies.

Next, those anomalies not crossed by more than one traverse line were critically re-examined. Fortunately, the major anomalies on the map are all intersected by more than one traverse, with the exception of the anomaly one mile south-west of St. Michaels's Mount. This consists of a negative flanked by two positives and indicates that the body causing the anomaly must be of only limited vertical extent, while the sharpness of the anomaly shows that it is very close to the plane in which the observations were made. Furthermore, adjacent traverses failed to give any

FIG 27 MAGNETIC MAP OF MOUNT'S BAY



indication of the anomaly, thereby proving that the body is also of limited lateral extent. Thus the cause of the anomaly must be of small lateral and vertical extent and must be close to the surface. The writer considers that these characteristics indicate an unmarked wreck rather than a geological feature. The long narrow anomaly south of Mousehole is also suspect because of its form and its nearness to the shore. Possibly, the readings may have been affected by power lines in the vicinity.

Of the other anomalies the principal ones are :

1. Four miles south-east of Newlyn, having an amplitude of 200 gammas.

2. Three miles south of Prah sands, having an amplitude of 200 gammas.

All the anomalies tend to be equidimensional though it is possible to pick out a longer axis.

A north-south line passing through the Greeb, roughly divides the area into two regions with different trends of contours. West of the line there is a tendency for the contours to strike north-east and east of the line the trend is north-west.

Apart from the most easterly anomaly, the others either show positive polarity only or else show a negative to the south of the positive. In Cornwall the dip

of the geomagnetic field is about 66° and this should give induced anomalies opposite to those actually encountered, so that some unusual feature is probably present. Gulatee and Reford have published a number of curves showing the variation in magnitude and shape of anomalies caused by changes in the attitude of the body and the dip of the geomagnetic vector. These curves show that only a thin horizontal slab could be expected to give profiles similar to those found in Mount's Bay. The geological feature which corresponds to a thin horizontal sheet is a lava flow, but if such a flow were present, the magnetic map would display a vastly different form. The hypothesis of a thin horizontal sheet may therefore be discarded.

A second possible means of creating a reversed magnetic anomaly is by a highly exaggerated topographic difference. Gaucher has reported such an anomaly in Quebec caused by a southerly dip of 40° in the outcrop surface which itself dipped at about 70° to the north. In Mount's Bay the measurements were made on a perfectly flat plane and an examination of echometer records showed no marked topographic effects to account for the reversed anomalies.

The only remaining possibility is that a strong component of natural remanent magnetisation has pulled

the resultant vector into a position at variance with that expected from the latitude. If NRM is present in some of the rocks, a proper evaluation of the anomalies is dependent on some knowledge of the magnetic properties of the rocks collected in the bay.

From the petrological examination of the samples from the sea-bottom, it was established that the rocks found on land continued into the bay. Since there are no magnetic anomalies on the terrestrial area it is likely that the cause of the anomalies in the bay is a rock type which is not exposed. However, there is a slight possibility that an apparent similarity in the petrology of the greenstones might conceal a difference in magnetic properties. Kuenen has stated that the chemical (and physical) decomposition of submarine rocks is less than that of terrestrial rocks. Hence it may be that the magnetic properties of the greenstones in Mount's Bay are preserved, whereas those on the terrestrial area have had theirs destroyed. Accordingly, cores of one inch in diameter were drilled in some of the greenstones and one inch lengths cut off. The cylinders were tested for susceptibility and natural remanent magnetisation.

1. Susceptibility Determinations.

The susceptibilities of the specimens were measured at 0.5 Oersted on an A.C. susceptibility meter designed by Bruckshaw and Robertson. The magnetising field was produced by passing a 450 cps alternating current through a pair of Helmholtz coils, within which a specimen holder carrying two windings is rigidly mounted. These are so connected and wound that changes in a uniform magnetic field passing through the double coil cause zero induction in it. A compensating coil is included to cancel perfectly the impedance between the two coils forming the pair. When a rock specimen is introduced into the holder it acts as an alternating magnet in the magnetising field. The e.m.f. induced in the double coil is measured by means of a phase sensitive synchronous amplifier which gives a deflection proportional to the susceptibility of the specimen. By including a few standard specimens the apparatus may be calibrated. However, each time the apparatus is used it must be recalibrated since it is difficult to regain a particular sensitivity. The instrument was capable of detecting susceptibilities of 3×10^{-5} e.m.u/cc.

2. Remanent Magnetisation.

The samples were also tested for natural remanent magnetisation. An astatic magnetometer set up within three sets of Helmholtz coils was used for the measurements. A serious obstacle to accurate determinations was the zero drift of the instrument. This was caused by movement of neighbouring magnetic materials (gas cylinders, lifts etc.) and by mechanical disturbances, all of which tended to displace the magnet system. The elimination of these factors proved to be impossible, though the effect was minimised by pointing the magnets towards the lift - the greatest source of magnetic disturbance. In the end the most satisfactory arrangement was to take measurements outside of normal college hours and to take repeated readings.

Of the 17 specimens tested only four showed appreciable magnetic susceptibilities, all others being near the limit of sensitivity of the instrument. The values for these four samples ranged from 90×10^{-6} - 100×10^{-6} emu/cc.

The determinations of NRM showed that all of the samples were non-magnetic.

Though the susceptibilities of four of the samples are sufficient to give anomalies with the magnitude observed, there cannot be reversed anomalies without a

component of NRM. This strongly indicates that the rocks exposed in the bay are not responsible for the observed anomalies. The conclusion may be confirmed by calculating the depths to the anomalous bodies.

Method of Calculating Depth to the Anomalous Bodies.

The indirect methods of interpretation enjoy wide popularity because they have the merit of not assuming ideal geometrical shapes for the bodies. But in Mount's Bay there is no way of reducing the number of unknown parameters and the depth, shape, attitude and magnetic properties of the body would all have to be assumed if a computed anomaly is to be fitted to an observed anomaly.

In the direct methods of interpretation, simple geometrical forms are postulated, but all other parameters may be treated as unknown and with the aid of master curves it is possible to obtain a solution for one of the factors, usually the depth. Hence, fewer assumptions are required in the direct method. However, most of the direct methods proceed on further simplifications, the most common being that the magnetic field from the body is produced by induced magnetisation only. Other assumptions are that the body is vertical or that the body is two-dimensional. These simplifications yield erroneous depth estimates when the actual geological conditions depart from those postulated.

Thus, if the depths to the anomalous bodies in Mount's Bay are to have any validity, it would be desirable to employ a method of interpretation in which neither a vertical body nor induced magnetisation only is assumed. Unfortunately this eliminates most of the standard methods.

However, Kunaratnam and Hall have both treated the case of a dyke-like body having an arbitrary direction of magnetisation and geological dip. It was already noted that the anomalies in Mount's Bay tend to be equidimensional and cannot be considered as originating from dyke-like bodies, but Kunaratnam has given a method or reducing anomalies from three-dimensional structures to those of two-dimensions.

The methods developed by Hall and Kunaratnam allow the depth of the body to be determined and also give an angle i dependent on the dip ϕ of the resultant polarisation vector in the vertical plane perpendicular to the dyke, the dip I of the geomagnetic field in the same plane and the dip θ of the dyke. I can always be estimated so that if either ϕ or θ is known the other can be determined.

In both methods the interpretation is based on special points of the field curve, but the authors have chosen different points. In Kunaratnam's solution, use is made of the positions of the maximum, the minimum and

three quarters, half and quarter of the maximum or minimum values. This has the disadvantage of being sensitive to errors in the position of the zero line, which is always difficult to find accurately. Hall avoids this difficulty by working with the maximum, minimum and the inflexion points, but in practice is is almost impossible to find the inflexion points with any precision. Since Kunaratnam's method treats the problem more clearly and comprehensively, this was the one adopted.

An attempt was made to reduce the anomalies to the equivalent two-dimensional anomalies, but the results were unsatisfactory. In B, C, D the asymmetrical nature of the anomalies gave distorted values to the result. In A, the narowness of the negative portion at right angles to the axis of the anomaly, caused a relative increase of the positive part in the summation process. The interpretations were therefore carried out on profiles drawn perpendicular to the strike of the contours.

The results obtained for the depth estimates are

Anomaly	Approx. depth in ft
A	350
B	1450
C	450
D	200

When allowance is made for the water depth, it is found that even though the depths are shallow, the anomalous bodies are not exposed in the bay. Some consideration must be therefore given to possible causes of the anomalies. The petrological examination of the rocks collected had shown that the strata present are Devonian shales intruded by greenstones and granites. It is therefore safe to assume that the cause of the anomalies is not younger than the Carboniferous. This eliminates the products of the Permian lavas as well as the New Red Sandstone rocks. The remaining possibilities are :

1. The pre-Devonian basement has been brought up close to the present day surface by folding or faulting. Hill has explained the magnetic anomalies in the south-west approaches as being caused by folding of this basement.

2. Spilitic lavas, or some of the related intrusives. On the aeromagnetic map there does appear to be a correlation between the occurrence of spilites and magnetic anomalies, but the intrusives seem to be non-magnetic.

3. Basic or ultrabasic intrusions emplaced during phase 1b of the magmatic cycle. The Lizard complex of basic and ultrabasic rocks is accompanied by a marked aeromagnetic anomaly.

The late Carboniferous granites are not eliminated merely because of their age, since some may have failed to reach the surface, but the Cornish granites are known to be non-magnetic.

In order to decide which of the three possibilities is the source of the anomalies, some knowledge of the magnetic properties of these rocks is required. Blundell has investigated the natural remanent magnetisation of the spilites and found that they have a very weak component of natural remanent magnetisation oriented in the opposite direction to the present geomagnetic field. Also, their susceptibilities were very low. These properties would indicate that the spilites are unlikely sources of the observed anomalies, but this renders their correlation with some of the aeromagnetic anomalies somewhat enigmatic.

For an investigation of the magnetic properties of the basement or of the basic-ultrabasic intrusions the only sampling source would be the Lizard peninsula which is conveniently near to Mount's Bay. Here are exposed not only the famous Lizard igneous complex but also a number of metamorphic schists which are alleged to be part of the pre-Devonian basement brought up to the surface by a thrust. It was therefore decided to collect samples from the Lizard for determination of susceptibility and NRM. An added

incentive to an investigation of the Lizard rocks is the fact that the nearest anomalies to Mount's Bay occur over the Lizard. Bullerwell has even remarked on the similarity between the Lizard anomalies and those of Mount's Bay.

A large variety of rock types are exposed on the Lizard but the most significant from a magnetic point of view were the metamorphic schists, the serpentine, gabbro, epidiorite and troctolite. The rocks of the crush zone and the metasediments north of it were ignored. This is justified by the absence of magnetic anomalies over that portion of the peninsula.

The specimens were collected by drilling cores of one inch in diameter in the rock outcrops with a portable drill. The accurate orientation of the cores was of fundamental importance and the procedure is given below.

3. Orientation of Samples.

The orientation was done by the determination of two axes mutually at right angles marked on the core. A line along the length of the core was chosen as the z-axis and a horizontal line perpendicular to it was designated as the y-axis. The dip of z and the true bearing of y permit the core to be re-oriented when it is removed from the outcrop. A simple contrivance is used in conjunction with a Brunton compass to measure the dip of the z and the bearing of y.

This consists of a brass cylinder attached to a platform carrying the compass. The cylinder is fitted over the core and placed so that the compass is horizontal and the north-south marking on the dial is perpendicular to the vertical plane through the core. This gives the magnetic bearing of y. Another bearing is taken on to a distant feature marked on the map. The true bearing of this sighting can be found by joining on the map the sampling point to the position of the feature. By subtracting the magnetic bearing from the true bearing the declination at the sampling point is found and hence the true bearing of y may be determined. Through a longitudinal slot in the cylinder a mark is made on the core with a brass wire. The mark represents the z-axis and its dip is obtained by measuring the dip of the brass cylinder.

In certain cases it is impossible to see distant objects. Under such conditions sightings were made on the sun. By noting the time of observation, the sun's azimuth could be computed from the formula

$$\cot A = (\sin \phi \cos h - \cos \phi \tan \delta)/\sin h,$$

where ϕ is the latitude of the observation point, δ the sun's declination and h the hour angle of the sun. The formula for obtaining h is

$$h = E + \lambda + T$$

where E is the difference between the Greenwich hour angle of the sun and Universal Time, λ the longitude of the observation point and T the GMT.

4. Results of Palaeomagnetic Determinations.

The direction and intensity of natural remanent magnetisation of the oriented cores was determined with the astatic magnetometer. These measurements gave the direction with respect to the two axes marked on the samples. The results were plotted on a Schmidt equal area net on the assumption that the z-axis of the cores was horizontal and that the y-axis was east-west. In order to get the true orientation of the NRM vector in space, the z-axis was rotated through the dip angle observed in the field and the y-axis was given its true bearing.

The mean direction for each rock group was obtained by applying Fisher's methods. The dip (IR) and declination (DR) are given by the relations

$$\sin IR = z/R$$

$$\tan DR = y/x$$

where $x = \sum_{1}^{n} \cos I \cos D$ $\qquad R = (x^2 + y^2 + z^2)^{\frac{1}{2}}$

$y = \sum_{1}^{n} \cos I \sin D$ $\qquad$ I = dip of the nth vector

$z = \sum_{1}^{n} \sin I$ $\qquad$ D = declination of the nth vector

The scatter of the results is given by

$$K = \frac{N-1}{N-R}$$

where N is the number of points. The circle of confidence with a 95% accuracy is given by

$$\alpha = 140^{\circ}/\sqrt{K}$$

The mean intensity was found by projecting the individual vectors onto the mean direction.

Table 1 shows the results of the susceptibility determinations as well as the results of the NRM determinations. The rocks are seen to fall into two distinct groups. The first includes the gneiss, gabbro, epidiorite, mica and hornblende schists; they are characterised by an absence of NRM and low susceptibility. One sample among the mica schists had a relatively high susceptibility, but from just one result it is not known whether this is a characteristic feature of certain horizons in the mica schist. The other group consists of the serpentines and the troctolite; these have high susceptibilities and appreciable NRM. There appears to be a difference in susceptibility between the various serpentines, but their intensity of NRM shows no lithological bias.

The direction of the NRM vectors for the samples of troctolite is shown in Fig. 2.8. Even without demagnetisation of the samples the grouping is remarkably uniform,

	Rock Type	No of Samples	No of Localities	Susceptibility x 10^{-6}	KH	Remanent Magnetisation D	I	Jx10^{-6}	QN	α
Group A	Gneiss	4	2	29.0						
	Gabbro	6	3	30.0						
	Epidiorite	6	3	46.9						
	Hornblende Schist	6	3	49.4						
	Mica Schist	3	1	102.0						
Group B	Tremolite	8	4	1474.7	694.80	198	-30	248.29	0.36	52^{o}
	Dunite	3	2	160.6	75.67	190.5	-32.2	375.76	4.97	
	Bastite	6	3	756.4	356.38	211	-18	382.11	1.07	30^{o}
	All Serpentines	17	9	831.6	391.81	203.1	-11.3	319.98	0.82	56^{o}
	Troctolite	6	1	971.55	457.75	197.1	-23.1	1163.24	2.54	14^{o}
	Qn > 1									
	Tremolite	3	2	882.13	415.62	195.8	-20.7	485.98	1.17	
	Bastite	3	2	523.43	246.61	208.2	-25.9	365.35	1.48	
	All Serpentines	9	6	522.06	245.97	197.4	-27.2	403.79	1.64	22^{o}

TABLE 1

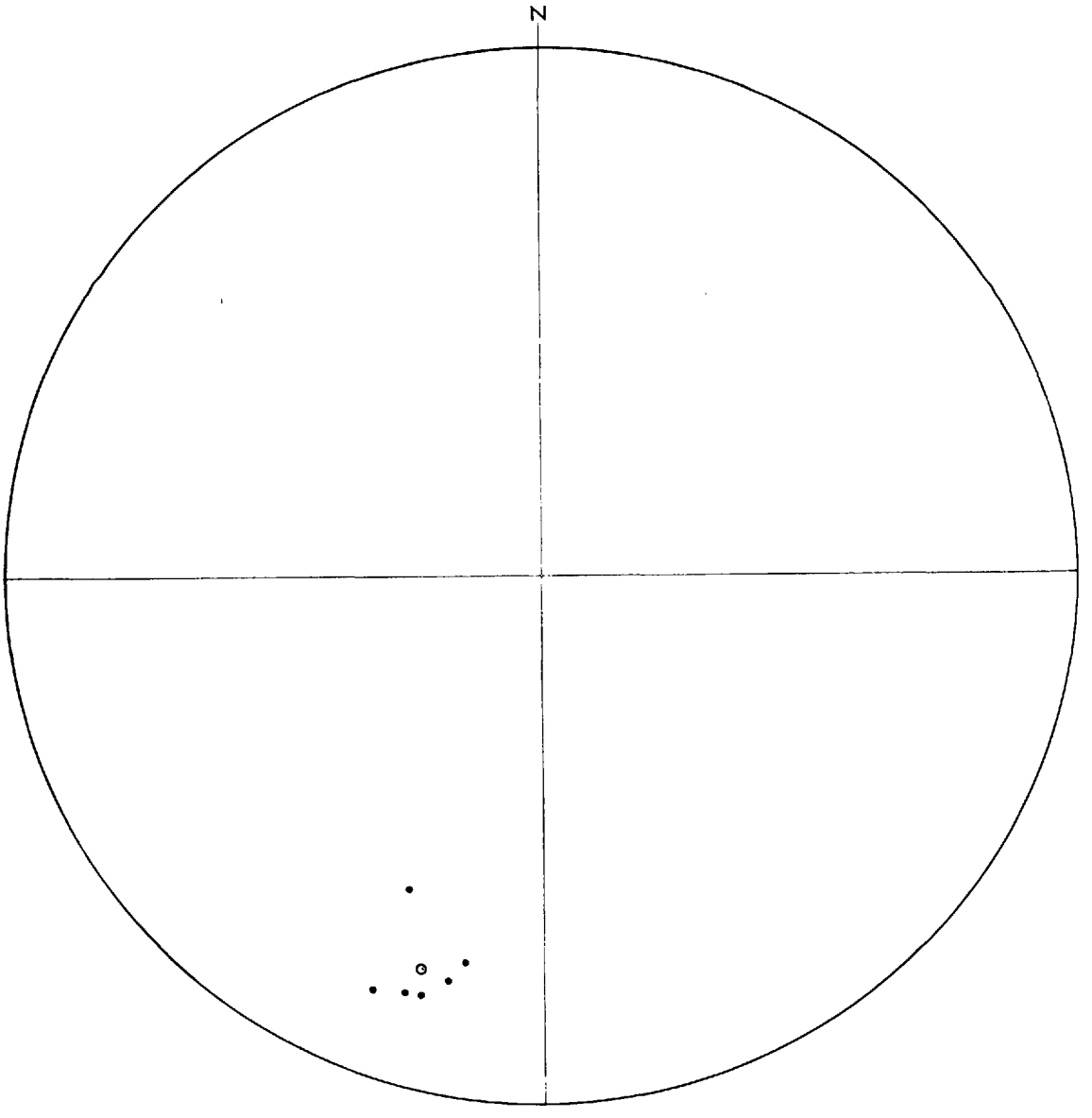


FIG.2.8 TROCTOLITE

• UP

o MEAN

but all specimens were obtained within a quarter of a mile of each other at Coverack. The direction of magnetisation is directed upward in the south-west quadrant and is approximately in opposition to the present earth's field. This indicates a very stable natural remanent magnetisation and the conclusion is confirmed by the high Qn ratio.

The direction of NRM in the serpentines is shown in Fig. 2.9. They are concentrated in the south-west quadrant and are mostly directed upward. Two of the samples dipping at about $+70^{\circ}$ in the north-east quadrant were taken on the beach at Kennack sands, and it is quite possible that the outcrop may have been a portion of broken-off cliff. This still leaves another sample in that quadrant dipping at about $+70^{\circ}$; there is no possibility of movement of the outcrop in this case, and a lightning strike is discounted because the intensity appears to be normal. These three samples, together with the other downward dipping direction, may be taken as an indication of a certain amount of inhomogeneity in the serpentine. If only those samples with a Qn ratio greater than one are plotted, the scatter is much reduced, as shown in Fig. 2.10. The serpentine possesses less stable remanent magnetisation than the troctolite, but the mean

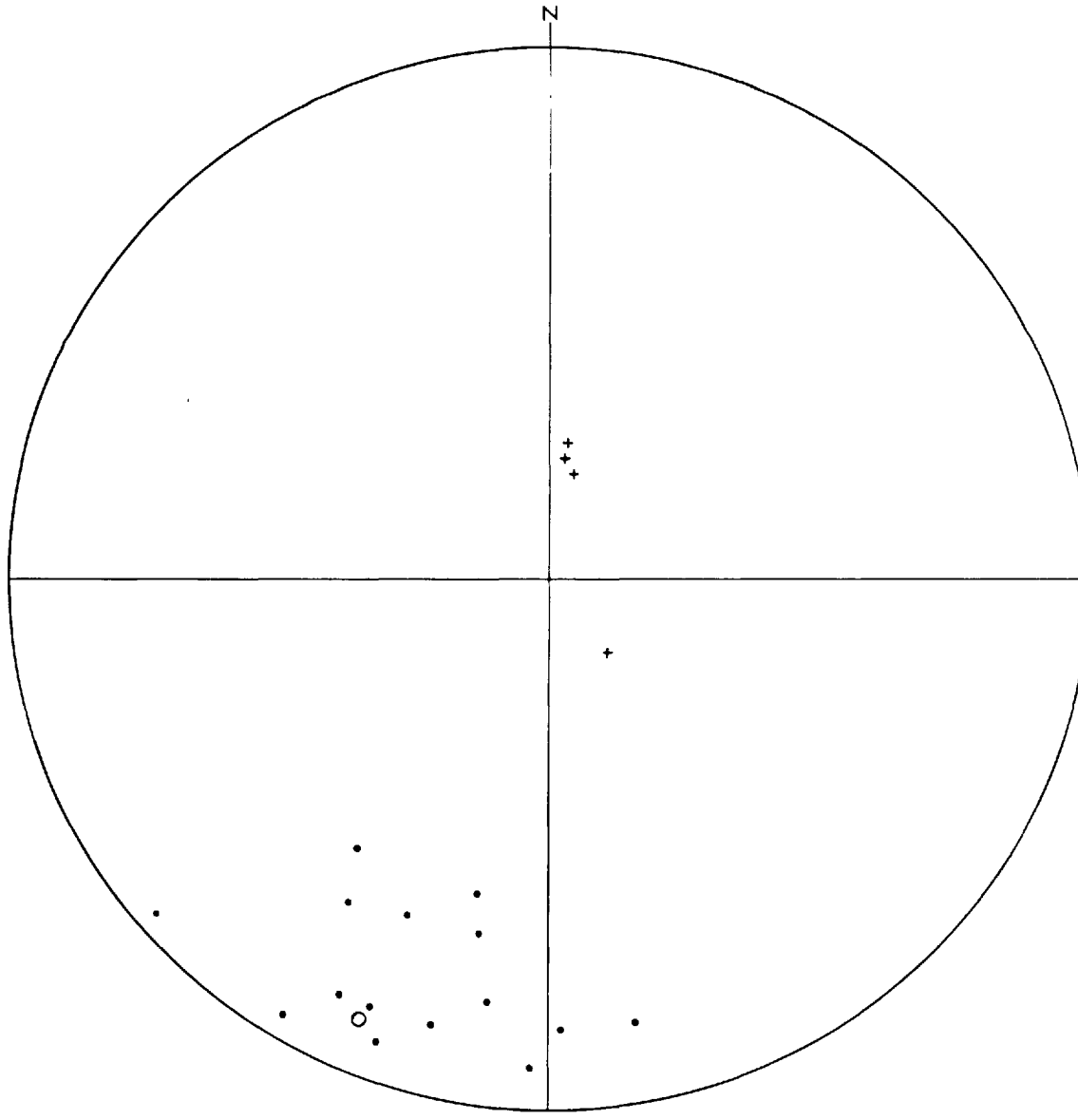


FIG.2.9 SERPENTINES

+ DOWN

• UP

O MEAN

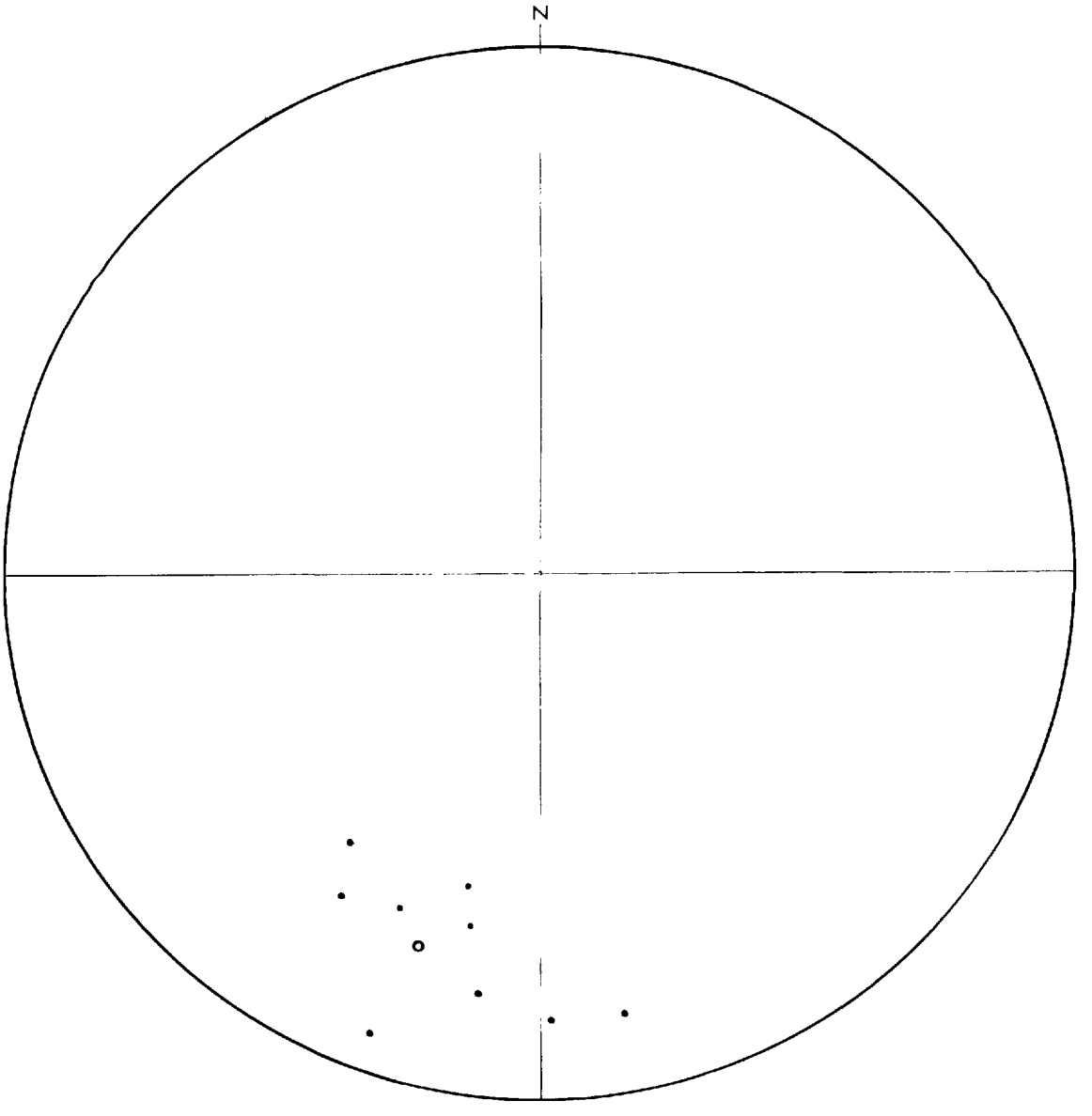


FIG.2.10 SERPENTINES

$Q_n > 1$

• UP

o MEAN

direction of magnetisation is almost coincident with that of the latter.

The ages of some Lizard rocks were determined by Dodson, and Miller and Green, all using the potassium/argon method and their results concur in indicating an approximate age of 370 my, corresponding to Middle or Upper Devonian. There are two groupings of Devonian pole positions; one of them is north of the present position of Australia and the other is in the north Pacific. The virtual geomagnetic pole position for the mean directions of the troctolite and serpentine gave a position 24°S, 157°E. This is about 400 miles north-east of Brisbane, and therefore falls within the first grouping of Devonian poles described by Irving.

The stability of natural remanent magnetisation in the serpentine raises the question of its origin. These rocks were originally peridotites but were converted to serpentine by a process of chemical alteration. Thus, if the palaeomagnetism is due to thermal remanent magnetisation, it must have survived somehow the chemical changes involved in serpentinisation. It may be significant that the troctolites which have a high proportion of olivine possess fairly strong remanent magnetisation as well. Even if the dominant contribution is made by chemical remanent

magnetisation, the direction indicates alteration during the Devonian.

Some important conclusions may be drawn from the palaeomagnetic results, but owing to the relatively small number of specimens they should be accepted with some caution. Nevertheless, the indication is that the hornblende and mica schists are non-magnetic. If these represent the Pre-Cambrian basement, then the anomalies in Mount's Bay cannot be caused by a rise in this basement unless it is assumed that the schists on the Lizard have lost their magnetic properties through unknown means.

Among the rocks of the Lizard igneous complex only the serpentine and troctolite may be expected to give appreciable anomalies. Either rock type is capable of producing the kind of anomaly observed over the Lizard peninsula and in Mount's Bay.

In the previous discussion on the possible sources of the anomalies in Mount's Bay several rock types had been considered, but a process of elimination has now restricted the choice to either the serpentine or troctolite. If it is assumed that the anomalies are caused by rocks with similar magnetic properties to either of these, the dips of the anomalous bodies may be calculated.

The interpretation for the depths to the anomalies gave an angle $i = \phi + I - \theta$. I could be estimated from the geomagnetic latitude, and ϕ could be determined from the susceptibility, and intensity and direction of remanent magnetisation of the troctolite and serpentine. The dip of the body θ could then be obtained.

In anomaly B, no ratio of parameters could be found to give intersections. In this case it was deduced that $i = 90^{\circ}$ because of the suppression of the minimum.

Anomaly	Dip	
	Serpentine	Troctolite
A	141°	154°
B	151°	162°
C	94°	106°
D	14°	26°

Thus, the source of anomaly A dips at a moderate angle to the south-south-east, the source of anomaly B dips at a shallow angle to the south-east, the source of anomaly C dips very sharply to the south-west and the source of anomaly D dips at a shallow angle to the north-west.

TERRESTRIAL SURVEYS

a. Gravity Survey.

The area covered in the survey is shown in Fig. 1.1. In all, 534 observations were made in an area of 200 square kilometres. By siting stations at Ordnance Survey Bench Marks, no levelling was necessary, though this meant that there could be no control over the distribution of observations. During the first visit to the area a World Wide gravimeter was used, and the territory was covered by running seven traverses arranged on a pattern of interconnected triangles.

It is usual practice to begin such a survey by establishing a network of base-stations, to serve as a framework for subsequent loops. However, the writer had no idea concerning the amount of progress likely to be made each day, and the long length of the traverses made traversing by loops impractical. It was therefore impossible to decide beforehand on the location of suitable base-stations.

The first survey which lasted for three weeks was made by taking observations while progressing from one end of a traverse line to the other. Convenient stations along the traverse were re-occupied about once every hour

for the drift correction and additional checks were made wherever possible by returning to stations on previous lines.

The results of the first survey indicated the need for further work in certain areas. This was done during two further visits to the region, in both of which a Worden gravimeter was used. The stations were covered by running loops from a base station at Leedstown and sub-bases were established where the use of loops from Leedstown became inconvenient.

Densities

In their regional survey Bott, Day and Masson-Smith had taken some pains to obtain reliable density values. They carried out laboratory determinations of density on 400 specimens representing all the important rock groups of South West England. In addition they carried out four gravimeter density profiles. With their results available, the writer was content to collect two samples of each rock type in the area. However, great care had been taken to select fresh specimens, and perhaps for this reason, the writer's values were slightly greater than those published though the relative difference between the granite and killas remained unchanged.

It is well known that the densities of rock samples collected at the surface may not accurately represent the density of the formation in bulk. To counteract this disadvantage, a density profile may be run over an erosional feature, but since the survey was restricted to the use of Bench Marks this could not be done. The following densities obtained by the writer were used in computing the various corrections

Killas	2.76 gm/cc
Land's End granite	2.66 gm/cc
Godolphin granite	2.66 gm/cc
Carnmenellis granite	2.66 gm/cc

Bott, Day and Masson-Smith are of the opinion that the estimates of the densities are likely to be correct to 0.03 gm/cc.

Tidal Correction

Because South West Cornwall is a peninsula, the sea is never far away and the tidal fluctuation gives a variation in the gravity field which is detectable by the instruments used. The correction for this effect was incorporated into the drift correction by taking readings at least once every hour.

Bouguer Correction

The gravimeter was always set up as close as possible to the Bench Marks so that the heights of the stations relative to Newlyn datum could be determined. All readings were reduced to Newlyn datum using the densities given previously.

Terrain Correction

The Formula for the Bouguer correction assumes that each station lies on the surface of an infinite horizontal slab of material. In practice this condition is not realised and a terrain correction must be added to correct for the Bouguer correction.

In the area covered by the survey the topographic changes are fairly gradual. The contours ascend smoothly to a height of 420 feet to form a gently rising plateau. At 420 feet, there is a former sea cliff marking the shores of some ancient islands of granite. The granites attain heights in excess of 800 feet in some parts, but on the whole the areas underlain by granite are undulatory in nature.

The largest terrain corrections would be expected on the peaks of the granite islands, while the smallest would occur on the plateau regions away from the granite peaks. Hammers' charts were constructed on a scale of 1:25,000

and the terrain corrections calculated for certain selected stations. The values ranged from about 0.80 mgal (for the highest points on the granites) to about 0.20 mgal (for the regions of small relief). From previous work, anomalies of 5-6 mgal were anticipated and the terrain correction frequently amounted to more than 10% of this value.

However, the correction is extremely laborious to compute and it was necessary to weigh the effort involved against the possible benefits to be expected. It was then realised that some 400 hours of toil would be required for the calculation and the primary interest of the survey was in the qualitative interpretation of the results. Accordingly, no terrain correction was applied, but since the geology is related to the topography, there was no danger of introducing spurious anomalies into the gravity map.

Latitude Correction

The survey was made between latitudes $50^{\circ}06'45"$ and $50^{\circ}13'12"$. Between these latitudes the variation in gravity is uniform and equal to 0.799 mgal/km. From the Bench Mark list the Northings difference in kilometres between the observation points was obtained and the correction made.

Bouguer Anomaly at Leedstown Base

The nearest station whose gravity value is known relative to Cambridge occurs at Falmouth docks, and during the course of the survey a gravimeter reading was taken at this station. The observed value of the Falmouth Base with respect to Cambridge is given as 981.10084 gals, from which the observed value of the Leedstown base with respect to Cambridge was calculated as 981.08309 gals. Using the International Gravity Formula

$$= 978.049\ (1 + 0.0052884\ \sin^2\phi\ - 0.000059\ \sin^2 2\phi)$$

the value of gravity at the Leedstown base should be 981.092884 gals. Thus, the Bouguer anomaly at Leedstown base is -9.79 mgal. This station is actually plotted on the gravity map as -1.0 mgal.

Interpretation

The relative gravity values were plotted on a scale of 1:25,000 and a reduction on a scale of one inch to one mile is shown in Fig. 2.11. The contour interval is one milligal.

That there is a definite correlation between the gravity field and the distribution of granite and greenstone is at once apparent, the granite outcrops all giving marked gravity lows, a relationship already established in the regional survey by Bott et al. They provide another

St. Ives Bay

Gwithian

Camborne

Hayle

Gwinear

St. Erth

Leedstown

Ludgvan

Marazion

Millpool

Nancegollan

Mounts Bay

Cudden Point

A

A'

B

B'

C

C'

D

D'

E

E'

F

F'

+5 +4 +3 +2 +1 0 -1 -2 -3 -4 -5

N

FIG 2.11

GRAVITY MAP OF S.W. CORNWALL

SCALE

1 0 1 mile

Granite

Greenstone

Killas

Great Fluccan Fault

Gravity Station

Base Station

Values in Milligals

example of post-tectonic granites giving rise to negative gravity anomalies (Bott, 1957). The density measurements showed that the granites are about 0.1 gm/cc lower than the killas, and this contrast is without doubt the cause of the anomalies. The gravity map may therefore be interpreted in terms of the presence or absence of granite, the presence of granite being indicated by low gravity values, and its absence by high values. In a crude way the gravity contours are an approximation of the actual granite topography.

It will be noticed that the trend of the contours does not follow exactly the margins of the exposed granites. From Camborne they run south-west to pass through Gwinear instead of taking the south-south-west direction to the edge of the Godolphin granite. This is an indication that the Godolphin and Carnmenellis granites are parts of one large unit which is broken in the region of the Great Fluccan fault by a depression. The north-west edge of the block passes from Camborne to St. Erth and lies some three kilometres to the north of the exposed margin of the Godolphin granite.

The Godolphin-Carnmenellis mass is separated from the Land's End granite by a zone of high values corresponding to a trough of killas, running from Gwithian to

Marazion. Between Hayle and St. Erth, the interruption of the trough indicates a subterranean connection between the two blocks.

Around Millpool, Nancegollan and Ludgvan, the contours display forms not matched by the exposed granite. At these localities the contours project like spurs from the areas of low gravity values, but they are not accompanied by similar granite features.

By virtue of their limited extent, the greenstones have exercised little active control over the trend of the contours. However, it is instructive to note their relation with respect to the run of the contours. The main belt of greenstones pass between Gwinear and Camborne following the trend of the contours, and between Marazion and Cudden point they are again parallel to the trend even though the contours have swung round through more than 90^{o}. Such a strict conformity between the greenstone and the contours once more suggests that the position of the greenstones is dependent on the underlying structure.

A more precise representation of the granite surface requires a quantitative interpretation, but since the terrain correction had been neglected, this would be in effect a semi-quantitative interpretation. For this

purpose it is necessary to estimate the regional field so that the residual anomalies may be isolated. The two types of method for doing this both have their pros and cons, and the choice must be decided by the local conditions.

The graphical method can be extremely effective since it may be adjusted to deal with varying conditions in the area. However, such a reliance on personal judgement could hardly be expected to go unchallenged in a scientific age, and several mathematical methods have been developed to confer some objectivity to the preceedings. But recently, the objectivity of the mathematical methods themselves has been impugned (Rao and Radhakrishamurthy, and Roy) and in any case their blind inflexibility has been a liability in some conditions.

In the area surveyed, the effect of the granite is so marked that it obliterates the influence of basement changes. The broader features on the map are therefore dependent not on deep seated or regional variations but on the granite topography instead. This granite topography bears an inverse relationship to the thickness of the killas; where there is a granite hill the killas is thin and where there is a valley in the granite surface, the killas is thick. Hence, if the effect of the granite

can be separated from the gravity map the residual field would reflect the thickness of the killas. It is clear that if a grid method is used to calculate the background, there will be a substantial contribution from the granites because of their widespread influence. On the other hand, the very pronounced features associated with the granites on the gravity map lend themselves readily to the graphical approach for the obvious trends may be easily picked out by eye. Thus the graphical method emerges as the most suitable choice.

The interpretation was carried out on a number of selected profiles. These were drawn at right angles to the contours and placed close to actual observation points wherever possible. The background field was estimated by drawing a straight line tangentially to the minima occurring over the exposed granites. The residual anomalies were then obtained by subtracting the values given by this base line from the observed values. Two assumptions had to be made in order to interpret the profiles. Firstly, the granite surface was assumed to be continuous below the killas. No proof exists that this is so, but it would be unreasonable to assume otherwise. Secondly, the anomalies were treated as arising from two-dimensional bodies, which Fig. 2.11 shows to be a reasonable approximation.

The problem was then to find a suitable cross-section of killas which would give a computed anomaly equal to the observed anomaly. Normally, there are an infinite number of solutions to an observed anomaly, but in this case there is sufficient geological information available to give a unique solution. Since it outcrops on the surface the top of the body is known, and the depths to the granite/killas interface along the profile gives the only other boundary of the body. The required depths can only be found by a process of trial and error and is therefore extremely tedious. However, Bott has devised a method of solving the problem with the aid of a high speed computer. Though his program was intended for sedimentary basins, the case of killas overlying granite is obviously analagous.

The top surface of the killas is known from the published geological maps of the area and the granite/killas boundary is found by computing the vertical extent of the killas at selected points along the profile. Each selected point is considered as the mid-point of a two-dimensional rectangular block which is given some arbitrary width, and its depth calculated. Thus, proceeding across the section, the depth of each rectangular block in turn gives an approximation of the granite/killas interface, and the approximation can be made to any required precision by

increasing the number of blocks, thereby decreasing their widths. The estimate for the depth of each block is made by assuming that the anomaly over its mid-point is due to an infinite slab of the killas at the surface. The thickness of this slab is used as the depth of the block and since its width is known, the anomaly due to the block is calculated. The total anomaly due to the combined effects of all the blocks is then computed and compared with the observed anomaly over the mid-point of each block. This difference in the anomalies is used to alter the depth of the underlying block, by assuming that the residual anomaly is caused by an infinite slab of killas at the surface. The thickness of this slab is added to the depth of the block and its anomaly recalculated. The process is repeated at the mid-points of all the blocks so that the depth of each one is altered in turn. The total anomaly is once again calculated and compared with the observed anomaly over each mid-point and the cycle repeated until the observed and computed anomalies agree to some specified limit.

Bott's method was applied to the selected profiles and found to give a computed anomaly nearly the same as the actual anomaly after ten repetitions. The program is shown in the Appendix. There was, however, a tendency to

produce unacceptable thicknesses for some of the end blocks. It was decided to smooth out the rectangular outlines of the masses and to fit the resulting curves to the observed anomalies by means of a two-dimensional graticule. This was constructed according to Jung's formula

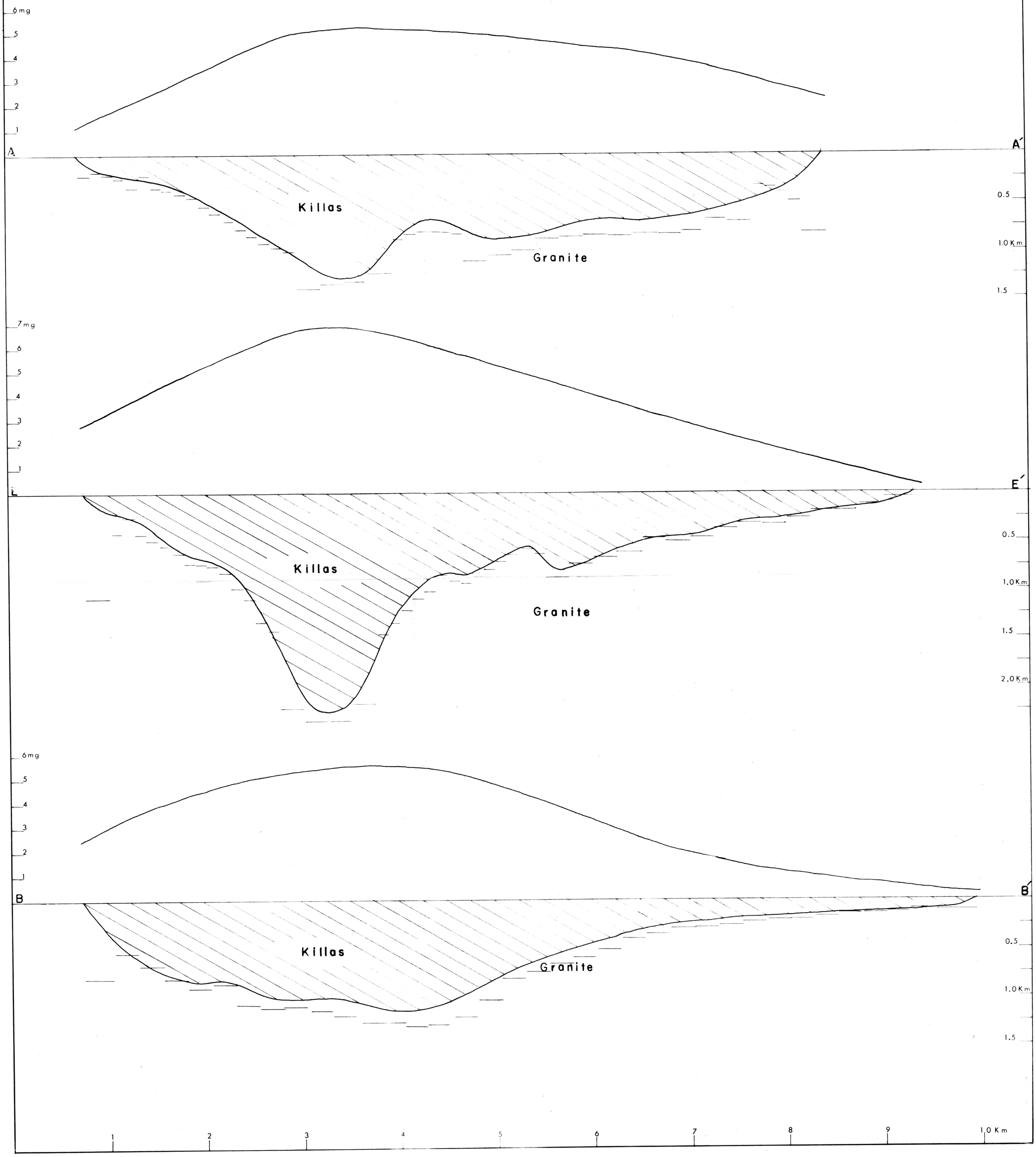
$$\Delta g = 2\,G\,\delta\,(r_{m+1} - r_m)(\cos\phi_{n+1} - \cos\phi_n)$$

Three density differences were tried on the first profile. The smallest of these was 0.1 gm/cc and it gave very thin blocks near the ends of the profile with very thick blocks near the maximum on the curve. From the known extent of the metamorphic aureole near to the granite margin it was deduced that such a profile was unlikely. The curve which seemed to give the best agreement with the known facts was obtained with a density contrast of 0.15 gm/cc. This was the value used in succeeding sections.

The interpretations obtained from sections AA', EE' and BB' are shown in Fig. 2.12. For the most part, the depth to the granite surface is well within one kilometre of ground level, but there is a deep drop along section EE', which becomes less pronounced on both AA' and BB'. This would indicate that the trough-like feature between St. Erth and Marazion (Fig. 2.11) is in reality more nearly basin-shaped. The slopes of the granite surface are mostly consistent with the width of the observed

FIG.2.12

INTERPRETATION OF THE GRAVITY PROFILES



aureoles around the exposed granites, but in section BB' the granite is very close to the surface at the Godolphin end. This should give a much wider aureole than the one actually found. However, a comparison with sections EE' and AA' shows that it is only a relatively narrow spur of granite which would probably not have a pronounced metamorphic effect.

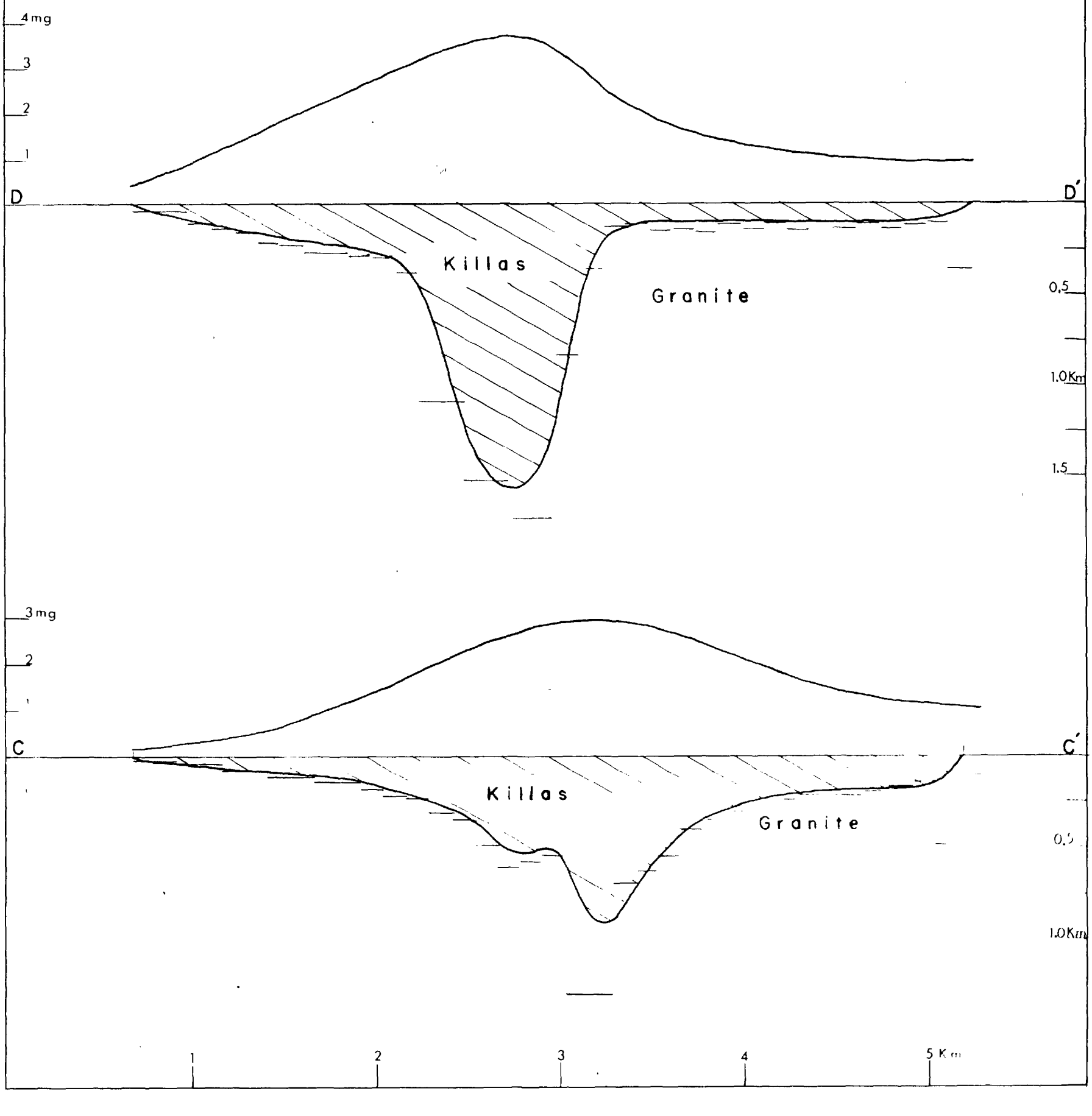
The interpretations obtained from sections CC' and DD' are shown in Fig. 2.13. Again the granite is within one kilometre of the surface except for the central part of DD' where the maximum depth on either profile is found. Thus, the depression lying between the Godolphin and Carnmenellis granites is deepest towards the northern end, showing that it is in the form of a basin rather than of a trough.

Second Vertical Derivative Maps.

Although it was shown previously that a grid method would not be a suitable means of removing the regional field, the second vertical derivative may be employed to advantage in the interpretation of the gravity data. The secondvertical derivative discriminates between masses at equal depths. These properties can lead to the detection of smaller variations in the granite surface which are obscured by the effects of the main bosses.

FIG.2.13

INTERPRETATATION OF THE GRAVITY PROFILES



The size of the grid for the computation of the derivative map is critical, since only those anomalies arising from depths comparable in magnitude to the radii of the rings are sharpened while others from sources too deep or too shallow relative to the size of the radii will be subdued. From the interpretation of the profiles, it is seen that the ma n granite surface is usually within one kilometre of the surface. This depth determines the maximum grid spacing. A smaller spacing is desirable, but as the grid size is decreased, errors and irregularities in the original values are magnified because the values become dependent on smaller differences multiplied by large coefficients. An additional factor to be considered is the increased labour resulting from smaller grid spacing. It was finally decided to use two different grid intervals.

The choice of computational method may be made from 30 available equations (according to Fajklewicz) and Elkins' formula was selected mainly because it employs a very convenient configuration of points.

$$\frac{d^2g}{dz^2} = \frac{1}{62\,S^2}\left[44H_0 + 4H(S) - 3H(S\sqrt{2}) - 6H(S\sqrt{5})\right]$$

where S is the grid spacing, H_0 the value at the centre-point, $H(S)$, $H(S\sqrt{2})$ and $H(S\sqrt{5})$ the sum of the values at distances of S, $S\sqrt{2}$ and $S\sqrt{5}$ from the centre-point.

When the gravity map is smooth the effects of the two inner circles tend to cancel approximately and the result is determined very largely by the centre-point and the outer ring. Thus, provided the original gravity map is smooth, the second vertical derivative map calculated with Elkins' formula would be of similar appearance to a residual map calculated by the one-ring system, having the ring equal in radius to the outer circle of Elkins' configuration, but the units will be different.

Fig. 2.11 shows that the gravity map is fairly smooth and it was decided to compute the second vertical derivative values with a formula given by Nettleton for the centre-point and one-ring system

$$\frac{d^2g}{dz^2} = \frac{4}{s^2}\left[G_o - G(s)\right]$$

where G_o is the value at the centre-point and $G(s)$ is the mean of eight values on a circle of radius s. As a check on the reliability of this map another second vertical derivative map was computed using Elkins' formula.

Fig. 2.14 shows the map obtained with the centre-point and one-ring system, with a grid spacing of $\sqrt{5}/2$ km, the values being computed at intervals of 0.5 km. Fig. 2.15 shows the results obtained with Elkins' formula using a grid interval of $\sqrt{5}$ km and computing the values

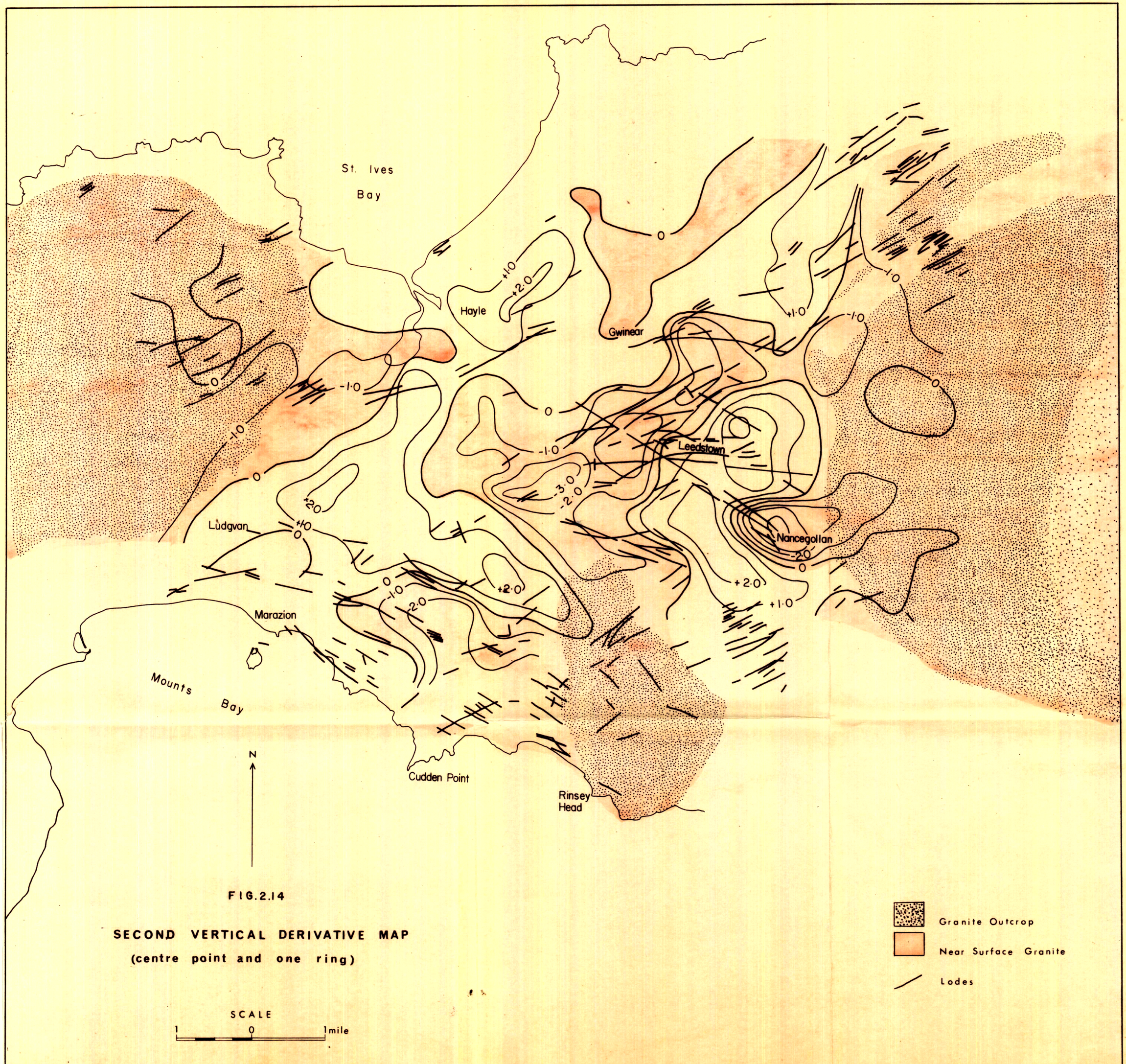


FIG.2.14

SECOND VERTICAL DERIVATIVE MAP

(centre point and one ring)

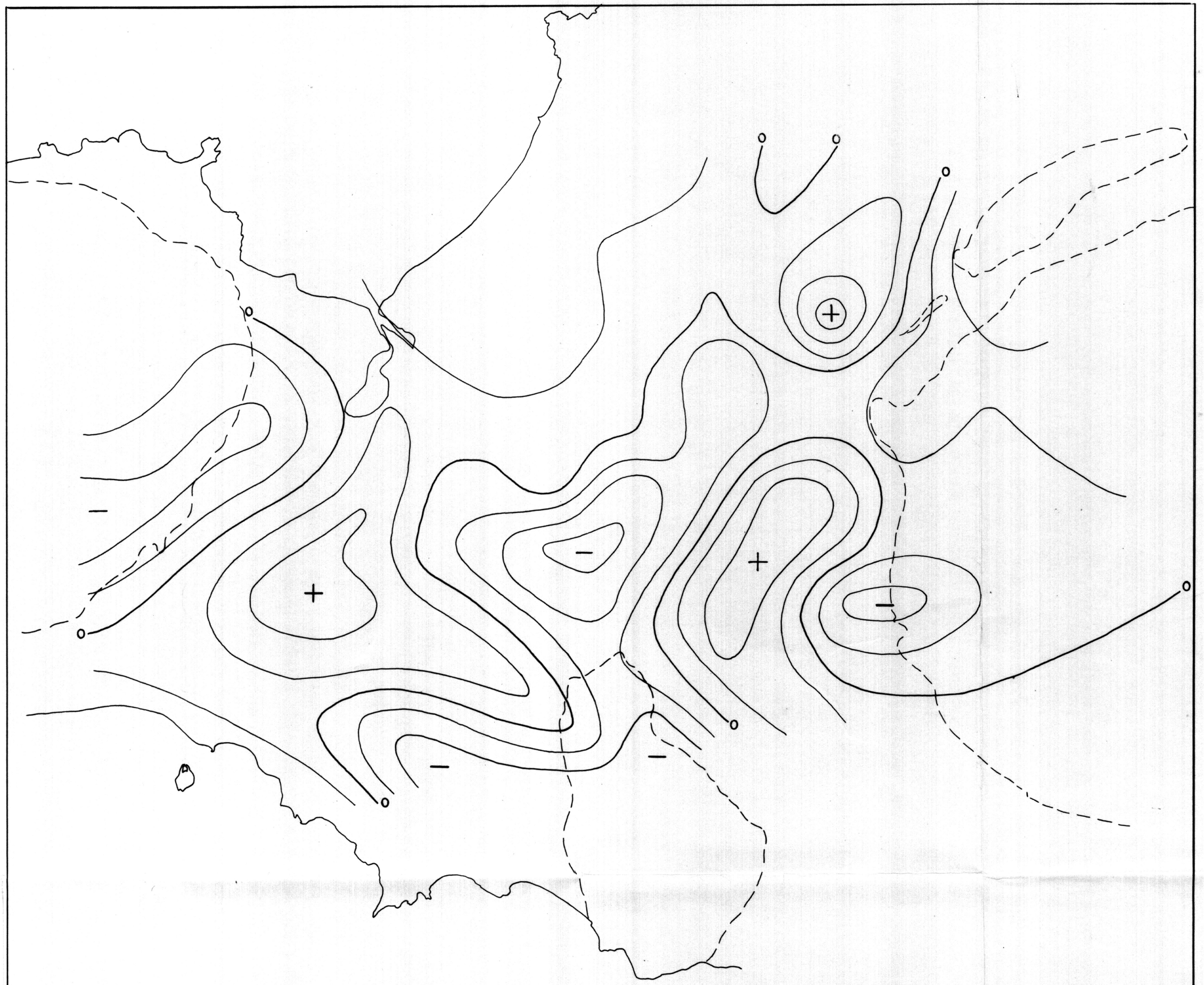


FIG.2.15

SECOND VERTICAL DERIVATIVE MAP
(ELKINS' FORMULA)

every one kilometre. The zero contours of the two maps are approximately in the same position, and this is accepted as an indication of the reliability of the map computed by the centre-point and one-ring method. The latter naturally shows more detail because of the smaller grid size employed, and the interpretation of the second vertical derivative results will be based on this map.

The values given by the second vertical derivative calculation are directly proportional to the curvature of the gravity "surface" (Nettleton) and Roy has generalised this relationship in mathematical form

$$\frac{d^n g}{dz^n} = 2^n g k^n$$

where g is the value of gravity at a particular point on the potential surface and k is the mean curvature at the same point.

Thus, the second vertical derivative map may be regarded as a curvature map of the gravity field, and its appearance is determined by the features present on the original gravity map. The granite cupolas are therefore marked by areas of negative curvature, which give way to areas of positive curvature with increasing distance from the cupolas. Hence, the areas of negative curvature mark the positions of the higher levels of the granite cupolas

where the influence of the granite is greatest. Though the zero line follows the margins of the exposed granites, it is seen that a substantial part extends into areas where killas outcrop on the surface. Thus a large proportion of the granite is hidden and this subterranean granite displays structural trends not indicated in the exposed parts.

The strong north-east grain of the region can be seen in the run of the contours but, clearly, there is some interference with this trend. The strike of the interfering pattern is perhaps best seen between Ludgvan and Rinsey Head, where it is predominantly north-west. In this region the north-east trend is completely eclipsed, but in the Leedstown area the north-east and north-west trends are equally potent. As the Carn Brea area is approached the north-west trend begins to die out and the north-east trend becomes predominant. This progressive change in the relative importance of the two trends is to some extent reflected in the strike of the lodes. In the Carn Brea region they are almost all striking north-east but as Gwinear is approached a north-west tendency appears in some of the lodes; further to the southwest the north-west strike of the lodes begins to supercede the north-east strike, until in the Rinsey-Ludgvan tract, the north-east trend has almost disappeared.

The other important features of the second vertical derivative map are the areas underlain by hidden granite. The ridge forming the Carn Brea mass extends continuously as far as the Leedstown area. Northwest of this ridge is another small rise in the granite surface, striking in a parallel direction. The tongues of granite at Nancegollan and Millpool had already been indicated on the original gravity map. However, the bulge in the original map at Ludgvan has given rise to an isolated anomaly on the derivative map extending partly over Marazion swamp. For this reason it cannot be positively explained by assuming a hidden granite since the lower density of the swamp sediments may have been the cause of the anomaly.

The interpretation of the gravity results given above has been based on the premise that the gravity values reflect the presence or absence of granite. It is reassuring to note that in each locality where a buried granite has been postulated there is geological evidence to support the interpretation. The anomaly south-west of Leedstown is accompanied by a metamorphic aureole at the surface; this is not shown on the one inch to one mile geological map, but it is marked on the 1908 edition of the six inches to one mile maps. In the region of Hayle the gravity contours show a protuberance which is matched

by a widening of the metamorphic aureole in this vicinity. In those instances where spurs or ridges of granite have been assumed, there are no metamorphic effects, but this might be due to the small size of the granite masses involved. However, in all such areas there are mineral lodes present and these strike roughly parallel to the presumed granite. The ridge north-west of the Carn Brea granite has also been reported by MacAlister from data unearthed during mining operations.

b. Magnetic Survey.

When locating the Bench Marks for the gravity survey the magnetic field was measured at these points with a proton precession magnetometer. It was found that the instrument was affected by roads, fences, overhead cables, and especially by walls which tend to be ubiquitous in Cornwall. The readings were therefore unreliable and they are not presented since it is felt that the aeromagnetic map of the area provides a more useful guide to the magnetic features.

PART 3

Geological Interpretation of the Results

THE FORMATION OF THE LODE FISSURES

It is often the case that lode structures are controlled by the shape of the associated granite mass, but is has been usually accepted that the strike of the lodes in Cornwall bears no obvious relationship to the shape of the nearest outcropping granite. The Carn Brea mass has been a noted exception and an unconvincing attempt has been made by Emmons to detect a radial disposition of the lodes around the Land's End granite. No satisfactory explanation for the anomalous behaviour of the Cornish mineral lodes has so far been advanced.

The second vertical derivative map has brought out the existence of a relationship between the lode trends and the structure of the underlying granite surface. It was found that in general the trend of the hidden granite surface is accompanied by a similar trend in the lodes. This correlation has been observed in the area between the

Carnmenellis and Land's End granites, and the question arises as to whether this locality is in some way different from the remainder of the mineralised region. The recognition of granite ridges is considerably hindered by the general homogeneity of the granites and it is likely that many of the original ridges have since been removed by denudation. Consequently, it is extremely difficult to establish by normal geological means that the granite ridges usually accompany the lodes. Nevertheless, Garnett, working on the St. Just area, was able to report "The known sub-surface contours of the granite contact indicate the existence of subsidiary north-west to south-east granite crests. These subsidiary crests, which tend to occur between adjacent mines exerted a structural control upon the regional (Pendeen-Botallack) extent of the mineralisation and the depth of the zone of economic tin mineralisation. They lie parallel to what appears to be a major north-west to south-east crest whose axis trends through the centre of the area."

Other examples of granite ridges are cited by Hosking. One of these occurs at Cligga and the other to the north of Carn Brea-Carn Entral. From this and other evidence Hosking concludes that "The evidence up to this point seems amply to justify the belief that the original

surface of the granite was characterised by a series of ridges which possess a dominant north-east to south-west strike...."

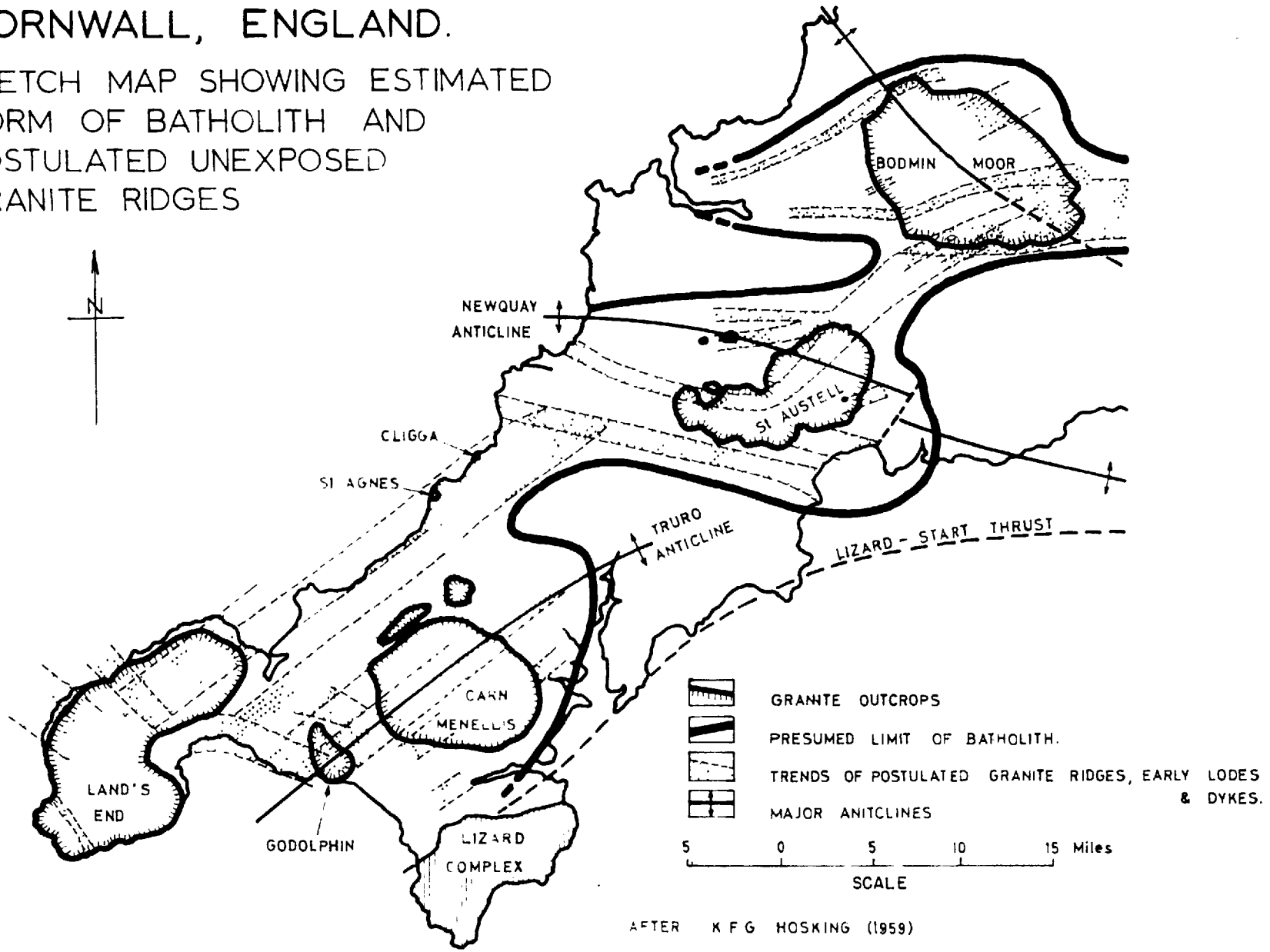
Thus, there is sufficient data to show that granite ridges occur in widely scattered localities. Proceeding on the assumptions that there is a connection between the orientation of the lodes and underlying granite crests, Hosking attempted to predict the form of the Cornish batholith by a process of extrapolation. Wherever there were groups of lodes and no known granites, he deduced that the granite was merely hidden by a cover of killas and that its strike was parallel to that of the lodes. His efforts are shown in Fig. 3.1 which purports to show ridges, tongues etc. in the hidden granite surface.

After Hosking had produced his map, Bott et al carried out a gravity survey in Devon and Cornwall. From their results they were able to establish the general form of the granite batholith and their findings were in good general agreement with those of Hosking's. The second vertical derivative map of the area between the Carnmenellis and Land's End granites is now able to test Hosking's predictions on a more detailed scale. If it is compared with Hosking's map, it is seen that the latter is remarkably correct, even though there is need for some

FIG. 3·1

CORNWALL, ENGLAND.

SKETCH MAP SHOWING ESTIMATED FORM OF BATHOLITH AND POSTULATED UNEXPOSED GRANITE RIDGES



AFTER K F G HOSKING (1959)

minor revision. In every case where a granite body has been inferred from the gravity results, Hosking has indicated a granite, and it is only in detail that his map needs slight modification. Clearly, the soundness of his working hypothesis is strongly vindicated since it has survived its most stringent test - the ability to make valid predictions. Therefore it must be accepted that there does exist a close empirical association between the granite and the lode trends.

However, even if the existence of such a correlation is freely granted, it does not necessarily follow that there is a causal relationship between them. It may be also supposed that the lode fractures were created during the pre-granite deformation and that the association of lode and granite merely represent two separate aspects of one process. The view that the granite did not control the disposition of the lode fractures was expressed by Webb "...the lode fractures are not directly caused by the granite intrusion at the present surface level.." and "..the only control on mineralisation exercised by the out-cropping granites was to cause the ore fluid rising in the localised fractures to deposit its ore mineral in the region of the granite peripheries."

Some other data are required if a correct choice is to be made between the points of view. The crucial point has been recognised by nearly all investigators working in Cornwall, though its significance may not have been appreciated. Hosking has expressed it in the statement "The strike of the hypothermal lodes tends to be coincident with that of one set of major joints in the granite, while the strike of the late mesothermal lodes is parallel to that of the second set and the fluxion (indicated by the alignment of the felspar phenocrysts)." Webb too was aware of "..a similarity of strike shown by the mineral lodes, the joints and the granite porphyry dykes."

However, Garnett realised that stereographic representations of joints nd lodes only bring out the agreement in attitude between typical members of the two features and that such work must be supplemented by underground observations. From his investigations in the workings at Geevor he concluded "From a combination of statistical and underground studies it is apparent that most of the Geevor lodes were formed by movement along, and the enlargement of primary and secondary granite joints. The attitude of the lodes has been substantially controlled by that of the joints and their existence in the present form is dependent to a very large extent upon

the heavily jointed nature of the granite before the onset of wallrock alteration phases. The intensive jointing sufficed to accomodate the increasing stresses during the mineralisation period and the formation of new fissures was not necessitated."

Thus, Garnett's work has provided the conclusive evidence needed to establish the coincidence in attitude and strike between the lodes and granite joints. This definitely ties the lode formation to the granite, rather than to pre-granite deformation. If the lode fissures had been caused during a period of intense deformation, it would be difficult to explain the correspondence with the granite joints, since it is accepted that the latter are the result of cooling processes. It is unreasonable to assume that two different processes resulted in coincident structures when the alternative assumption is that the coincidence is due to a common origin. Hence, the empirical association noticed by Hosking may be accepted as a casual link between the lodes and the granite.

However, there does not appear to have been any attempt at explaining the preference shown for the Q-joints in the mineralising process. There are three main joints in all the granites with subsidiary sets of diagonal joints, and yet it is usually the lodes parallel

to the Q-joints which carry the hypothermal minerals. Now that the lodes have been linked with the granite, the control must be sought in the stresses operating at the time of emplacement of the granite.

In the preceeding paragraphs the parallelism between the lodes and Q-joints has been underlined, but it must not be forgotten that the elvan dykes share this common strike direction. As already stated, the elvans occupy a fracture system different from that of the lodes and joints, but like the latter they form in planes created during the stretching of the granite surface. The direction of stretching is also indicated by the trend of the flow structures and these confirm the existence of tension acting at right angles to the elvans and Q-joints. Since the lodes are parallel to these, it follows that tensional forces were exerted at right angles to the lodes as well. The stretching of the granite surface is inevitably communicated to the enclosing rocks as Ghosh noted in the case of the Carnmenellis granite. He states "After infilling the anticline, the magma exerted a centrifugal hydraulic pressure on the confining walls and thereby produced local cleavages and altered the strikes of beds in the metamorphic aureole in such a manner as to re-aline them parallel to the granite margin." Thus the

tensional forces exerted by the granite, affects not only the granite itself but also the country rocks in the immediate vicinity of the pluton. The other effect of the granite is a vertical compression caused by the upward push of the intrusion acting against the weight of superincumbent rocks. This compression tends to produce conjugate fractures over the apex of the intrusion. Both processes of tension and vertical compression could give fractures parallel to the main axis of the granite body.

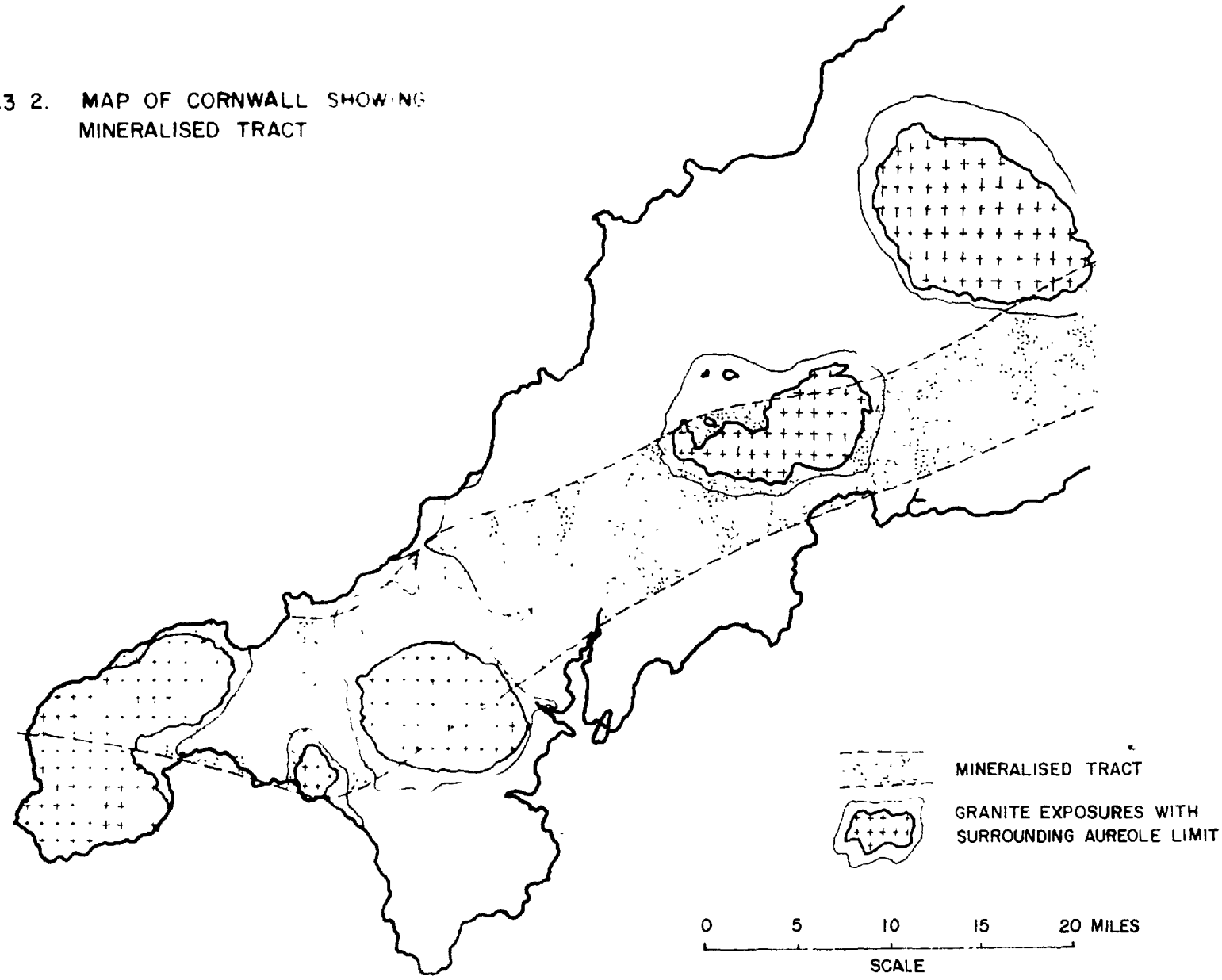
These two effects of granite intrusions have been consistently invoked to explain the formation of mineral lodes in many parts of the world, but as an explanation for the Cornish lodes their application has been inhibited by the lack of correspondence between the lodes and the shapes of the granites. Now that the original granite surface has been shown to consist of ridges striking parallel to the lodes some attempt may be made at converting the Cornish lodes to orthodoxy.

Though both processes were operative, the writer feels that the stretching effect of the granite probably played the predominant role in Cornwall. Such features as flat dipping lodes, cross-cutting lodes and the coincidence between the lodes and the Q- and S-joints of the granite are indicative of formation during the cooling

of the granite. On the other hand, some lodes occupy conjugate fractures dipping at steep angles and this favours a formation by vertical pressure. Unless full recognition is given to the role of stretching, the positions of the lodes cannot be adequately explained. It is for this reason that despite Hosking's success in predicting the form of the granite batholith, the origin of the lode fractures is still uncertain.

One objection to Hosking's ridge hypothesis has been made by Bott and his co-workers. They found that the belt of mineralisation as defined by Dewey (10 miles wide and trending north-east through the Cornish peninsula) (Fig. 3.2) is displaced to the south of the axis of the minimum gravity anomalies. They concluded "A connexion seems to exist between the granite belt and the mineralisation although the exact relations are not clear. Hosking has suggested that the mineralisation 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 mineralisation 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

FIG.3 2. MAP OF CORNWALL SHOWING MINERALISED TRACT



proportion of the total country rocks; sheets more than 200 metres thick should produce a detectable anomaly." Bott felt that the peculiar position of the belt of mineralisation was related to the asymmetry of the granites, but as suggested by Emmons, the effect of asymmetry is not to shift the fracturing away from the apex but to produce a shear zone above it.

Another objection which Bott et al might have raised is that in the Carn Brea-St. Agnes Head area, the gravity results show that the axis of the granite runs north by east while the strike of the lodes is east-north-east.

Both these objections may be overruled if the stretching of the granite mass is taken into account. The direction of stretching merely indicates the direction of tension and the requirement is that the lodes should be in the perpendicular direction; this is found to be the actual case. The lodes formed by upward pressure would, in general, be parallel to those formed by tensional effects, both being in the same direction as the strike of the pluton, but the actual location of the fractures should theoretically lie close to the apex of the intrusion while there is no restriction in the latter case. Thus the mineralised belt appears to be displaced southwards only if it is expected to overlie the apex of a granite crest.

In certain instances the direction of tension may not even be reliably indicated by the strike of the body. This state of affairs is perhaps shown in the Carn Brea-St. Agnes Head area where the axis of the granite runs north by east while the lodes strike east-north-east. The geological evidence suggests that the granite beneath St. Agnes Head is a northern extension of the Carnmenellis granite. The interpretation by Ghosh of theflow structures in this mass is interesting to note. "Intrusion was initially at a high angle (85° to 75° in places) in the south-east and the south; the magma then moved northwards, and finally disappeared and spread in undulating manner, beneath the cover of sediments to the north." This flow would produce tension in the perpendicular direction (east-north-east) which is indeed the direction of the lodes.

The anomalous strike of some of the lodes between the Carnmenellis and Land's End granites cannot be demonstrated to be related to stretching of the granite, since this is not exposed and therefore the flow structure is not known. However, the confirmation by the gravity survey that there are subterranean granites striking parallel to the lodes is a good indication that the anomalous strike is more apparent than real.

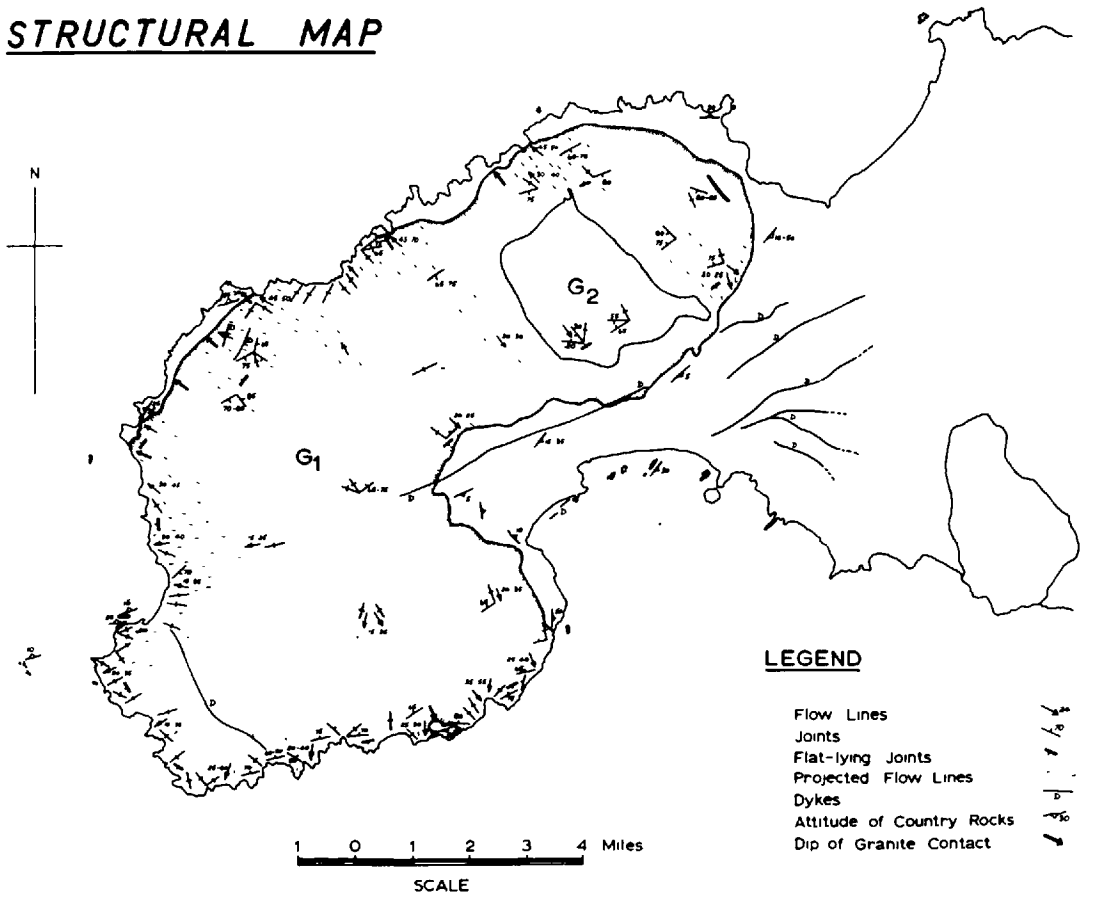
With regard to the lodes in the Land's End granite the situation is rather challenging since the direction of the flow structures is known (Fig. 3.3) and there are localities famous for the departure of the lodes from the usual strike. In the eastern part of the granite the characteristic flow direction strikes north-west while in the western part the general flow direction strikes east-west. Thus, the orientation of the flow structures has swung around through a large angle and there is a corresponding swing in the lodes from north-east in the eastern part to north-west in the western part. It may be objected that the flow direction in the St. Just district is not strictly at right angles to the lodes, but it must be borne in mind that the orientation of flow structures is very susceptible to minor variations and eddies in the magma flow. Fortunately, it was in the St. Just district that Garnett established by direct underground observation that the lodes coincided with the granite joints. Thus it is entirely legitimate to explain the slight discrepancy between the lodes and the apparent tension direction as the result of inaccuracy in the determination of the general flow direction.

The flow structures in the eastern part of the Land's End granite show that the tensional forces were

FIG. 3.3

THE LAND'S END GRANITE

STRUCTURAL MAP



north-west to south-east, while in the western part tension was predominantly east-west. This implies that in the intervening region, the tension was both north-west and north-east and this might explain the equal development of north-west and north-east lodes around Ding Dong. There is, however, no direct evidence in the granite structures that these hypothetical forces did exist in the district.

Other lode variations from the north-east strike are also apparent in the area south of the St. Austell granite. These have been already accounted for by Exley. He has stated "...the strikes of the lodes east of St. Austell change from NE-SW to NW-SE as the town is approached. The westerly lodes, therefore, have a strike that is discordant with the neighbouring granite margin, but concordant with the perimeter of the eastern arch just described, while all dip towards the centre." The arch referred to was the inferred position of the original boundary of one of the two granites making up the St. Austell mass.

Thus the realisation that the granite surface consists of ridges striking parallel to the trend of the lodes, has gone a long way towards explaining the formation of the lode fissures. In most cases, formation has been due to

vertical stress created by the intruded magma, combined with the stretching of the granite surface. The latter effect is particularly noticeable in those instances where the ridge theory seems inadequate.

CROSS FOLDING

Minor Cross-Folding.

South West England was subjected to the Asturic phase of the Hercynian orogeny in the Upper Culm, and the folded strata were intruded by the Carboniferous granites. The positions of the granite instrusions is believed to have been controlled by these pre-granite structures. It is generally considered that the cores of anticlines were especially favourable loci for granite infilling, and the idea is supported by evidence from the flow structure of the granites. Ghosh, for example, concluded from his study of flow structures in the Carnmenellis granite that "...while the main flow spread from south to north (under enormous hydraulic pressure from the south) offshoots from the main flow were frequently forced downwards - under constraint imposed by the roof of the dome beneath which the granite was emplaced." A similar study of the Land's End granite prompted Bagchi to comment "Intrusion of the granite probably started from the south at low angles into the pre-existing anticline."

No doubt the original structures were modified by the diapiric action of the invading magma but apparently

this effect was slight. The high tectonic level of the plutons, the comparatively low metamorphic grade of many of the inner aureole rocks and the general absence of associated migmatite facies support Read's contention that ".. in South West England the Carboniferous granites were almost dead when they arrived in their present position." The slight diapiric effect is also indicated by the marked uniformity in direction of the flow structures, joints and lodes of the various granite bosses. Had diapiric action been a prominent factor, each boss would have exhibited concentric features akin to salt dome structures. Thus the granites must not be envisaged as disruptive elements imposing their own imprint on the original environment, instead they seem to have played a largely passive role, allowing the pre-existing structures to dictate the ultimate form of the granite. In the Bodmin Moor granite Exley found that the coarseness of grain and megacryst development follow synforms and antiforms on a large scale. In the Dartmoor granite Brammall found that the granite surface was hummocky, domed and grooved in various directions, probably from the imprint of the country rocks.

It would seem, therefore, that not only was the position of the granites determined by the location of the

anticlines, but also their shape was controlled by that of the enclosing rocks. This general principle has found articulation in Hosking's words "It is believed that the presence of these ridges are best explained by assuming that they were impressed upon the surface by the moulding action of the sedimentary rocks which the granite encountered during the emplacement." This is an important concept to recognise for it allows the elucidation of the structures in the country rocks by two methods. If straightforward mapping by conventional means is not applicable, then a viable alternative is to reconstruct the nature of the granite surface.

A study of the flow-structures etc. of the granites is restricted to the areas of outcrop, which represent only a fraction of the whole Cornish batholith. However, this fraction may be enlarged by employing a suitable geophysical technique, e.g. gravity surveying. In order to deduce the nature of the granite surface from the gravity results, the second vertical derivative map must be computed (as previously shown).

This was done in the area between the Carnmenellis and Land's End granites and the resulting map (Fig. 2.14) showed the existence of two main trends in the hidden granite. The predominant trend was north-east and this

was replaced by a north-west trend between Rinsey Head and Ludgvan. Since the granites followed the cores of anticlines it is concluded that there were two sets of anticlines striking north-east and north-west.

Ramsay has shown that the interference patterns produced by the superposition of folds of similar type is so distinctive that their recognition permits the nature of the separate movements to be deduced. The pattern seen in the second vertical derivative map is one of domes and basins superimposed on ridges trending parallel to the two fold directions. According to Ramsay, domes and basins are developed if the 'a' direction of one set of folds lies close to the axial planes of the other folds. Furthermore, when the intensities of folding are variable, the domes and basins tend to be elongated parallel to the more intense structures. Thus the form of the contours on the second derivative map is explained if there are two fold systems of varying intensities, intersecting at right angles, the 'a' direction of one set being close to the axial plane of the other.

Cross-folding has not been previously reported from this locality, but cross structures have been recognised at several neighbouring areas. Lambert has described main folds trending west-south-west to east-north-east and

cross-folds trending north-west to south-east in the Gramscatho beds near the mouth of the Helston River. Booth computed the deviations from arithmetic means of various parameters related to the mineralogical distribution in the Land's End granite and found a number of ridges and troughs trending north-north-east to south-south-west and west-north-west to east-south-east. From these data and from studies of the foliation and layering of different granite types he concluded that the Land's End granite was thrown into a series of antiforms and synforms trending north-north-west to south-south-east with roughly one to two miles wave length (personal communication). In the Pendeen-Bottallack area a predominant fold trend of N17°E has been mapped by Garnett with a second, less important set of folds striking north-west to south-east.

In some localities, though cross-folding is either not present or only poorly developed, some form of cross-lineation may be present. Between Hayle and Portreath, Smith has found a strain slip cleavage striking north-north-west to south-south-east with occasional associated folding. In the Porthleven area, Stone and Lambert have mapped a north-west lineation at right angles to the fold axes and parallel to the cleavage dip. This

north-west lineation was also noted by Reid and Flett who reported that, generally, the more fine-grained beds of killas in the Land's End region very often show the cleavage crossed by a strain-slip cleavage at right angles.

Thus, the cross-folding indicated by the second vertical derivative map is far from being a purely local phenomenon. It is part of a regional pattern; usually the cross-structures take the form of a lineation, but in certain localities, as at Helston, the Leedstown area and in the Land's End granite, cross-folding is developed.

Major Cross-Folding.

In Fig. 3.4 the positions of the exposed and the buried granites are plotted; on land the subterranean extent of the granite is indicated by the zero contour of the second vertical derivative map, and on the offshore area the position of the submarine granite is given by its metamorphic aureole.

The form of the Godolphin granite as shown in the Figure deserves some attention. The exposed part of the Godolphin boss is elongated in the north-north-west direction and this trend is emphasized by a ridge of hills running along the mass in the same direction. If this axis is projected northwards, it runs along the hidden

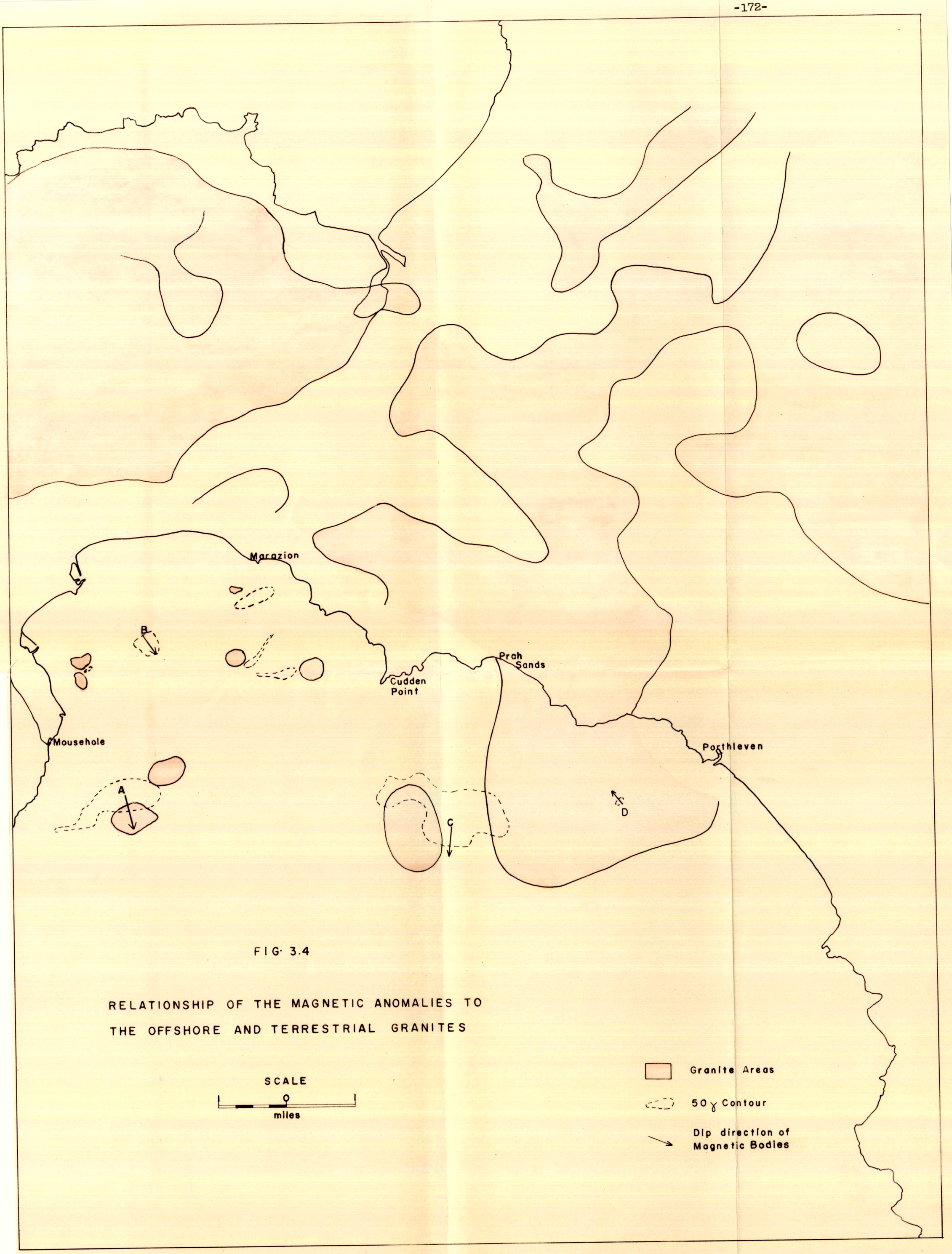


FIG. 3.4

RELATIONSHIP OF THE MAGNETIC ANOMALIES TO THE OFFSHORE AND TERRESTRIAL GRANITES

granite ridge which passes to the west of Leedstown. If the axis is projected southwards into Mount's Bay, it is found that the submarine granite lies on the extension. It would therefore seem that the emplacement of the Godolphin granite (with its northern and southern extremities) was controlled by a feature stretching for at least ten kilometres in a north-north-west direction. It is concluded that a major anticline trending north-north-west passes through the area now occupied by the Godolphin granite.

Other large structures in the region which have a similar strike are the great Fluccan fault and the western part of the Land's End granite. This boss has a peculiar shape with the right angled bend around Madron giving it the form of an L. Its outline suggests the intersection of a north-west and a south-east trend and the flow structures in the granite lead to the same suggestion. In the part trending north-west the flow structures strike east-west or north-east to south-west confirming that the structural axis is north-west; in the part trending north-east the flow structures strike north-west to south-east confirming that the structural axis is north-east.

Thus, the form of both the Godolphin and Land's End granites suggest the existence of major anticlines striking parallel to the great Fluccan fault in a roughly north-west direction. This interpretation is supported by the behaviour of the greenstone outcrops. Unlike the lodes and elvans, the greenstones are not related to minor crests in the granite, or to the direction of tension. They were emplaced as massive sills and their present attitude is conditioned by the intense folding which occurred in the Asturic phase of the orogeny. Between Rinsey Head and Marazion the greenstones strike north-west, sub-parallel to the proposed Godolphin anticline. Around Mousehole they dip north-east off the granite and strike north-west parallel to the anticline passing through the Land's End granite. As the granite takes its right angled turn to strike north-east so the dip and strike of the greenstone faithfully mimic the change.

It was previously shown that minor cross-folding in South West Cornwall is part of a regional pattern and this leads to the expectation of major structures corresponding to the small scale structures. Until now, no suggestion has been made that there is large scale cross-folding in Cornwall, but the available evidence does indicate the existence of these large folds trending north-west. It is realised

that more data ~~is~~ are required before these structures can be accepted as proved, but there is sufficient evidence to warrant making the hypothesis.

Fig. 3.4 further shows that the magnetic anomalies are spatially associated with the granite areas, both following the general curve of the bay. It may be recalled that a similar relationship was found between the greenstones and gravity contours (Fig. 2.11) and it had been caused by the fact that the original greenstone sills were folded into anticlines, the cores of which were infilled by granite. If a similar explanation holds for the magnetic rocks in Mount's Bay, it would be expected that they would dip away from the granite areas. Fig. 3.4 shows that this is so for anomalies A, B, C and also D which dips north-west towards the depression immediately south of the Godolphin granite (Fig. 2.5). It is therefore concluded that originally the magnetic rocks of Mount's Bay were more or less concordant with the bedding. It was previously shown that the source of these magnetic anomalies was likely to be a rock with magnetic properties similar to that of the serpentine or troctolite of the Lizard igneous suite. Unfortunately, current opinion is that the Lizard suite was intruded along a great thrust and this view is incompatible with the suggestion that there are similar rocks in Mount's Bay

which were emplaced parallel to the bedding. However, recent data shows that the accepted view on the origin of the Lizard rocks may be erroneous, and the writer has decided to re-examine this question.

The authoritative reference on this area is the memoir of the Geological Survey of Great Britain, published in 1946 by Flett entitled "The Geology of the Lizard and Meneage". This gives the facts accumulated up to that time, and a concise history of previous research. Flett was well aware of the equivocal nature of many of the observed phenomena, but was not afraid to give his interpretation of them. The memoir owes its authority to the success of the author in separating the facts from his personal opinions, and constant reference will be made to it in the following pages. Flett's map of the Lizard geology is shown in Fig. 3.5.

The Lizard district is divisible into a southern part separated from the northern part by the Lizard boundary. The rocks to the south of this boundary are the Lizard series of metamorphic schists and gneisses with plutonic intrusions. All these rocks are in a variable but intense state of metamorphism. To the north of the boundary are Cornish killas, clay-slates and grits never highly metamorphic. Between these two

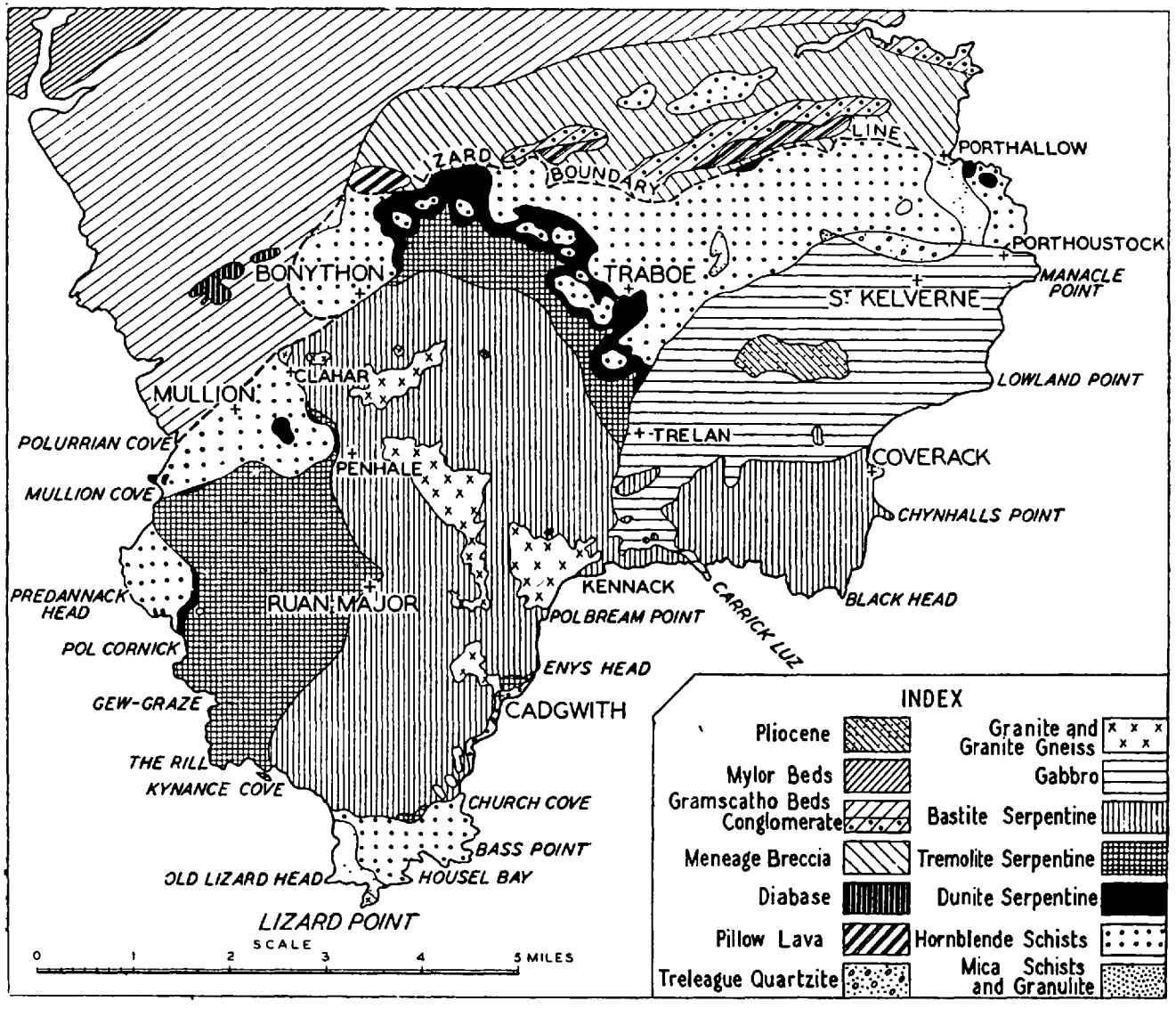


FIG. 3.5 THE GEOLOGY OF THE LIZARD

series, on the east side of the peninsula, there is a zone in which the strata are reduced to a regional breccia, the Meneage Crush-zone. The Lizard series includes the following rocks :

Granite and granite gneiss

Dolorite and epidiorite dykes

Gabbro and flaser gabbro (with troctolite)

Serpentine (bastite, tremolite and dunite)

Man o' war gneiss

Hornblende schist

Mica schist, granulite and green schist.

Two great controversies have raged unabated up to the present day. The first concerns the nature of the Lizard boundary, and the second is whether or not the metamorphic schists are metamorphosed Devonian sediments. Of the Lizard boundary, two divergent opinions hold the field. According to Flett's view, the Lizard boundary is a great dislocation or series of dislocations bringing together two series of rocks differing widely in composition, state of metamorphism and in age. The dislocation was later extended in an east-north-east direction as a sweeping curve passing through Dodman Head and the Start peninsula, and it is now known as the Lizard thrust. The alternative view, held by Hill, was that the fractures

along the boundary line could not be proved to be everywhere the site of faults or thrusts. The rocks on opposite sides of the boundary line were of the same age but those of the Lizard series had undergone great metamorphism through the agency of igneous intrusions, acting during a period of earth movement.

It is not proposed to set down here the evidence put forward by the rival factions in support of their cause. The mere fact that the controversy has been so enduring is sufficient proof that much of the evidence is inconclusive. One of the reasons for the insolubility of the problem may have been the isolation of the Lizard series on the tip of a rather small peninsula. Since the publication of the memoir, new ideas have been presented from re-mapping of some of the Lizard geology by various authors, and new information has been obtained by the use of geophysical methods and coring of the offshore areas.

On the terrestrial area, there are now magnetic and gravity results available, and on the offshore area there is data from magnetic and coring surveys. These geophysical results are especially important for an understanding of the nature of the deeper geological structures. From the coring results, Whittard prepared a geological outcrop map of the sea-bed around the South West Approaches.

His map shows that the Lizard series is confined to the Lizard peninsula. They are not continued on the east, south or west of the peninsula, being entirely surrounded by Devonian slates. The metamorphic schists on the Start peninsula extend into the offshore areas but the outcrop is not continuous and does not persist further west than Fowey. If there were a major thrust on the Lizard it would be extremely difficult to explain the disappearance (along the strike of the thrust) of the Lizard series of rocks.

The magnetic results of Allan on the offshore area are in complete agreement with the implications of Whittard's map. The sharp magnetic anomalies over the south-east Lizard die out rapidly at sea; they also terminate abruptly at the northern margin of the complex. Furthermore, the anomalies strike north-west to south-east while the supposed Lizard thrust strikes east-north-east. The aeromagnetic results also agree with those of Allan and they indicate that the magnetic anomalies of the Lizard might have a north-west extension in Mount's Bay.

The gravity survey on land by Bott et al showed that the gravity values over the Start peninsula were inconsistent with a thrust outcropping at the boundary of the Start schists. The gravity gradient over the Lizard

peninsula is similar in character to that over the Start, but is less easy to interpret owing to the presence of the Carnmenellis granite ten kilometres away. Though the gravity results confirm the existence of denser rocks thickening southwards over both peninsulas, the thrust theory would definitely have to be modified to explain the gradient on the Start, and on the Lizard peninsula, the effect of the Carnmenellis granite must be appealed to if a similar modification of the thrust theory is to be avoided.

Thus, the coring, the offshore and aeromagnetic results are all unanimous in suggesting that there is no Lizard thrust. The gravity data are less conclusive, but do require an adjustment of the thrust theory. These combined results are sufficient to tip the balance against Flett's hypothesis, and the latest published work on the Lizard topples the scale overwhelmingly on Hill's side. Lambert has re-examined the rocks of the Meneage zone and has concluded that the structures in the zone are of primary origin, being probably due to sub-aqueous slumping. Hitherto, the Meneage rocks were interpreted as a crush-breccia and was, for this reason, one of the cornerstones of the thrust theory.

In view of the geophysical, coring and Lambert's results this writer feels that the thrust hypothesis is not acceptable. There is no firm evidence in favour of it while there is strong evidence against it.

With regard to the other great controversy - the origin of the metamorphic schists - the position is still uncertain. Since the publication of the memoir, Scrivenor, Sanders and Hendriks have all advocated a formation by metamorphism of Devonian sediments. Despite this, Green is still prepared to assert that "The hypothesis that the Old Lizard Head Series are metamorphosed lower Devonian sediments can no longer be considered." However, the point will be pursued later. It will be sufficient for the moment to establish that the origin of the metamorphic schists is not definitely known.

It must be recalled that the Lizard geology was discussed because the dips of the magnetic bodies in Mount's Bay led to a geological interpretation incompatible with the generally accepted version of the Lizard geology. It was previously held that the Lizard igneous complex was intruded as a plug along a very powerful thrust zone. But the existence of the Lizard thrust has been found to be doubtful, and it is now proposed to examine the evidence in favour of an intruded plug.

Flett was led to suggest that the serpentine was a plug inserted into the surrounding schists because of its irregular rounded shape. However, he did point out that there was no direct evidence for this. From Pol Cornick to Traboe and Trelan the margin describes a great semi-circular curve and along this line the serpentine is everywhere folded with the hornblende schists that surround it. Numerous areas of hornblende schists are found in the serpentine outcrop, and in the hornblende schist areas there are outcrops of serpentine. This relationship may be explained in either of two ways; either the serpentine underlies the hornblende schist, in which case the serpentine areas in it are anticlinal and the hornblende schists in the serpentine are synclinal, or alternatively serpentine areas in the hornblende schists are the summits of dome-shaped intrusions and the hornblende schists in the serpentine are inclusions. Flett pointed out that no intrusive dykes or sills of serpentine have been clearly demonstrated, which is some evidence against it being an intrusive plug.

On the other hand, the hornblende schists seem to dip under the serpentine at Cadgwith, Polbarrow, Landewednack and Pentreath, which suggests that the serpentine is a sill-like body. Sanders investigated the south-east area

of the Lizard near Cadgwith and was able to show that the serpentine there took the form of a sheet overlying the Landewednack hornblende schist. Green has since re-examined this area and confirmed that the serpentine was generally concordant with the flat-lying hornblende schist.

Thus, though the nature of the serpentine contacts is usually ambiguous, where the relationship is clear (at Cadgwith) the serpentine is a flat-lying body resting on more or less horizontal hornblende schists. This indicates that if the serpentine is intrusive it was emplaced as a sill. It may be noted that although De la Beche was quite convinced of the intrusive nature of the serpentine, he felt that it was poured in a state of fusion into a basin formed in the hornblende schist.

It is now clear, that neither the thrust hypothesis nor the assumption of an intrusive plug of serpentine is based on really sound evidence. However, if these two concepts are to be rejected, some alternative hypothesis, in accord with the facts, must be substituted.

So far, the facts available are that there is no major thrust on the Lizard peninsula and the serpentine is essentially concordant with the underlying rocks. Two other major lines of thought also run consistently through Flett's memoir.

The first of these is the conviction that the members of the Lizard igneous suite represent a complete suite of magmatic differentiation. This idea was explicitly stated "With the banded gneisses, the aplites and quartzose veins, the sequence of Lizard intrusives comes to an end. A complete series of igneous rocks has emerged, from ultra-basic dunites to highly acid felsites and pegmatites. As usual the succession has been from basic to acid types. Between the injections there were pauses but it is difficult to believe all the intrusives (excepting the Man o' war gneiss) were not the products of differentiation of a single magma."

The overall differentiation trend is accompanied by differentiation within the individual members of the suite. The earliest type of serpentine is the dunite (almost entirely of olivine) which gives way to tremolite serpentine (mostly olivine and tremolite with a little enstatite) and the final product is bastite serpentine (small olivines and a high proportion of large enstatite). The various serpentines grade perfectly into each other. Within the bastite serpentine are bands of chromite, several yards in breadth, described by Flett as fluxion bands, and obviously caused by magmatic segregation.

In the next group, the gabbro and troctolite, there is increasing crystallisation of plagioclase. The older gabbro or troctolite is still very rich in olivine but contains white spots of felspar. This is followed by the main gabbro mass in which the proportion of felspar has markedly increased. There are several varieties of gabbro, no less than nine types being recognised, some of which represent variations in texture as well as composition. One variety is the black gabbro which is rich in olivine and at the other end there is a white gabbro consisting of felspar and white pyroxene (malacolite).

The next rock type in the series is the olivine dolerite which occurs mostly as dykes, known as the black or epidiorite dykes. Because of their narrow widths it is difficult to find signs of differentiation, but nevertheless Flett reported that "in a few places these black dykes contain red, acid, felspathic streaks which do not seem to be injections from adjacent or contiguous granite masses."

The final products of the Lizard series are the Kennack gneisses. The great majority of these are banded; the bands consist of a basic and an acid element imperfectly mixed. The dark component is doleritic and the acid part is a white, pinkish or yellowish quartzo-felspathic rock with abundance of felspar and obvious quartz.

Flett's other main line of thought is that each member of the suite was affected by movement while it was being emplaced. Each serpentine exhibits fluxion-banding and fluxion-foliation which is partly caused by flow in a semi-fluid mass. Of the gabbro which followed the serpentine Flett stated that "Crushing was apparently in progress after a large part of the rock had crystallised but new magma was still being introduced and this in turn was shattered by movement shortly after solidification." The gabbros were succeeded by the epidiorite whose appearance in certain localities led Flett to remark that they looked as if they had suddenly been squeezed when in a plastic condition. Movement continued until the final stages of crystallisation for Flett attributed the structure of the banded gneisses "to the fluxion of this heterogeneous and often pasty magma as it was injected into older rocks of the complex."

Any hypothesis on the formation and emplacement of the Lizard rocks must, therefore, take into account the sill-like character of the body, the operation of magmatic differentiation and the constant movement in the mass. A hypothesis which explains these features has been proposed by Brunn. He has found, in common with other workers (Hess and Bilibin), that ophiolitic suites usually occur in

a geosynclinal environment. However, he considers that the suites are formed in situ by magmatic differentiation of basaltic magma on the floor of the geosyncline. Previous theories had always supposed that there was successive extrusion of the various magmas comprising the suite.

According to Brunn basaltic magma ascends open fractures in the early stage of the geosyncline and is extruded on to the sea-bed in a thick pile. The rapidly crystallised crust of the extrusion gives the best indication of the composition of the magma because of its rapid formation which does not allow appreciable differentiation. It is usually olivine basalt. Within the solidified crust the magma collects as a thick pouch which spreads out on the ocean floor. The crust provides a seal which inhibits further reaction between the magma and the sea-water, and the magma pouch becomes a vast chamber in which magmatic differentiation proceeds, in situ on the ocean floor. Some of the volatile elements escape through the crust by diffusion and by fissures, thereby augmenting the basicity of the magma which remains in the chamber. Outside the pouch the fugitive phases set off the proliferation of radiolarites. Judging from the accumulations of radiolarian chert in the neighbourhood of ophiolites, there must be considerable loss of silica through the crust.

The consolidation of the remainder of the extrusion occurs along two fronts of crystallisation within the magma chamber. One proceeds from the solidifying border towards the interior and the other proceeds from the base towards the top. Where these two progressing fronts finally meet each other, the limit of the two domains may be blurred by the convergence of conditions. But more often the lower part of the descending zone (doleritic zone) was made turbulent by the influx of volatile elements from the deeper levels. This causes the already formed solid phase tc become unstable in the modified conditions and results in alternations and complicated interpenetrations of the various layers. This is without doubt the origin of the pseudo-veins which often appear and which give apparently contradictory age relations. Thus it is not a process of straightforward gravity differentiation. Other phenomena which intervene are the reactions between the solid phase and liquid phase, the delay of crystallisation and the viscosity of the magma. The final sequence of rocks is typically :

Radiolarian Chert	
Pillow Lavas	
Spilites	Fine-grained
Basalts	

Dolerites	)	Medium-grained
Quartz Diorites	)	
	)	
Diorites	)	
	)	
Gabbros	)	
	)	Coarse-grained
Pyroxene-Peridotites	)	
	)	
Pyroxenites	)	
	)	
Peridotites	)	

This well marked differentiation is found in a vertical and lateral sense. The complete sequence is only found in the median parts of the pouch.

The mechanism proposed by Brunn is adequate to explain many features of the Lizard complex which had remained unsolved puzzles. A selection of some of these features is given below.

1. The advance of the frontal part of the flow set off sub-aqueous slumping in the unconsolidated sediments on the floor of the geosyncline; these disturbed sediments are now seen in the Meneage zone. Lambert's re-interpretation of the structures in the Meneage is in complete accord with such an explanation. Other breccias at the extremities of ophiolitic masses have been reported by Dubertret. Slumping also explains why the Meneage breccia is only found on the eastern part of the peninsula.

2. The presence of pillow lavas and radiolarian chert on Mullion island and throughout the northern boundary zone has always been an acute embarass¢ment to the thrust hypothesis. The "Lizard thrust" emerges at the coast near Polurrian and if continued along its strike, would pass north of Mullion Island, thus including the island in the Lizard complex. Yet the pillow lavas and cherts of the island are not to be found on the mainland opposite. Furthermore, as Flett noted, "The perfect preservation of the pillow structure and of the bedding of the shales and cherts shows that the rocks have escaped pressure in a marvellous manner." The same phenomenon is found in the outcrops of pillow-lavas in the Meneage "crush-zone." Flett wrote "in many places they occur within a few yards of the Lizard hornblende schists to which they present a complete contrast, as though both series are originally igneous rocks the lavas retain their primary igneous structures and characters in great perfection, while the Lizard rocks are typical metamorphic schists."

On the other hand if the Lizard complex is the front of an ophiolitic flow the presence of unsheared pillow lavas and cherts along the margins of the serpentine would be a necessity rather than an embarass¢ment.

3. The complicated nature of the Lizard boundary has been the source of much dispute. According to Flett, "In some places the margin is sharply faulted and the faults run in straight lines, but for a large part of its course the boundary describes sinuous curves." Also, "In its course from Porthallow across country westwards to Polurrian, the Lizard boundary describes a sinuous and irregular line and passes mostly through cultivated land. As a rule its presence is not expressed by a marked surface feature." These ambiguous characteristics would be remarkable if the Lizard boundary is the site of a great thrust, but if the Lizard rocks were a submarine flow, it would be quite normal to have a sinuous boundary which is faulted in some localities and unfaulted in others. A further consequence of emplacement as a submarine flow would be the enclosure of the Lizard rocks by Devonian sediments. That this is the case is also a severe blow to the thrust hypothesis.

4. Many of the igneous textures of the Lizard rocks cannot be explained if they were intruded along a thrust.

Flett noted "In the metamorphism of the igneous rocks the most striking feature is its variable and sporadic development. As a general rule the metamorphism is not extreme, but every member of the series shows types which

are perfectly foliated and other types in which the original igneous minerals and structures are in quite good state of preservation. The serpentine, for example, is often not very different from a normal peridotite; in other places it is a talc-tremolite-schist. Adjacent dykes of gabbro may be normal gabbro-pegmatites and gabbro-schists with platy foliation. The banded gneisses have often a close resemblance to the Lewisian gneisses, but in the granite areas there are occasionally rocks that look like normal granites. In the dykes the change from dolerite to schist sometimes takes place in a few yards and is apparently connected with planes of dislocation and movement. ..... It is not possible to advance a complete explanation of the facts..."

These phenomena are best explained by movement of the entire magma chamber while still in a state of incomplete crystallisation. The partially crystallised layers are subjected to tension and compression (in localised areas) created by the differential movement of various parts of the mass.

5. Around Treleague farm (near St. Keverne) there is a quartzite which is not found anywhere else in the Lizard and Meneage. It consists essentially of quartz, but what makes it distinctive is the presence of siliceous

cementing material which is richly charged with fine needles of hornblende.

Flett thought that the hornblende proved a low grade of metamorphism, but the quartzite is partially enclosed in the gabbro so that Flett considered it to have been older than the gabbro. However, its metamorphic grade would be much lower than the other metamorphics which are older than the serpentine. This led to the suggestion of two distinct metamorphic periods pre-dating the intrusion of the Lizard complex.

A simpler explanation is proposed by the present writer. The peculiarity of this rock is due to its formation as a very late stage differentiation product. Its appearance was already anticipated by the character of the banded gneisses. Some bands of the gneiss consist mostly of dark green hornblende and felspar, and these are interbanded with quartzo-felspathic layers. With a decrease in the basic component and shift towards the acid end, the hornblende has decreased in size and abundance, while the quartzo-felspathic bands have evolved towards a purely quartzose residuum.

It may be noted that although the rock is classified as a quartzite Flett wrote "The Treleague quartzite seldom shows obvious traces of bedding or of pebbly structure

and is not accompanied by shales...", all of which would be direct evidence for a clastic origin.

6. The gabbro, epidiorite and banded gneisses are all confined to the serpentine areas; they never occur in the surrounding hornblende-schists. If the peninsula were regarded as the focus for intrusive activity, the restriction of these intrusions to the serpentine outcrops would be extremely peculiar, whereas this would be expected if the Lizard suite were formed from the consolidation of one extrusion.

Additional points may be brought forward, but it is already apparent that the currently accepted version of the origin of the Lizard complex is inadequate. It is also clear that the features mentioned above are best explained by the hypothesis of extrusion and differentiation in situ of basaltic magma. But it is always possible that the adoption of a new hypothesis creates more problems than it solves, and it will be necessary to examine Brunn's theory from this view-point.

There appear to be three implications which need to be considered.

1. The members of the Lizard suite which came after the serpentine have been described by Flett as intrusive into earlier members, which implies that the differentiation did not take place in situ.

2. If the Lizard boundary marks the margin of a submarine flow, the rocks north of the boundary are no different in age from those south of the boundary. Since the rocks north of the Lizard boundary are lower or middle Devonian, it would mean that the metamorphic schists are the same age.

3. The Lizard metamorphic schists must therefore be altered Devonian sediments.

These three points will be discussed in turn.

1. The intrusive features found in the Lizard suite are often shown by stratified basic-ultrabasic lopoliths. In the Bushveldt complex there are rock types, whose mineral composition conforms to an origin by crystal accumulation, cutting across the more normal igneous rocks, e.g. there is dunite cutting vertically across pyroxenite.

In the Skaergaard complex small volumes of hedenbergite granophyre and sodic acid granophyre locally invade upper levels of the gabbro mass.

Brunn also described a thick ophiolitic suite in Macedonia, in which veins, rich in felspar, cut obliquely layers formed earlier. He suggested that these cross-cutting veins were formed by descending material rather than by ascending injections. A similar occurrence is

found in the Lizard complex. Sanders has reported quartzo-felspathic dykes in the serpentine, striking approximately east-west that do not appear to occupy faults which extend into the formations beneath the serpentine. He suggested that they occupy tension fractures, resulting from the northward relative movement of serpentine over its floor.

Thus, in the Skaergaard and Bushveldt lopolites, despite the existence of veins of later-rocks cross-cutting earlier layers, it is accepted that magmatic differentiation in situ has been the mechanism producing the peculiarities. Furthermore, Sanders' observations of the east-west quartzo-felspathic dykes supports the contention that Brunn's hypothesis is applicable to the Lizard igneous suite.

2. There is no radioactive dating of the serpentine itself, but mica-schists, hornblende-schists and Kennack gneisses have all been dated by the K-Ar method. The 18 samples of these rocks gave a grouping around 370 my (Table 2). In the revised Phanerozoic time scale this corresponds to a lower-middle Devonian age.

The age of the Kennack gneisses is particularly relevant in view of the fact that they are regarded as the final differentiation product of the magma which gave

TABLE 2: *Age Determinations in the Lizard Area*

Rock Unit	Mineral	% K_2O	No. of determinations	Age (millions of years)	*δt.	Method		Specimen No	and Rock
Old Lizard Head Series	Muscovite (coarse)	9.03	5	357	3.25	KA, Total Volume	Cambridge	96388	Muscovite chlorite schist
" " " "	Muscovite (fine)	9.01	5	352	3.21	KA, Total Volume	Cambridge	96388	" " "
" " " "	Muscovite (coarse)	9.17	5	355	3.20	KA, Total Volume	Cambridge	96391	" " "
" " " "	Muscovite (fine)	9.11	5	359	3.27	KA, Total Volume	Cambridge	96391	" " "
" " " "	Muscovite	7.68	3-4	349	—	KA, Isotope Dilution	Oxford	9372	Muscovite Schist
" " " "	Muscovite I	9.49	3-4	348	—	KA, Isotope Dilution	Oxford	20557	Muscovite Schist
" " " "	Muscovite II	8.58	3-4	352	—	KA, Isotope Dilution	Oxford	20557	Muscovite Schist
Landewednack Hornblende Schist	Hornblende	0.375	8	371	3.37	KA, Isotope Dilution	Cambridge	96396	Blue-green hornblende, plagioclase, sphene amphibolite
" " "	Hornblende	0.425	6	442	3.94	KA, Isotope Dilution	Cambridge	96389	Blue-green hornblende, plagioclase, sphene amphibolite
" " "	Biotite	6.4	3-4	369	—	KA, Isotope Dilution	Oxford	9380	Hornblende, Biotite schist
Traboe Hornblende Schist	Hornblende	0.211	7	357	3.25	KA, Isotope Dilution	Cambridge	96395	Brown-green hornblende, plagioclase, diopside amphibolite
" " "	Hornblende	0.242	7	492	4.43	KA, Isotope Dilution	Cambridge	96394	Brown hornblende, augite, hypersthene granulite
Kennack Gneiss	Hornblende	0.577	7	366	3.33	KA, Isotope Dilution	Cambridge	96392	Biotite, hornblende amphibolite
" "	Biotite	6.97	5	397	3.58	KA, Total Volume	Cambridge	96392	Biotite, hornblende amphibolite
" "	Biotite	5.98	5	384	3.47	KA, Total Volume	Cambridge	96393	Biotite, hornblende amphibolite
" "	Biotite	7.39	3-4	368 (av.)	—	KA, Isotope Dilution	Oxford	9406	Granite gneiss
" "	Biotite	(—	—	352 ± 10	—	Rb-Sr, Isotope Dilution	Oxford	—)	Granite gneiss
		(—	—	353 ± 13	—	Rb-Sr, Isotope Dilution	Oxford	—)	

*δt = Error in age (millions of years) due to a 1% error in proportion of K_2O or volume of radiogenic argon.

the Lizard suite. Flett found evidence to show that the various members consolidated within a short interval of each other. He states that the various serpentines "have consolidated within a comparatively short period and the injection was probably gradual and continuous. The serpentine was followed by the gabbro after an interval which was not very prolonged." The epidiorite dykes often show chilled margins (though never glassy) and Flett concluded that the gabbro must have cooled down before the emplacement of the epidiorite dykes. Of the last igneous episode Flett wrote "the banded gneisses came not long after the black dykes." If there is an appreciable time interval between the emplacement of the serpentine and Kennack gneisses, it could only have been between the gabbro and epidiorite. It is seen from Table 2 that two samples gave markedly greater ages than all the others, and Green regards them as a pointer back towards an earlier event around 490 my. He then proceeds to associate the serpentine with this earlier event which leads to the conclusion that the age of the serpentine is 490 my. If this is so the serpentine was intruded in pre-Caledonian times, then after an interval of about 100 my the final products of differentiation (the epidiorite and the Kennack gneisses) arrived at the Lizard!

Geological processes do take some time, but nonetheless 100 my represents a considerable period. The least ridiculous hypothesis is that the serpentine is not greatly different in age from the Kennack gneiss, and is therefore lower or middle Devonian.

This age is also indicated by the associated spilites and radiolarian cherts. Serpentine, spilite and radiolarian chert are so universally associated that they are known as Steinmann's Trinity. That these rocks are usually contemporaneous is an established fact and is one of the reasons which led Brunn to postulate differentiation as a means of explaining the relationship. The spilites and radiolarian cherts on the Lizard are accepted as lower or middle Devonian, so that it is more than likely that the serpentine is the same age. Furthermore, there was widespread emplacement of ophiolitic masses during the lower-middle Devonian in the Hercynian geotectonic cycle.

The age of the serpentine can therefore be accepted as lower-middle Devonian because of :

1. The age of the Kennack gneisses (370 my).
2. The age of the associated spilite and radiolarian cherts.
3. The age of ophiolitic activity in the Hercynian geosyncline.

It is always possible to claim that the serpentine is a remnant of an earlier magmatic cycle, which just happens to be associated with Devonian spilites and cherts, but there is no shred of evidence for such a speculation. Indeed, this suggestion merely introduces more problems, while it does not solve any existing ones.

As previously indicated, the origin of the Lizard metamorphic schists is uncertain. The petrological characteristics appear to be confusing. In the Old Lizard Head series staurolite, kyanite-sillimanite, almandine and epidote in various assemblages indicate regional metamorphism in the almandine-amphibolite facies. On the other hand, andalusite, cordierite and anthophyllite suggest contact metamorphism to the hornblende-hornfels facies. The textures are described by Green as lepidoblastic and also as granoblastic. Tilley thought that these features showed that they were a series of lavas, tuffs, quartzose and pelitic sediments folded at a high temperature, undergoing both thermal and dynamic metamorphism.

The hornblende schists are divided into the Landewednack hornblende-schists and the Traboe hornblende-schist. The latter is so closely connected with the serpentine that Flett considered it to be "a basic intrusive rock preceeding the serpentine and affected by the

same movements, and no great lapse of time separated the two intrusions." He thought that the hornblende-schists were much older but at Ogo Dour they form a banded metamorphic complex with the serpentine, both rocks being involved in a common system of folding. The evidence at that locality proved that schists and serpentine were contemporaneous.

Green found that criteria given by Flett to distinguish the Landewednack and the Traboe hornblende-schists are valid ones and could be used to map the distribution of the two types. However, he found that the Landewednack hornblende-schist pass transitionally into the Traboe hornblende-schist at Porthallow and Porthkerris. Also, chemical analysis showed that the two rock groups have extremely similar compositions. From the detailed petrology and mineralogy, Green concluded that the Traboe hornblende-schists are almandine-amphibolite and granulite facies derivatives of the Landewednack hornblende-schist. The agent of dynamothermal metamorphism being the Lizard peridotite.

Both Green and Flett assert that the hornblende-schists are not metamorphosed lower Devonian sediments. The actual field evidence, however, proves that there is an intimate relationship between these schists and the

serpentine, and it is not really possible to disentangle the two groups into an intruded and an intrusive member. Such a relationship is perfectly compatible with the hypothesis that the serpentine was a submarine flow.

Thus there are no serious difficulties involved in accepting that the serpentine was emplaced as an extrusion. The conclusion that the magnetic rocks in Mount's Bay were originally concordant with the bedding may be therefore allowed to stand. Petrological examination of the rocks from Mount's Bay had confirmed that basic lavas (Devonian) are present; that these were probably spilitic is indicated by the abundance of calcium-rich minerals (calcite, epidote, zoisite) and by the association with chert. The presence of spilite in Mount's Bay is consistent with the aeromagnetic results from the South West England region, which showed that spilites give aeromagnetic anomalies. This relation appeared to be questionable because Blundell had shown that the spilites have low susceptibilities and low intensities of NRM. However, if the extrusion hypothesis is accepted, the spilites are only a relatively thin crust surrounding coarser (and more ultrabasic) members of the ophiolitic suite, and their association with magnetic anomalies becomes understandable.

ECONOMIC IMPLICATIONS OF THE RESULTS

The granites found by the gravity survey and by the sea-bottom sampling have definite economic potential. As already seen, the formation of the lode-fissures is genetically related to the granite intrusions and the mineral-bearing solutions are also closely connected with certain parts of the granites. Instead of being distributed around the actual granite bosses, the mineralisation is restricted to "emanative centres" which are not necessarily related to the form of the bosses themselves. But while it is true that not every boss was an emanative centre, the converse is always true and every emanative centre must be a granite. Therefore, the first prerequisite for mineralisation is the presence of a granite cupola. However, three possibilities need to be considered with regard to prospective mineralisation accompanying a granite cupola. In the first place there may have been no mineralisation at all, and secondly, even if there had been, the lodes may have been removed by erosion; the remaining possibility which is the most interesting, is that there are lodes waiting to be discovered.

Originally, the survey area was chosen partly because of the dense mineralisation in South West Cornwall, so that all the unexposed granites discovered in the course of the present investigations are necessarily within the mineralised belt (Fig. 3.2). Even though the existence of these granites was hitherto unknown, their associated mineralisation has been already exploited in most cases. The Leedstown-Gwinear area for instance, has always seemed peculiar in that it is richly mineralised while being at least one and a half miles away from the nearest exposed granites, and there has been much speculation as to the whereabouts of a hidden emanative centre in the region. The gravity survey has now shown the location of no less than three cupolas situated on a ridge running between Gwinear and Leedstown (Fig. 2.14), but the most prominent of them appears in an area relatively free of known lodes. The combination of favourable location with regard to proven mineralisation, together with the apparent scarcity of associated lodes in its vicinity, makes this cupola of particular interest.

The deposition of the mineral lodes around the emanative centre follows a regular pattern. At the contact with the killas, and within the granite itself tin is deposited; from the contact outwards to a distance of

about 2000 feet is the zone of copper deposition; lead/zinc may occur between 2000-4000 feet from the granite and furthest of all is the iron zone which is found from 4000-5000 feet. Thus, if the depth to the granite cupola is calculated it would be possible to assess the effect of erosion.

Fig. 3.6 shows the gravity profile over the body. It is seen from Fig. 2.14 that the granite ridge passing through Carn Brea continues into the Leedstown area, and a good physical approximation of the body would therefore be a horizontal cylinder. The depth to the surface of the cylinder may be calculated using a formula given by Nettleton (1942).

$$g = Kf(x/z)$$

where g is measured in milligals, then

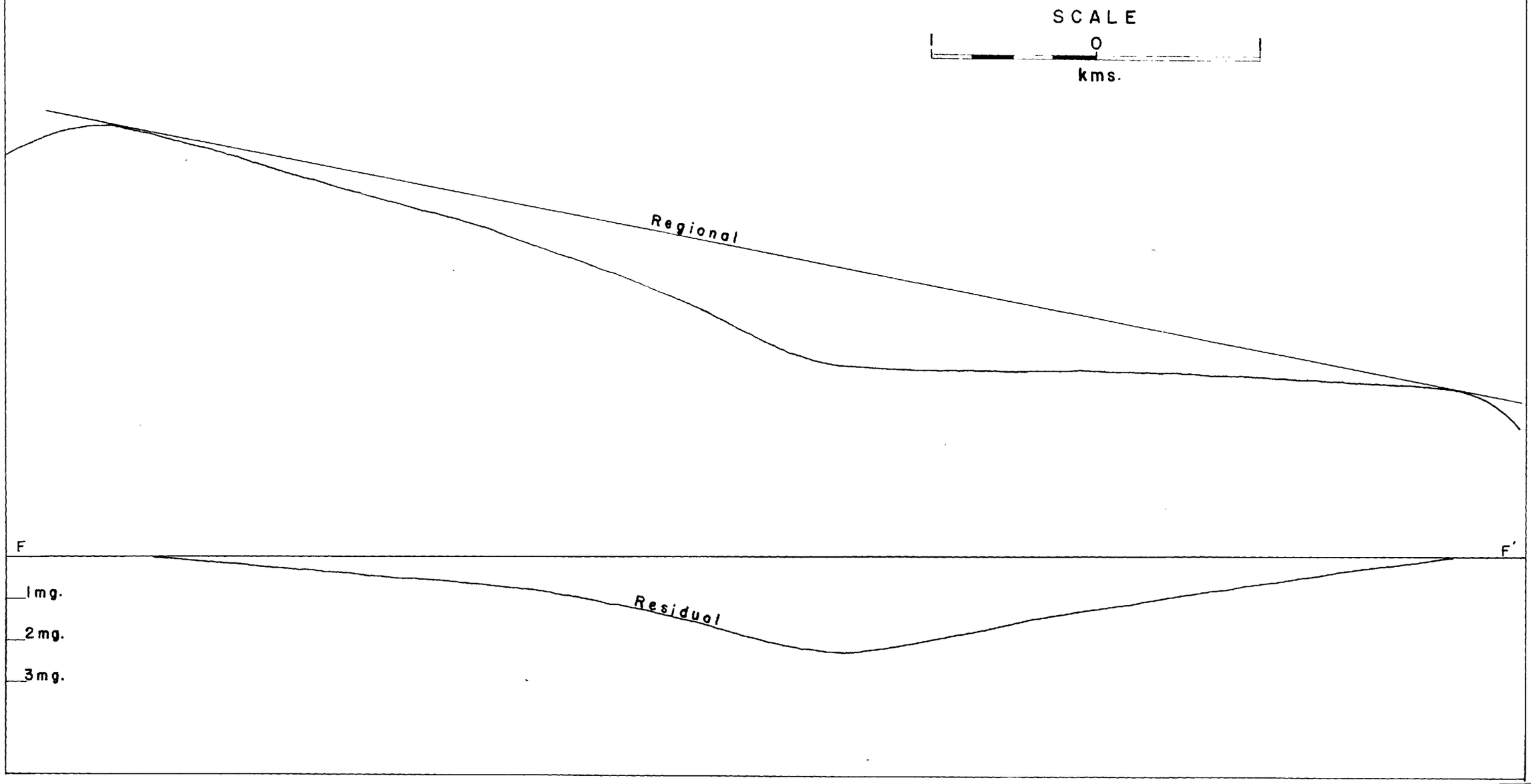
$$K = 12.77\ \delta\ R^2/z$$

where R is the radius of the cylinder in kilo-feet, z the depth to its centre in kilo-feet and δ the density. When $x = z$, $f(x/z)$ is equal to $\frac{1}{2}$ so that

$$g = \tfrac{1}{2}\ g\ \text{max} \quad \ldots\ldots\ldots\ldots (a)$$

From Fig. 3.6, $x = 1.75$ km or 1.5 km for condition (a), the curve being asymmetrical. This gives an average value of 1.63 km for z.

FIG. 3.6 INTERPRETATION OF THE GRAVITY PROFILES



The maximum gravity value is at $x = 0$ for which $f(x/z) = 1$. Thus

$$g \text{ max} = 2.3 \text{ mgal} = \frac{12.77 \delta R^2}{1.63 \times 3.2808}$$

giving $R = 0.76$ km if $\delta = 0.15$ gm/cc

Hence the depth to the highest point of the cylinder is 1.63 - 0.76 km = 0.87 km. This calculation involves making a crude approximation of the form of the anomalous body and in any case the gravity values on the profile had not been corrected for terrain effects. Nevertheless this depth estimate will be of the right order of magnitude. If the depth to the granite cupola is taken as 2700 feet, only the iron zone and part of the lead/zinc zone have been eroded, leaving most of the copper zone and all of the tin zone intact.

It is significant that the Leedstown-Gwinear district has been primarily a producer of copper and it is interesting to note that the only noteworthy producer of tin in the whole area has been one of the deepest mines - the Tremayne mine - extending to 900 feet. On the available data there is a distinct possibility of further mineralisation associated with the granite cupola west-south-west of Leedstown.

The extension of the Godolphin granite south-south-west into Mount's Bay is also of possible economic

significance, especially since the geochemical work in the bay suggested the existence of some mineralised veins trending north-west (Ong). Judging from the metamorphic grade, this granite is fairly close to the surface and much of the mineral zones may have been removed. However, as long as the granite is not itself exposed, at least part of the tin zone must be intact. In view of its position at sea, further exploration of this granite is perhaps not as attractive a proposition as the granite cupola west-south-west of Leedstown.

PART 4

Regional Problems

ORIGIN OF THE FOLDING IN SOUTH WEST ENGLAND

It has been previously shown that there is a general development of cross-structures in South West Cornwall. If now the regional area of South West England is considered, it is also found that cross-structures are of widespread occurrence.

At Porthwrinkle in South Cornwall, Dearman has described folds in lower Devonian slates plunging 40° to the west-south-west in one part of an outcrop, and 50° to east-north-east in another part. The hinges of adjacent groups of folds change direction through a right angle, while maintaining a constant axial direction. Dearman has also found two sets of folds at Lydford, Devon. The first has an axial trend varying from north-west to south-west in areas where the cleavage is flat. The second set of zig-zag folds with strain-slip cleavage trend north-east.

Between Holywell Bay and Dinas Head, North Cornwall, there are two well defined sets of folds, termed main and cross-folds by Ripley. The former trend north-east to south-west and west-north-west to east-south-east, while the latter trend north to south, but they are not as well developed.

At Boscastle, North Cornwall, Zwart found recumbent folds with axial plane schistosity; their axes have a north-north-west strike, varying from north - south to N30°W. There is another set of folds striking east to west.

Other cross-structures have been reported from South Cornwall. McKeown describes minor folds at Dodman Point with constant axial planes dipping at 50° to 130°. A second set of minor accordion folds have axial planes dipping at 80° to 130° and 80° to 40°. In the Torquay area, Richter has found minor folding with development of horizontal slaty cleavage trending east-west, and overturned to the north. Kinking of this cleavage by near vertical kink bands strike north-south.

It is clear that development of cross-structures is a very common occurrence in South West England, and its presence raises a serious problem. It is normally accepted that the direction of deformative stress is given by the

orientation of fold or fault systems. One of the principal stresses is always assumed to be necessarily vertical, because the surface of the earth with gravity perpendicular to it is by far the most important plane of discontinuity that enters into the stress fold. In the horizontal plane, the principal stress bisects the acute angle of a set of tear faults, or better still, is perpendicular to the longer axis of folding, or to the strike of the thrust planes.

As a rough approximation, the two sets of folds developed in South West England strike north-east to south-west and north-west to south-east. Thus, it may be concluded that there was principal pressure along a north-west to south-east direction as well as along a north-east to south-west direction, for it is inconceivable that a fold making an oblique angle with the major stress, would be formed unless some local factor of disturbance is present and makes the major stress deviate from its regional direction. The widespread occurrence of cross-structures makes an appeal to local disturbance unacceptable.

The problem of accepting two different directions of compression has been recognised by Dearman who stated "The reality of at least some of these superimposed

structures is beyond reasonable doubt, but the facts of two separate deformations in the slates-with-lenticles have to be reconciled with evidence for continuous sedimentation throughout Upper Devonian and Carboniferous times. If the evidence of the sediments is accepted, then all the structures in the area must have been formed towards the end of the Carboniferous period or early in the Permian period during the Hercynian mountain-building movements. On the other hand, if the structures in the slates-with-lenticles are regarded as being widely separated in time, there is evidence of Hercynian structures having been superimposed on earlier structures in Upper Devonian or very earliest Carboniferous strata. This implies an orogenic phase after the deposition of the slates-with-lenticles and before the formation of the lower Culm Measures."

There appear to be two possible choices :

1. To deny the sedimentary evidence and accept polyphase folding.

2. To accept the sedimentary evidence and attempt to derive the cross-structures from one folding.

Both alternatives have had their share of adherents.

Osman felt that there were three foldings which affected the area. The oldest was Caledonian, and this

was followed by a North and South Malvernian folding, and finally by an East and West Armorican folding.

According to Evans "... the Hercynian epoch of crustal instability was signalised by the development of strong pressure from the south or south-south-east which threw the strata into numerous over-folds, with an east-west or east-north-east to west-south-west strike, and ultimately gave rise to well marked slaty cleavage and to overthrusts....Somewhat later an east-west pressure, at right angles therefore, to the previous compression gave rise to pleating in the already highly cleaved slate."

Dewey accepted that there was folding at the close of the Carboniferous along east-west lines, and attempted to obtain two fold trends from this event, by assuming that it was modified by north-east to south-west folds in the basement caused by earlier earth movements (Caledonian).

From a study of the granite structures Ghosh felt that the regional pressure must have repeatedly varied its direction from north - south before the granite intrusion, to east-west soon after the emplacement, and back to north-south still later on. Garnett tried to explain the cross-structures in the Pendeen-Bottallack area by one period of deformation, for he was unable to find evidence to show a significant age difference between the cross-folds.

He wrote "Until further evidence to the contrary is available the writer considers that the two fold trends may be assigned to local variations in a regional stress system acting throughout a period of earth stress, and/or to overall changes of short duration in a delicately balanced stress system operating during one period."

Neither approach yielded satisfactory results. The assumption of polyphase folding immediately meets the objection that it is contrary to the sedimentary evidence, and the proponents of one deformation have been unable to suggest a mechanism whereby a north-west to south-east compression is able to produce folds in the parallel direction.

However, some confusion may be avoided, if it is realised that the existence of cross-structures is not proof of polyphase folding, for it is possible to generate a complex stress system by varying responses to the deforming force. As Campbell has shown, one period of deformation has led to the development of en echelon folding in many Australian pre-Cambrian and Palaeozoic fold systems. In an en echelon arrangement of folds, there is a parallel series of short folds, whose long axes are oblique to some major structure, such as folds of a lower order, or the trend of strike-slip faulting, or

regional cleavage. Thus in a system of en echelon folds, the folds are not perpendicular to the principal stress but are oblique to it instead. Furthermore, where there is a large difference in plunge of adjacent folds, cross-folds may develop. According to Mendelsohn, en echelon folding is also the dominant type of folding in the Roan Antelope rocks of Northern Rhodesia.

In South West England en echelon folding has not been reported but nevertheless a slight search shows that the large scale anticlines are arranged in such a fashion. The relationship is detectable because of the presence of granites within the cores of the anticlines. The granites trend generally north-east to south-west through the peninsula, but in detail this trend is broken up into a number of smaller east-west segments en echelon. The pattern is best seen on the Bouguer anomaly map of the region (Fig. 4.1) which gives the true distribution of the granite areas.

Where the en echelon east-west anticlines overlap it is possible to have development of cross-folds, if the opposing plunges of the anticline is sufficiently large. But cross-folding in South West England is not related to the regions where the major anticlines overlap. It therefore appears unlikely that the regional cross-folding is due

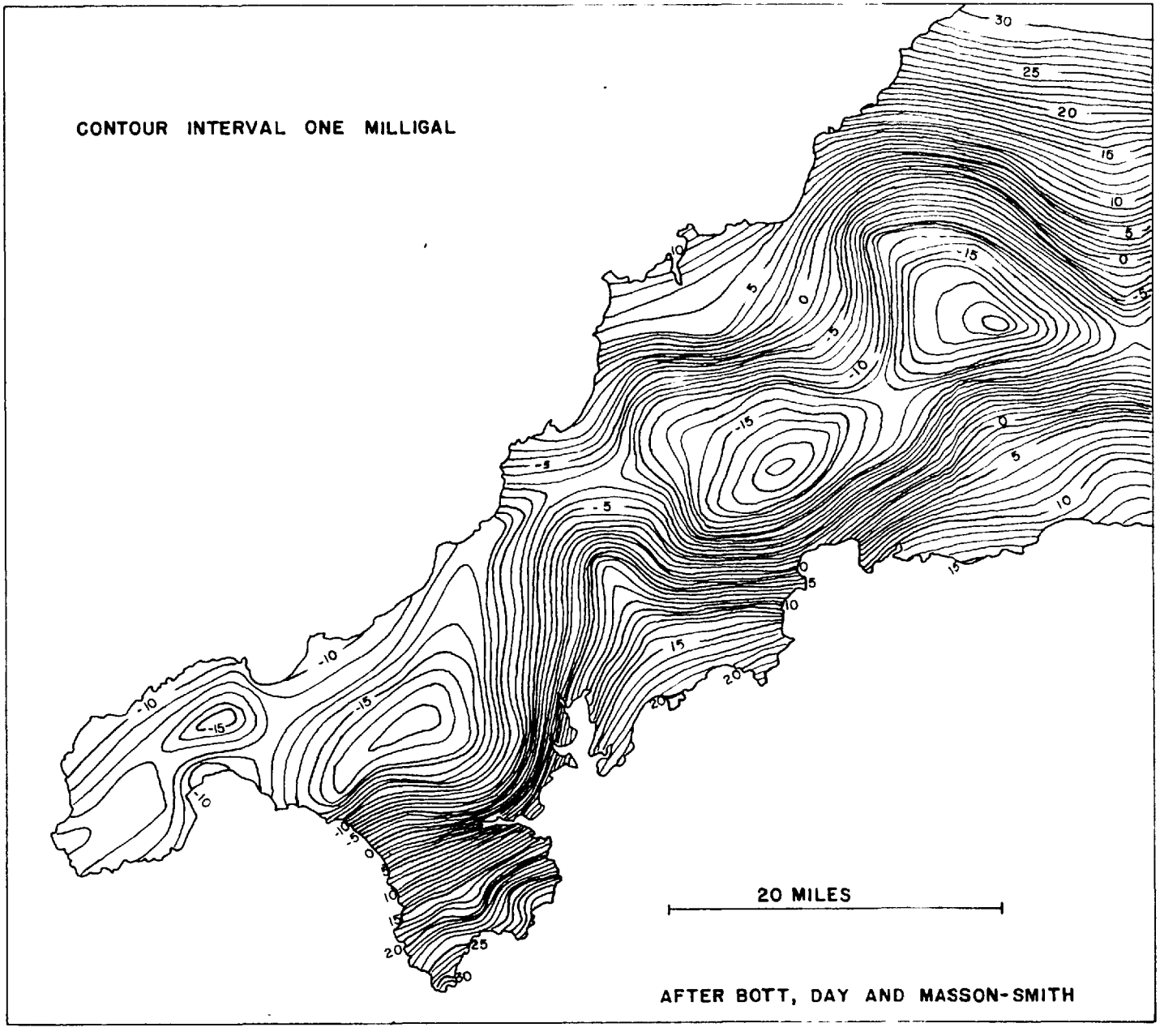


FIG. 4·1 CORNWALL GRANITE CHAIN BOUGUER ANOMALY CONTOURS

to a process similar to the one described by Campbell at Burbanks.

However, this does not disprove the possibility that the cross-structures may be due to one period of folding. In discussing the outcrop patterns produced by superimposed folds, Ramsay admitted that it is possible to confuse the effects of two superimposed deformations with the effects of just one deformation. He gave three criteria for distinguishing between the two alternatives.

a. Pattern from one deformation

1. One set of axial planes forming slight fans.
2. One cleavage or schistosity.
3. Change in fold plunge not usually large.

b. Pattern from two deformations

1. Two sets of axial planes - one with constant orientation or arranged in slight fans, the other set irregular and folded (except where the "a" lineation of the second movement lies on the axial plane of the first folds).

2. Two cleavages or crossing schistosities. The orientation of one or both of these lines may be very regular over wide areas.

3. Change in plunge of individual folds often greater than 90^{o}.

With these criteria in mind it may be possible to decide whether there is one or two phases of folding in South West England.

At Porthwrinkle, Dearman has found a strong slaty cleavage, and the fold axial planes are constant in direction, even though the hinges of the folds change direction through a right angle. The folds plunge evenly to the north-east at about 25°, but there may be local reversals of 25° to south-west. These features would suggest one deformation.

At Lydford, Dearman has described an early slaty cleavage and bedding clearly deformed by later zig-zag folding and by strain-slip cleavage. There is also a wide variation in plunge of the axes of earlier isoclines. These characters would suggest two superimposed deformations.

Between Hayle and Porthreath a slaty cleavage subparallel to bedding, trends east-north-east to west-south-west and is refolded about approximately horizontal north-east to south-west axes with axial plane strain-slip cleavage. Two late strain-slip cleavages (north-north-west to south-south-east and east-west) both occasionally with associated folding cut earlier structures. Smith's work in this area therefore indicates at least two deformations.

At Holywell, north-east to south-west and west-north-west to east-south-east folds share a common axial plane in localities where they can be seen in juxtaposition. The plunge of folds is usually less than 10° but may increase to 30° in some cases. Ripley considers that these folds are contemporaneous. At Helford River, the main folds (WSW-ENE) and the cross-folds (NW-SE) are both related to an apical plane cleavage which dips generally towards the south-east. Lambert concluded that the two systems of folds developed simultaneously.

Thus the unsatisfactory conclusion must be faced that in some localities cross-structures are contemporaneous, while at others the structures were formed during separate periods. In other areas the structures may be so complicated that it is difficult to make any valid generalisation. Several such structures were described by Zwart. At Welcombe Mouth, for instance, he found "... the occurrence of vertical folds low in the cliffs, whereas folds of the same kind, but with a horizontal axial plane, occur high in the cliffs. Far more intriguing is a beautiful, almost diamond-shaped fold exactly at Welcombe Mouth. This fold has one vertical and one horizontal axial plane and it is also of the accordion type." Zwart described another complicated structure near Steeple Point, "Again three trends of folds are to be seen : steep undeformed F1 folds, flatter and

tightened F1d folds, and recumbent F2 folds." Zwart interpreted the structures in the Carboniferous rocks from Bude to Rusey as due to two phases of folding. This view is sharply disputed by Freshney, McKeown, Williams and Dearman. These authors claim that there is a structural unity of a broad tract of country stretching from the coast as far as the margin of north-west Dartmoor. They feel that the structural pattern as a whole is consistent with one phase of folding and postulate a series of chevron folds on the limbs of a complex major anticlinal fold overturned to the south. However, as Zwart has pointed out this hypothesis cannot explain the complicated structures he found at Welcombe, at Steeple Point and at several other localities.

It is therefore apparent that both one phase or polyphase folding hypotheses need to be modified to fit the observed facts. There are only two possible choices :

1. One period of deformation gave two directions of folding, which were simultaneous in some localities, but which had a time lag in other localities.

2. Two separate periods of deformation occurred, but in some localities they were simultaneous.

Both suggestions are ridiculous, and the position becomes even more preposterous if more than two phases of folding

are inferred. Since the field data apparently leads to untenable hypotheses it could only mean that the fundamental assumptions are incorrect.

The absurdity arises because of the instinctive desire to assume that folding is caused by a horizontal compression at right angles to the trend of the folds. As stated earlier, one of the principal stresses is always vertical and it is only by taking this into consideration that the complexities of the fold systems can be explained. Nappe structures are characteristic of geosynclinal belts and they have been extremely instructive in demonstrating the role of gravity in the formation of large scale complex fold structures. Some geologists, notably Beloussov, have even gone so far as to state categorically that folding in geosynclines cannot have been produced by horizontal compression of the geosynclinal belt by pressure applied from outside. It will be shown below that if instead of thinking in terms of horizontal compression, the concept of vertical uplift is accepted, then the problem of the cross-structures in South West England is resolved.

Beloussov gave three main reasons for his conclusions.

1. Geosynclinal fold belts consist of a number of connected ovals forming the links of a chain, but various

parts of the chain have complex trends and blind ends, in which the terminal parts are surrounded on three sides by rigid parts of the crust. It is difficult to see how such terminal ends could be subjected to horizontal compression.

2. Geosynclinal belts always contain folds whose trend crosses the main trend of the folded zone. Tangential compression cannot produce folds parallel to the direction of pressure.

3. The development of folding in time moves from the axis to the periphery. If there is tangential compression the margins should be the first to fold, and the intensity of folding would be greatest there, rather than in the centre of the folded zone.

Beloussov considers the orogen to be divided into blocks by steep faults or flexures. These are of varying widths and are usually elongated along the geosynclinal zones of uplift, though they are sometimes oblique to this trend. They move upward and downwards as entire blocks and may be disposed in step fashion with respect to each other. The folds which form in the geosyncline are caused by the vertical uplift of the blocks which brings into play two factors.

There is "dynamic squeezing" out of plastic beds from the crest of the tectonic uplift into its sides by the resistance exerted by the overlying beds against the growth of uplift. The other factor is straightforward gravitational gliding.

Block structure is formed transversely across the geosyncline as well as longitudinally along the belt. Complications may arise because the uplift of the block may take place unevenly, first one side may be elevated and then the other. Moreover, at various stages the boundaries of the rising blocks may be in different positions, so that the places in which the folding occurs may also be displaced with time. An additional complication is the probability that some of the blocks repeatedly move upward and downward.

The step-like structure explains why it is impossible to find extensive zones in which the material has been displaced outward from the crests of the central uplifts. If there had been gravity sliding of the material down the smooth flanks of uplifts, this would have led to the formation of folds mainly at the feet of the slopes. The steps constitute obstacles to this flow of material acting as a succession of dams. The boundaries between the blocks control the trends of the folds, and since the block

structure is found both transversely and longitudinally to the geosyncline, two directions of gravity sliding and of dynamic squeezing will operate at right angles to each other. In some localities the two foldings will be simultaneous, but because of irregular or sporadic movement of the blocks, a later fold trend may be superimposed on an earlier set of folds in some areas.

The mechanism proposed by Beloussov, for folding in geosynclines is sufficiently complex and flexible to explain the features encountered in South West England. This alone is a strong argument in favour of predominant vertical uplift in the region, as the cause of the folding. The hypothesis is further strengthened by direct evidence indicating that South West England is divided into blocks.

1. Dearman has shown that South West England is crossed by a number of north-west trending dextral wrench-faults. The cumulative horizontal displacement from Dartmoor in the east of the region to the Scilly Isles in the west, is 21 miles. This represents a considerable displacement and it shows that the basement itself has been involved in the movement.

2. As Shearman pointed out, escarpments which trend north-west to south-east are common features of the northern and central parts of the peninsula. Some of these

face south-west, but others face north-east. This suggested to Shearman that the vertical components of Tertiary movement along the faults tended to produce a horst and graben structure, shown in the present distribution of high and low ground. Blyth also pointed out that from Dartmoor to the Scilly Isles the granite areas are at successively lower topographic levels. Thus, a longitudinal section along the axis of the peninsula shows an overall decrease in height south-westwards, accomplished in a series of drops, and may be best described as having a step-structure. Furthermore, the fact that the granites always occupy the higher ground definitely shows that there is continuing vertical movement, for the granites were emplaced at the close of the Carboniferous and it would be expected that subsequent erosion would have planed down the region. Hence, uplift of the granite areas relative to the surrounding rocks must have exceeded the rate of erosion.

Much of the movement (horizontal as well as vertical) on these faults has been dated as Tertiary, but Dearman has intimated that they originated in the Hercynian. Garnett has found horst and graben movement on a more minor scale in the Land's End granite, and Exley has described vertical movement along two fault belts in the

Bodmin Moor granite. Both Garnett and Exley concluded that the movements were of Hercynian origin.

The evidence for the existence of block structure in South West England must be coupled with the evidence for gravitational gliding.

In the Mylor beds near Porthleven, Stone has described two sets of folds. In particular, the later F2 folds have been produced by a vertical or near vertical compression acting on the steep limbs of the F1 folds. Stone suggests that "the vertical compression responsible for the formation of F2 and associated structures was caused by an increase in superincumbent load due to large scale sliding."

Near the Helford River, Lambert has shown that the main and cross-folds are both related to an apical plane cleavage which dips between 30^{o}-40^{o} south-east. He concluded "If shearing is admitted as the primary stress during the stage of deformation represented by the folds, it would follow that the stresses acted approximately at right angles to each other in main fold and cross-fold zones. It is, however, difficult to relate this stress distribution to a uni-directional regional stress. If on the other hand, the primary stress is regarded as acting normal to the apical planes of the folds, the

orientation of this stress would coincide in main fold and cross-fold zones. A regional stress acting normal to the apical planes of the folds can therefore be inferred." Since the apical plane cleavage dips at 30°-40° to the south-east the perpendicular stress direction would be 30°-40° from the vertical, indicating that it is a gravitational effect.

In the north-west Dartmoor area, Dearman and Butcher reported "The structures have been divided into four major units which show a progressive change in fold attitude from south to north. The pre-granite structural pattern over the whole area comprised recumbent zig-zag folds broken by normal strike faults parallel to the bedding in the folds." This pile of recumbent zig-zag folds is suggestive of gravity sliding, though alternative explanations may be possible. However, the ambiguity is removed by the authors themselves who stated "This variation in the structural pattern suggests that the folds were originally recumbent over the whole area, and that the emplacement of the granite lifted up the folds. As a result the characteristic structure of the Meldon Unit, namely folds overturned to the south, is really the result of the tilting to the north of the recumbent folds." The effect of the granite is not merely to tilt the folds,

for Dearman and Butcher stated "... additional slip on the northerly dipping faults is closely related to the mechanism of emplacement of the Dartmoor granite." Because of the slip on these northerly dipping strike-faults along the bedding, there is a repeated juxtaposition of the lithological series to the north of the Upper Devonian slates.

Further west, on the coast near Rusey, Freshney noted a similar "repetition of the Carboniferous sequence within its own outcrop and within that of the Devonian." This, too, has been caused by low angle north dipping faults. Dewey and Wilson had thought that these faults were localised at Boscastle, but Freshney has shown that they are a general feature of the region south of Wanson Mouth. Thus, within a belt of country from Lydford to the coast there is a regional picture of a pile of recumbent zig-zag or chevron folds, spread out by faults along the limbs. Though the large north-south elongation in the Lydford area has been attributed to slip on the northerly dipping faults brought about by the intrusion of the Dartmoor granite, in the coastal area there is no adjacent granite mass to give a similar effect. Freshney found that the ruck-fold axes do swing in trend by 30° from Wanson Mouth to Tintagel, but this could not be due to the flexing caused

by the subsequent formation of the Davidstow hemidome. Freshney concluded "It therefore seems probable that the axes are normal to original radiating transport directions. The arcuate nature of these faults and contained nappes is expressed by the swing of the repeated outcrop of the stratigraphic units around the hemidome." Thus the author expressely embraces the hypothesis of nappe structures in the area.

The view that the foldings in South West England are best explained on a hypothesis of vertical uplift, is therefore indicated because of the following reasons.

1. The hypothesis of horizontal compression of the belt leads to insuperable difficulties.

2. The hypothesis of folding produced by vertical uplift is sufficiently complex and flexible to be a suitable mechanism.

3. The South West England region does appear to be divided into fundamental blocks.

4. Gravity sliding has actually been found in several localities both to the north and south of the granite belt.

CONCLUSION

This thesis has presented data on several aspects of the geology of the Mount's Bay region. The gravity survey of the terrestrial area and the magnetic survey of the offshore area have extended and amplified some previous geophysical work. The other investigations, Echometer and Sparker surveys, sea-bottom sampling, palaeomagnetic determinations, are all standard techniques as well, but they had never before been applied to South West England. Although a great deal of information is already available, new data are always helpful to an understanding of the area, especially geophysical data which by their nature are able to give valuable pointers to the deeper structures. The results have more than fulfilled expectations and by integrating the raw data into his personal interpretation of the regional geology, the writer was able to draw some important conclusions. These touch on several of the fundamental problems of the area, including the origin of the mineral lodes, the origin of the Lizard rocks and the origin of folding in South West England. On a less controversial level there has been the discovery of several subterranean and sub-marine granites, and of cross-folding on a minor as well as on a major scale.

The study area was originally selected partly for its economic significance, and though the main import of the results has been of a purely geological nature, the commercial implications are by no means negligible.

Part of the difficulty in a study of Cornwall is the lack of correlation between particular areas. Although some localities have been studied in great detail there has been little attempt to relate results from different parts in order that a general picture of the regional geology could be recognised. Because of this the student of Cornish geology is in grave danger of being submerged in an avalanche of disconnected facts from separate areas. The writer was made keenly aware of the problem by reading through the literature and in order to give some unity to the various facets of the geology of Cornwall, it was found necessary to view the region in its geotectonic setting. In the past there has been a tendency for Cornwall to be isolated by the sea surrounding the peninsula, but it is vital to view the area as part of the Hercynian geosyncline. Its sedimentation, structure and magmatism must all be related to similar features in corresponding zones of the geosynclinal belt. Miss Hendriks appears to have been alone in realising this and she has consistently tried to relate the stratigraphy and structure

of Cornwall with those of Central Europe. Her account in 1937 of the "Rock Succession and Structure in South Cornwall" is even now more or less the official geology of that region. Some of the ideas introduced into this thesis by the writer, would also have been impossible without a firm committment to the geosynclinal concept. In particular the hypotheses concerning the origin of the Lizard rocks, and the origin of the folding in South West England, are both revolutionary in the context of Cornwall, though they have won wide acceptance in other geosynclinal settings. Their admission to the geology of South West England would have tremendous repercussions in an appraisal of the region.

There seems to be a general dearth of hypotheses concerning the fundamental geological framework of South West England. In recognition of this fact, Simpson has drawn attention to the contrast in approach between British and German geologists, "Whereas we have preferred not to put forward theories until we believed we could prove them, German geologists have put forward their theories as soon as they thought of them. This difference is one of temperament and tradition. I do not believe the one method is right and the other wrong. There is no doubt of the stimulating effect of having a working hypothesis, and so long as one's observations are

meticulously made, and so long as one is ready, as soon as evidence tells against the hypothesis, to admit the fact, good progress can be made." The prejudice against working hypotheses is summed up in the charge of "armchair geology", aimed at deflating such attempts. However, it is necessary to maintain a sense of perspective and it should be realised that both field-work and theorising have a valid function. Research in Cornwall is more than 200 years old and there is an abundance of data accumulated over the years, but this is robbed of its significance for want of a unifying principle. It is fashionable to end geological contributions with a plea for more field-work, but though this is desirable, a better understanding of the region may be obtained by interpreting existing information. The writer thinks that it would be more appropriate to plead for more theorising.

APPENDIX

COMPUTER PROGRAM FOR THE INTERPRETATION OF THE GRAVITY PROFILES

```
FUNCTION-XANOMALY(X,W,D,Y)=A
A→4
A1=XMOD(Y-X)+0.5W
A2=XSQRT(DD+A1A1)
A3=XMOD(A1-W)
A4=XSQRT(DD+A3A3)
B=XMOD(XARCTAN(A1,D)-XARCTAN(A3,D))
A=A1XLOG(A2A3/X(A1A4))+WXLOG(A4/A3)+DB
EXIT
CLOSEF

CHAPTER 0
A→48
B→48
C→48
D→48
W→48
X→48

23)I=XTAPE(0)
PUNCH(I)
JUMP24,I=27
JUMP25,I≠0
24).J=I
25).JUMP23,I≠6
JUMP23,J≠0
NEWLINE

READ(DM)
READ(N)
READ(M)
W=0
I=1(1)N
READ(AI)
BI=0
READ(WI)
XI=0.5WI+W
W=W+WI
DI=0
REPEAT
```

```
R=0
1)I=1(1)N
CI=AI-BI
DI=DI+CI/X(13.34£D7)
BI=0
REPEAT
.I=1(1)N
I=1(1)N
BJ=BJ+XANOMALY(XI,WI,DI,XJ)
REPEAT
BJ=13.34D7BJ
REPEAT
R=R+1
JUMP1,R≠M

NEWLINE
CAPTION
BLOCK    THICKNESS          ANOMALY          RESIDUAL
I=1(1)N
NEWLINE
PRINT(I)3,0
SPACE 2
PRINT(DI)0,2
SPACE 2
PRINT(BI)0,3
SPACE 2
PRINT(AI-BI)0,2
REPEAT
JUMP2,3

0)END
CLOSE


COMPILER EXCHLF
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BIBLIOGRAPHY

Aarons and Yennic, 1950, Phase distortion of acoustic pulses. J. Acous. Soc. Am., V22, No 2.

Agocs, W.B., 1951, Least squares residual anomaly determination. Geophysics, V16.

Agrell, S.O., 1939, Adinoles of Dinas Head, Cornwall. Min. Mag., V25.

Allan, T.D., 1961, A magnetic survey in the western English Channel. Quart. J. Geol. Soc. London, 117.

Anderson, E.M., 1942, "The Dynamics of Faulting."

Aubouin, J., 1965, "Geosynclines."

Balk, R., 1937, Structural behaviour of igneous rocks. Mem. Geol. Soc. Am., No 5.

Bagchi, T.C., 1947, The Geology and Petrology of the Land's End Granite and its Contacts. Unpub. Ph.D. thesis, Univ. London.

Beckman, Roberts and Luskin, 1959, Sub-bottom depth recorder. Geophysics, V24.

Beloussov, V.V., 1954, "Basic Problems in Geotectonics."

Bilibin, I.A., 1955, Provinces metallogeniques et epoques metallogeniques. Traduction 1521 de Bureau de Recherches Geologiques et Minieres.

de Blavons, P., 1933, Slope corrections for echo sounding. Int. Hydrographic Rev., V10, No 1.

Blundell, D.J., 1957, Some Geological Applications of Rock Magnetism. Unpub. Ph.D. thesis Univ. of London.

Books, K.G., 1962, Remanent magnetisation as a contributor to some aeromagnetic anomalies. Geophysics, V27.

Booth, B., 1964, Petrogenesis of the Land's End granite. Proc. Ussher Soc., V1, Pt3.

Bott, Day and Masson-Smith, 1958, The geological interpretation of gravity and magnetic surveys in Devon and Cornwall. Phil. Trans. Roy. Soc. London, Ser. A, No 992, V251.

Bott, M.H.P., 1957, A geophysical study of the granite problem. Quart. J. Geol. Soc. London, 112.

1960, The use of rapid digital computing methods for direct gravity interpretation of sedimentary basins. Geoph. J. Roy. Astron. Soc., V3.

Brammall and Harwood, 1923, The Dartmoor granite : Its mineralogy, petrology and structure. Min. Mag, V20.

1926, The Dartmoor granite : Its mineralogy, structure and petrology. Proc. Geol. Assn.

Browne, B.C. and R.I.B. Cooper, 1950, The British submarine gravity surveys of 1938 and 1946. Phil. Trans. Roy. Soc., A, No 242.

1952, Gravity measurements in the English Channel. Proc. Roy. Soc. (B), No 139.

Brunn, J.H., 1960, Mise en place et differentiation de l'association pluto-volcanique du cortege ophiolitique. Revue de Geographie, Physique et de Geologie Dynamique, 2 Serie, V3, F 1.

Bucher, W.H., 1955, Deformation in orogenic belts. Geol. Soc. Am., Special Paper 62.

Bullard, Gaskell, Harland and Kerr-Grant, 1940, Seismic investigations on the palaeozoic floor of East England. Phil. Trans. Roy. Soc. London, (A), V239.

Bullard and Mason, 1961, The magnetic field astern of a ship. Deep Sea Research, V8.

Bullerwell and Terris, 1965, Investigations into the underground structure of southern England. Adv. of Science, V22, No 98.

Busby and Richardson, 1957, The absorption of sound in sediments. Geophysics, V22.

Campbell, J.D., 1958, En echelon folding. Econ. Geol. V53.

Caulfield, D.C., 1962, Predicting some pulse shapes of underwater spark discharges. Deep Sea Research, V9.

Cook, A.H., 1950, Values of gravity at stations in southern Britain. Geoph. Suppl. to the Mon. Notices Roy. Astron. Soc., V6, No 1.

Creer, K.M., 1957, Palaeomagnetic investigations in Great Britain. Phil. Trans. Roy. Soc. London, (A), No 974.

Day, A.A., 1958, The pre-Tertiary geology of the western approaches to the English Channel. Geol. Mag., XCV.

Day, Hill, Laughton and Swallow, 1956, Seismic prospecting in the western approaches of the English Channel. Quart. J. Geol. Soc. London, 112.

Dearman, W.R., 1962 (a), Devonian and Carboniferous stratigraphy of Cornwall. Geol. Mag., 98.

1962 (b), The structure of mid-Devon and North Cornwall. Geol. Mag., 99.

1963, Wrench faulting in Cornwall and South Devon. Proc. Geol. Assn., V74, Pt 3.

Dearman, W.R., 1964 (a), A comparison of minor structures at Lydford, Devon, and Boscastle, north Cornwall. Proc. Ussher Soc., 1.

1964 (b), Stratigraphy and structure at Boscastle, Cornwall. Geol. Mag.,101.

1964 (c), Dartmoor : Its geological setting. In Dartmoor Essays, Devonshire Assoc.

1964 (d), Refolded folds in the Dartmouth slates at Porthwrinkle, South Cornwall. Proc. Ussher Soc., V1, Pt3.

Dearman and Butcher, 1959, The geology of the Devonian and Carboniferous rocks of the north-west border of the Dartmoor granite, Devonshire. Proc. Geol. Assn., V70, Pt 1.

Dearman, Freshney and McKeown, 1964, Early folds and the a-lineation at Tintagel, Cornwall. Nature 203, pp 933-935.

Dewey, H., 1925, The mineral zones of Cornwall. Proc. Geol. Assoc., V36.

1948 South West England. British Regional Geology.

Dewey and Flett, 1911, British pillow-lavas and the rocks associated with them. Geol. Mag., V 8.

De Sitter, L.V., 1964, "Structural Geology."

Dines, H.G., 1956, The metalliferous mining region of south-west England. Mem. Geol. Surv. G.B., V I and II.

Dodson, M.H., 1961, Isotopic ages from the Lizard peninsula, South Cornwall. Proc. Geol. Soc. London, No 1591.

Dodson, Miller and York, 1961, Potassium-argon ages of the Dartmoor and Shap granites using the total volume and isotopic dilution techniques of argon measurement. Nature 190, pp 800-802.

Dollar, A.J.T., 1941, The Lundy Complex : Its petrology and tectonics. Quart. J. Geol. Soc. London, VXCVII.

Emmons, W.H., 1937, "Gold Deposits of the World."

Evans, J.W., 1925, Regions of tension. Quart. J. Geol. Soc. London, V81.

1926, Regions of Compression. Quart. J. Geol.Soc. London, V82.

Ewing and Tirey, 1961, Seismic profiler. J. Geoph. Res., 66, No 9.

Exley, C.S., 1959, Magmatic differentiation and alteration in the St. Austell granite. Quart. J. Geol. Soc. London, 114.

1965, Some structural features of the Bodmin Moor granite mass. Proc. Ussher Soc., V1, Pt 4.

Falcon and Tarrant, 1951, The gravitational and magnetic exploration of parts of the Mesozoic-covered areas of South-Central England. Quart. J. Geol. Soc. London, V106.

Fajklwicz, Z.J., 1965, Fictitious anomalies of higher vertical derivatives of gravity. Geophysics, V30, No 6.

Freshney, E.C., 1965, Low-angle faulting in the Boscastle area. Proc. Ussher Soc., V1, Pt 4.

Freshney, McKeown, Williams and Dearman, 1966, Structural observations in the Bude to Tintagel area of the coast of North Cornwall, England. Geologie en Mijnbouw, 45e Jaargang.

Flett, J.S., 1946, Geology of the Lizard and Meneage. Mem. Geol. Surv. of G.B., 2nd Ed.

Fitch and Miller, 1964, The age of the paroxysmal Variscan orogeny in England. The Phanerozoic Time Scale : A Symposium, Quart. J. Geol. Soc., V120.

Garnett, R.H.T., 1962, The Geology and Mineralisation of Geevor Tin Mine, Cornwall. Unpub. Ph.D. thesis, Univ. London.

Gaucher, E., 1965, Quantitative interpretation of the 'Montagne du Sorcier' magnetic anomaly, Chibougaman, Quebec. Geophysics, V30, No 5.

Gay, S. Parker, 1963, Standard Curves for interpretation of magnetic anomalies over long tabular bodies. Geophysics, V28, No 2.

George, T.N., 1962, Devonian and Carboniferous foundations of the Variscides in north-west Europe. In Some Aspects of the Variscan Fold Belt. Ninth Inter-University Geological Congress.

Ghosh, P.K., 1934, The Carnmenellis granite : Its petrology, metamorphism and tectonics. Quart. J. Geol. Soc. London, V90.

Gignoux, M., 1955, "Stratigraphic Geology."

Goldring, R., 1962, The Bathyal lull : Upper Devonian and Lower Carboniferous sedimentation in the Variscan geosyncline. In Some Aspects of the Variscan Fold Belt. Ninth Inter-University Congr.

Graham, J.W., 1955, Evidence of polar shift since Triassic time. J. Geophy. Res., 60.

Green, R., 1960, Remanent magnetisation and the interpretation of magnetic anomalies. Geoph. Pros., V8, No 1.

Green, D.H., 1964, A re-study and re-interpretation of the Geology of the Lizard peninsula in Present Views of some aspects of the geology of Cornwall and Devon. Roy. Geol. Soc. of Cornwall.

Gulatee, B.L., 1938, Magnetic anomalies. Prof. Paper No 29, Survey of India.

Hall, D.H., 1959, Direction of polarisation determined from magnetic anomalies. J. Geoph. Res., V64, No 11.

Hall, S., 1930, The geology of the Godolphin granite. Proc. Geol. Assn., V41, (2).

Hendriks, Miss E.M.L., 1937, Rock succession and structure in South Cornwall. Quart. J. Geol. Soc. London, V93.

1939, The Start-Dodman-Lizard boundary in relation to Alpine structure in Cornwall. Trans. Roy. Geol. Soc. Cornwall, V18, Pt 1.

1959, A summary of present views on the structure of Cornwall and Devon. Geol. Mag., VXCVI, No 3.

Hess, H.H., 1955, Serpentines, orogeny and epeirogeny. Geol. Soc. Am., Special Paper 62.

Hill and Mason, 1962, Diurnal variation of the earth's magnetic field at sea. Nature, 195, pp 365-66.

Hill and Vine, 1965, A preliminary magnetic survey of the western approaches to the English Channel. Quart. J. Geol. Soc. London, V121, Pt 4.

Hosking, K.F.G., 1949, Fissure systems and mineralisation in Cornwall. Trans. Roy. Geol. Soc. London, V18, Pt 1.

1961, Primary mineralisation of the Variscan fold belt. Ninth Inter-Univ. Geol. Congress.

Hosking and Trounson, 1959, The mineral potential of Cornwall. I.M.M. Symposium, London.

Ide, Post and Fry, 1954, The propagation of underwater sound at low frequencies as a function of the acoustic properties of the bottom. U.S. Naval Res. Lab. Rep. S-2113.

Irving, E., 1964, "Palaeomagnetism."

Keunen, Ph.K., 1950, "Marine Geology."

King, W.B.R., 1954, The geological history of the English Channel. Quart. J. Geol. Soc. London, CX.

King, Lester, 1962, "The Morphology of the Earth."

Krause, D.C., 1962, The interpretation of echo sounding profiles. Int. Hydro. Rev., V39, No 1.

Kunaratnam, K., 1963, Applications of Digital Electronic Computers to Gravity and Magnetic Interpretation. Unpub. Ph.D. thesis, Univ. of London.

Lambert, J.L.M., 1959, Cross-folding on the gramscatho beds at Helford River, Cornwall. Geol. Mag., 96.

1965, A re-interpretation of the breccias in the Meneage crush zone of the Lizard boundary, south-west England. Quart. J. Geol. Soc. London, V121, Pt 3.

Lees, G.M., 1952, Foreland folding. Quart. J. Geol. Soc. London, 108.

MacAlister, D.A., 1903, A cross-section and some notes on the tin and copper deposits of Camborne. Trans. Roy. Geol. Soc. Cornwall, V12, Pt 9.

McKeown, M.C., 1962, Structural studies at Dodman Point, Cornwall. Proc. Ussher Soc. V1, Pt 1.

MacKintosh, D.M., 1966, Tectonics of the north Cornish coast, England. Geologie en Mijnbouw, Feb. 1966.

Marke, P.A.B., 1966, The Development and Use of Off-Shore mineral exploration techniques. Unpub. Ph.D. thesis, Univ. London.

Mendelsohn, F., 1959, En echelon folding. Econ. Geol. V54, pp505-515.

1958, The structure of the Roan Antelope Deposit. Bull. I.M.M., V68.

Middleton, G.V., 1960, Spilitic rocks in south-east Devonshire. Geol. Mag., V XLVII.

Moo, J., 1965, Analytical aeromagnetic interpretation. Geoph. Pros., June 1965.

Nagata, T., 1961, "Rock Magnetism."

Nettleton, L.L., 1940, "Geophysical Prospecting for Oil."

1942, Gravity and magnetic calculations. Geophysics, V7.

1954, Regionals, residuals and structures. Geophysics, V19.

Officer, C.B., 1959, Continuous seismic profiler aids marine exploration. World Oil, April 1959.

Ong, P.M., 1966, Geochemical investigations in Mount's Bay, Cornwall. Unpub. Ph.D. thesis, Univ. London.

Osman, C.W., 1928, The granites of the Scilly Isles and their relation to the Dartmoor granites. Quart. J. Geol. Soc. London, V84.

Owen, T.R., 1961, Age of the orogeny and granites in south-west England. Nature 191, p 486.

Owen, D.E., 1950, Carboniferous deposits in Cornubia. Trans. Roy. Geol..Soc. Cornwall, V18, Pt 1.

Parasnis, D.S., 1962, "Principles of Applied Geophysics."

Pekeris, C.L., 1948, Theory of porpagation of underwater sound in shallow water. Geol. Soc. Am., Mem. 27.

Phillips, F.C., 1962, The study of small.scale structures in the Variscan fold belt. In Some Aspects of the Variscan Fold Belt. Ninth inter-Univeristy Geol. Congress.

Prentice, J.E., 1962, The sedimentation history of the Carboniferous in Devon. In Some Aspects of the Variscan Fold Belt. Ninth Inter-University Geol. Congr.

Ramsay, J.G., 1962, Interference patterns produced by the superposition of folds of similar type. T. Geol., V70, No 4.

1962, The geometry and mechanism of formation of similar type folds. J. Geol., V70, p 309.

Rast and Platt, 1957, Cross-folds. Geol. Mag., V94.

Rao and Radhakrishnamurthy, 1965, Some remarks concerning residuals and derivatives. Pure and App. Geoph., V61.

Read, H.H., 1949, A contemplation of time in plutonism. Quart. J. Geol. Soc. London, V CV.

1955, Granite series in mobile belts. In The Crust of the Earth. Geol. Soc. Am. Special Paper 62.

Reid and Dewey, 1908, The origin of the pillow-lava in Cornwall. Quart. J. Geol. Soc. London, V LXIV.

Reid and Flett, 1907, Geology of Land's End. Mem. Geol. Surv. England and Wales.

Reford, M.S., 1964, Magnetic anomalies over thin sheets. Geophysics, V29, No 4.

Reynolds and Holmes, 1954, The superposition of Caledonoid folds on an older fold system in the Dalradians of Mallin Head, Co. Donegal. Geol. Mag. V91.

Richardson, W., 1923, A micrometric study of the St. Austell granite. Quart. J. Geol. Soc., V79.

Richter, D., 1965, Observations on the vulcanicity and tectonics of the Torquay area. Proc. Ussher Soc., V1, Pt 4.

Ripley, M.J., 1965, Structural studies between Holywell Bay and Dinas Head, North Cornwall. Proc. Ussher Soc., V1, Pt 4.

Robson, J., 1945, The structure of Cornwall. Trans. Roy. Geol. Soc. Conrwall, V17, Pt 5.

1948, Geology of the Land's End peninsula. Trans. Roy. Geol. Soc. Cornwall, V17, p 427.

Roy, A., 1961, Some properties of residuals and derivatives. J. Geoph. Res., 66, p 543.

1962, Ambiguity in geophysical interpretation. Geophysics, V27.

Sanders, L.D., 1955, Structural observations on the S.E. Lizard. Geol. Mag., V92.

Scrivenor, J.B., 1949, The Lizard-Start problem. Geol. Mag., 86.

Selwood, E.B., 1961, The upper Devonian and lower Carboniferous stratigraphy of Boscastle and Tintagel, Cornwall. Geol. Mag. V98.

Shor, Moore and Huckabay, 1963, Deep-sea tests of a non-explosive continuous reflection seismic system. J. Geoph. Res., V68, (5).

Shumway, G., 1960, Sound speed and absorption studies of marine sediments by a resonance method, Part 1. Geophysics, V25.

Simpson, S., 1962, Variscan orogenic phases. In Some Aspects of the Variscan Fold Belt. Ninth Inter-University Geol. Congr.

Smith, Miss M.A.P., 1965, Repeated folding between Hayle and Portreath. Proc. Ussher Soc., V1, Pt 4.

Stone, M., 1962, Vertical flattening in the Mylor beds, near Porthleven, Cornwall. Proc. Ussher Soc., V1, Pt 1.

Stone and Lambert, 1956, Shear folding in the Mylor slates near Porthleven, Cornwall. Geol. Mag., V92.

Stride, A.H., 1960, Recognition of folds and faults on rock surfaces beneath the sea. Nature, V185, p 837.

Subbarao, G., 1962, A Study of the Godolphin Granite. Unpub. Ph.D. thesis, Univ. London.

Tidmarsh, W.G., 1932, Permian lavas of Devon. Quart. J. Geol. Soc. London, V XXXVIII.

Tilley, C.E., 1935, Metasomatism associated with the greenstone-hornfelses of Kenidjack and Botallack, Cornwall. Min. Mag., V24.

Tilley and Flett, 1930, Hornfelses from Kenidjack, Cornwall. Summ. of progress for 1929, Part II, Geol. Survey of G.B.

Vacquier, Steenland, Henderson and Zietz, 1951, Interpretation of aeromagnetic maps. Geol. Soc. Am., Mem. 47.

Vincenz, S.A., 1952, Remanent Magnetism of some Igneous Rocks of Great Britain and its Geological Significance. Unpub. Ph.D. thesis, Univ. London.

Von Bubnoff, S., 1963, "Fundamentals of Geology."

Webb, J.S., 1947, The Origin of the Tin-Lodes of Cornwall. Unpub. Ph.D. thesis. Univ. London.

Weiss, L.E., 1959, Geometry of superimposed folding. Geol. Soc. Am. Bull., V70.

White, P., 1949, Gravity data obtained in Great Britain by the Anglo-American Oil Company Ltd. Quart. J. Geol. Soc. London., V CIV.

Whittard, W.F., 1961, The Geology of the English Channel. Proc. Roy. Soc. London, (A) 265.

Wilson, G., 1951, The tectonics of the Tintagel area, North Cornwall. Quart. J. Geol. Soc. London, V CVI.

Wills, L.J., 1929, "The Physiographical Evolution of Britain."

1951, "Palaeogeographical Atlas of the British Isles and Adjacent Parts of Europe."

Zwart, H.J., 1966, A reply to : Structural observations in the Bude to Tintagel area of the coast of North Cornwall, England, and Tectonics of the North Cornish coast England. Geologie en Mijnbouw, Feb.

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MAP A

INDEX MAP OF LOCALITIES

SCALE

¼ inch = 1 mile



MAP B

PART OF THE AEROMAGNETIC MAP OF S.W. ENGLAND

SCALE

$\frac{1}{4}$ inch = 1 mile

Spilite

