PERMO-CARBONIFEROUS AND LATER PRIMARY MINERALISATION OF CORNWALL AND SOUTH-WEST DEVON

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CONTENTS

I. INTRODUCTION

Although the region of Cornwall and South-West Devon is thought of by the economic geologist and mining engineer primarily as one from which large quantities of tin and copper have been won, it must be remembered that substantial amounts of other metals have also been extracted from its ores. Of these, the most important, though not in order of importance, are antimony, arsenic, bismuth, cobalt, iron, manganese, lead, nickel, silver, tungsten, uranium and zinc. In addition, it is amongst the world's major producers of china clay.

Because of limitations of space the writer has confined this paper to those primary deposits which are generally believed to be genetically related to the Permo-Carboniferous granite but which may, on occasion, have been modified to varying degrees by mineralising agents during Jurassic and Tertiary times. As the treatment only excludes a few deposits, which are all of minor economic importance, such as the veins of native copper in the Lizard serpentinites and the spilite-related manganese deposits of North-East Cornwall, it is felt that little is lost. For the same reason, oxidation and secondary sulphide enrichment phenomena and placer deposits are excluded.

II. THE GEOLOGICAL SETTING

The region under review is a peninsula with a north-east to south-west trend, which is fringed along the south-east by the Lizard, Dodman and Start Peninsulas, and from each it is separated by what are probably exposed parts of a single thrust.

Ignoring the fringing peninsulas, which lack mineral deposits of the group under consideration, the region is composed of Devonian and Carboniferous, essentially non-calcareous, intensely folded and faulted sediments (the " killas ") which are often devoid of fossils and commonly lack ' marker horizons ', and contemporaneous basic and ultra basic intrusives and effusives (collectively termed ' greenstones ') into which were intruded in Permo-Carboniferous times a granite batholith and related minor acid dykes and veins, and minettes. The greenstones tend to cluster around the exposed ' high spots ' of the granite and both are largely confined to the argillaceous rather than the arenaceous sediments. The greenstones and sediments are contact altered near the granite and this has served to make the problem of unravelling the structure of the region still more difficult—a problem which until it is solved will not permit a full understanding either of the factors which determined the disposition of the granitic rocks or of the ore-bodies which are related to them.

A phase of hypothermal mineralisation in which veins and lodes (generally steep-dipping and narrow bodies) rather than massive replacements were usually developed, commenced before the last of the granite had been emplaced. Though there are many exceptions, these bodies tend to strike approximately north-east to south-west in the western part of the region and about east to west in the eastern part.

In due course hypothermal mineralisation gave way to mesothermal. On occasion mesothermal species were deposited in late-reopened hypothermal veins and sometimes they developed along fault fissures whose strikes paralleled those of neighbouring hypothermal lodes, but more commonly they were deposited in and along faults which trend approximately at right-angles to the early lodes of the district.

During the Mesozoic it is probable that most of the region was land and at this time the higher parts of the granite were uncovered and some of the ore-bodies must have been oxidised and eroded. Miller and Mohr has shown that the phonolite of the Wolf Rock and the Epsan Shoal is of this Era (personal communication). So also is the pitchblende which occurs in north-north-east fractures which intersect an east-west copper lode at Wheal Bray, Altarnun (Darnley *et al.* 1963).

Following the Alpine disturbance much of the area was submerged and was then little more than an archipelago of essentially granite islands. It has long been suggested that incipient mineralisation occurred during the Tertiary Era (see, for example, Hill and MacAlister 1906, p. 9) and recent uraninite age determinations have established that some was, indeed, deposited then (Pockley 1963; Darnley *et al.* 1963). In addition, it is now firmly established, as a result of the work of Millar and Fitch (1962) and Dodson and Long (1962), that the Lundy Island granite is of Tertiary age (from 50 to 55 million years old). Furthermore, Dearman (1963) has recently given good reason for believing that during the Alpine orogeny north-north-westerly Armorican tensional structures were rejuvenated and converted to wrench faults on which there has been a cumulative dextral displacement of considerable magnitude which effected marked modifications of the pre-Tertiary plan-form of the batholith and of the early lode and dyke patterns. This topic will be referred to again later, but it is pertinent to state at this stage that if the faulting, which Dearman postulates, did take place, then it follows that many major channelways for ore-forming solutions were available during this time.

There is little doubt that the mineral deposits of the South-West, when considered collectively, are the products of several distinct phases of mineralisation which occurred between the emplacement of the batholith and the Eocene. Perhaps the hot chloride-rich springs which have been reported in several of the Cornish mines (Phillips and Louis 1896, pp. 201-202) are the end-products of the Tertiary phase of mineral development as, indeed, may also be the gelatinous silica and opal currently being deposited in some of the quartz veins of the kaolinised St. Austell granite. However, in view of the comparatively modest igneous actively which occurred in the region during the Mesozoic and Tertiary Eras it is, in the writer's opinion, likely that the associated phases of mineralisation were likewise unspectacular when compared with that associated with the Permo-Carboniferous granite: it is his view that the later phases were primarily ones in which mineralogical changes were made in the lodes largely by remobilisation and subsequent redeposition of earlier components rather than by the introduction of large quantities of 'new' ore components.

Geological events subsequent to the Alpine orogeny will be ignored as they are irrelevant to the present topic.

III. RELATIVE AGES OF THE GRANITIC INTRUSIVES, MINERAL DEPOSITS AND BARREN CROSSCOURSES

From the foregoing it will be apparent that the broad sequence of events is granite, acid dykes, granite pegmatites, metallised pegmatites (perhaps, more correctly, hypothermal deposits with pegmatite affinities), "normal" hypothermal deposits, mesothermal deposits of several distinct phases of mineralisation, barren quartz veins and clay-filled crosscourses. However, this is an over-simplification of the case as the following pieces of evidence (which have been dealt with comprehensively elsewhere: see Hosking 1949, pp. 9-13) serve to show:—

1. The writer (Hosking 1952) has demonstrated that pegmatites developed in the South-West before, during, and after the emplacement of the granite.

2. At Hawkswood Mine (Bodmin Moor) a porphyry dyke intersects and displacs a felspathic wolframite/arsenopyrite vein. (Hosking, unpublished studies.)

3. Collins (1912, p. 74) states that at Great Wheal Fortune (Breage) a swarm of cassiterite-bearing veinlets has been cut and displaced by a porphyry dyke.

4. Dines (1956, p. 523) figures the Castle-an-Dinas (St. Columb) wolframite lode as it appears in the No. 4 level where it is clearly penetrated by granite apophyses. Specimens of these granite tongues containing xenoliths of lode material have also been collected by the writer. (That certain lodes predate the latest granite to be emplaced in the South-West reminds one that a similar state of affairs occurs elsewhere. Thomas and MacAlister (1920, p. 94) note that "in the Zinnwald a proof of the close connection of the tin veins with the consolidation of the granite is certified by the occurrence of dykes of aplite cutting the veins.")

5. Garnett (1961) demonstrated that at Geevor Mine the 'guides' (barren, quartz-filled crosscourses) which were thought to post-date the tin-lodes entirely, developed from fractures which were in existence before any cassiterite had been deposited and exercised an important control on the development of the tin lodes. He also suggests that similar controls operated elsewhere in the South-West.

6. At South Crofty Mine the writer (Hosking, unpublished studies) has seen a quartz vein, with a strike direction approximately the same as a nearby tin lode, passing undisturbed through a barren quartz crosscourse which had displaced the lode in question. Other similar examples have recently been recorded by the mine geologist. (Mr. R. Taylor, personal communication.)

Collectively the above facts serve to emphasise the complex character of the history of mineralisation in the South-West and, at the same time, to confirm the validity of Hulin's observation (1945, p. 3) that "mineralisation (associated with major acid intrusives) ordinarily follows the igneous activity, frequently being entirely later, but occasionally overlapping in time."

IV. STRUCTURAL FEATURES OF THE LODE/DYKE/CROSSCOURSE FISSURES

Porphyry dykes, lodes and barren veins are similar in that considerable variation in length and width occurs between members of each of the three groups, they may, or may not branch and each individual may exhibit dimensional, directional, and other physical, mineralogical and chemical variations along its dip and strike.

In any given mineralised area it is usual to find a series of lodes in which most of the members strike approximately parallel to each other and to any porphyry dykes which may be present, and another later series of fissures (the crosscourses) striking along lines roughly at right-angles to the early lodes and dykes, and frequently displacing them. In certain areas the pattern is considerably more complex; thus in the Gwinear Area both N.E.—S.W. and E.—W. early lode/dyke systems occur. There is also overwhelming evidence to show that faulting has played a major role in the development of most of the lodes and all of the crosscourses. This evidence, which has been discussed in some detail in an earlier paper (Hosking 1949, pp. 9-49) is the displacement of earlier bodies by lodes, etc., the presence of fault clay and brecia in the lodes, drag phenomena (including the development of tension fractures in the hanging wall and shattering of the latter) etc.

Many of the early hypothermal lodes appear to have developed as a result of normal faulting though commonly there appears to have been a certain amount of contemporaneous lateral movement and on occasion the latter may have been dominant: in any event, le Neve Foster (1878) is of the opinion that the East Wheal Lovell tin pipes were determined by vertical openings along which mineralising agents moved, and which were formed essentially by one wall of a joint of variable strike moving laterally across the other wall.

There is also good evidence, which is given later, for believing that on occasion reverse faulting played a part in the development of certain tin lodes.

Whilst it is clear that faulting has usually played a dominant rôle in the development of the lodes some are thought to have developed in fissures which have been subject to little or no movement. Hill (1903, p. 31) has stated that some of the Wendron tin lodes show little evidence of vertical displacement of the walls, and the authors of the St. Austell and Bodmin Memoir say that the tin veins of the Beam Mine are not filled fault fissures. It seems quite likely that the comparatively narrow greisen-bordered, and other, veins could, at least on occasion, have developed as a result of replacement effected by a very tenuous mineralising agent ascending open joints. The presence of replacement veins in the granite which are characterised by the presence of bridging feldspars and which have been described by Webb (1946) and by the writer (Hosking 1952) lend support to this suggestion.

The crosscourses, which, in any given area, intersect the hypothermal lodes almost at right-angles may contain a mesothermal suite of minerals, or barren quartz or simply fault clay. Those containing fault clay are undoubtedly the last to be developed as on occasion they intersect and displace both crosscourses containing mesothermal minerals and those filled solely with quartz.

Dearman (1963) having assembled and analyzed the available data relating to the crosscourses divides these bodies initially into three groups according to whether they trend just west of north-west, slightly east of north or north-north-west. In his opinion the first two "correspond to the directions of probable pre-granite complementary wrench-faults genetically related to the regional tectonic trend, that is to folds with east-north-east axes," whilst the third direction corresponds to tension points "such as are commonly formed at right-angles to fold-axes." Invasion by the granite and the development of local cusps imparted a dip-slip component to all these fractures and some were subsequently mineralised. During the Alpine orogeny pressure along N.—S. or N.N.E.—S.S.W. lines converted the earlier tension joints to barren dextral wrench faults and, by so doing, profoundly altered the plan-shape of the batholith and the plan-pattern of the early lodes and dykes. Dearman's views will be considered further in a later section.

There is not the slightest doubt that in all the major hypothermal lode areas the history of faulting is far more complex than has generally been imagined and in many instances it is probable that normal, reverse and tear faulting all played some part in the development of the final pattern. Unfortunately, little or no attention was paid to the structural aspects of the mineral deposits when most of the mines were operating, and in any case even the elements of structural geology had not been worked out when access could be obtaind to more than a few mines: consequently data of the type required to conduct a structural analyses of the lodes, etc., of most of the mines is unavailable. However, fortunately the structural control of the mineralisation of Geevor Mine has been studied intensively by Garnett (1961) and his work amply demonstrates the complexity of the problem there and suggests that similar controls may have operated elsewhere in the South-West. Briefly Garnett believes that at Geevor the lodes and crosscourses have developed along regional fractures which pre-date the earlist phases of hypothermal mineralisation. " Between successive pairs of steeply-inclined crosscourse fissures . . . . blocks of ground moved alternatively up and down relative to one another." The longer horizontal axes of the blocks are aligned parallel to the strike of the cross-course fissures which " are mainly vertical and were subject to normal faulting. When steeply inclined in the same direction alternate fissures were subject to reverse and normal faulting."

Within the uplifted blocks, or horsts, movement took place along fractures striking about at right-angles to the crosscourses and in such a way that each block developed a horst and graben structure. These fissures were the sites of the main hypothermal mineralisation.

" Subsequent displacements along both the lodes and cross-course fissures under the same stress distribution resulted in further phases of mineralisation. The final phase, consisting of quartz, calcite, siderite, etc., occurred in conjunction with a relaxation of the stresses. A subsidence of the uplifted blocks between the lodes marked the termination of the tin-copper phases."

" After a long period of quiescence a maximum horizontal stress initiated tear faulting along the crosscourse fissures and post-mineralisation conjugate faults along newly-formed fractures . . . . Relaxation of the same stress caused infilling of the crosscourse fissures with quartz and low-temperature mineral assemblages, especially where the local strike direction deviated from the average. Some of the lodes were also affected by this final mineralization phase normally associated with the crosscourses."

That lode development arising out of the establishment of a horst and graben structure was not confined to Geevor Mine is probable: the transverse section of the East Pool and Agar Mine (Dines 1956, p. 328) certainly suggests that the structure in question occurs there.

The patterns developed by the lode/dyke, etc., systems in transverse section are made up of some or all of the following components:— Major acid intrusives, minor acid and other intrusives, mineralised and barren fissures. The variations in age, strike and dip of the mineralised and barren fissures, together with the fact that the majority, if not all, of the fissures are the product of faulting of one kind or another, and changes in the degree and type of fracturing which occur on passing from one rock unit to another, are the other major factors which have contributed to the building up of the numerous patterns found in the South-West. These are further complicated by the various mineralogical patterns which have been superimposed upon them.

It is clearly impracticable to do more than to indicate certain of the commoner patterns and motifs commonly incorporated in the more complex patterns and to give a description of the very anomalous types.

1. A system of parallel veins, each with a constant dip.

This pattern is found in the centres of some of the major granite outcrops and in the small granite crops and in both cases it probably generally arises from the preferential mineralisation of one set of joints which has been opened by faulting. Examples are to be found at Ding Dong, New Balleswidden and St. Michael's Mount. A variation of the above occurs at Cligga (near Perranporth) where a system of parallel greisen-bordered cassiterite/wolfram veins, each showing great variation in dip, has probably developed along joints parallel to the original contact which were initiated and opened as a combined result of stresses set up by contraction of the cooling granite and by gravity. (Fig. 1.)

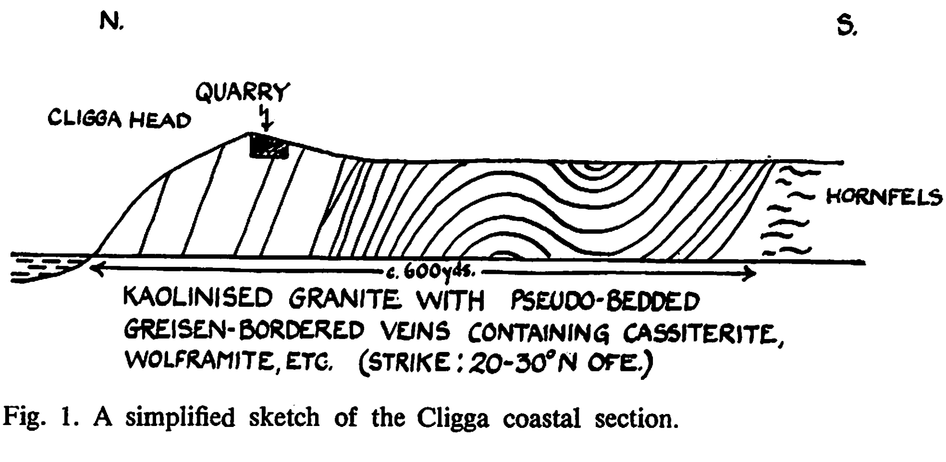

Fig. 1. A simplified sketch of the Cligga coastal section.

2. Conjugate systems.

It is probable that conjugate vein systems occur in the region. Sections of the Gwyn and Singer Mine, for example, show two systems of intersecting veins dipping in opposite directions but not displacing each other. It is also possible that where one series of veins has been displaced by another dipping in the opposite direction that the two systems may have been formed at the same time (i.e., conjugate) but that the displacement has been caused by later movement along one set only.

However, a vein may intersect an earlier one without displacing it (an excellent example can be seen, for example, at Rinsey) and so it follows that when two opposite-dipping systems of lodes intersect each other without displacement it cannot be assumed that they are conjugate unless there is no indication that the lode material of one cannot be traced through the other.

3. Intersecting systems involving displacement.

It would be pointless to attempt to enumerate the numerous patterns which can be produced when basic and acidic dykes, lodes of varying ages and dips and barren crosscourses are the units involved and when the type and degree of faulting associated with the development of the lodes and crosscourses are variable. Sufficient is it to note that all these units occur within many individual mines and the history of faulting is probably often quite as complex as that recorded at Geevor Mine. It is, however, pertinent to consider briefly the lode/dyke associations.

Commonly, the hypothermal lodes in any given area strike approximately parallel to the porphyry dykes though lack of parallelism does occur and results in intersections. Intersections may also occur as a result of differences in dip of the lodes and dykes. Normally the lodes post-date the dykes and so when an intersection occurs it is the latter which are displaced. However, on occasion the age relationship as noted earlier, is reversed. Sometimes the dyke itself has been fissured and the fissure infilled wide lode material. Thus at Wheal Basset, Paddon's Lode is largely in a dyke and Paddon's Branch entirely so. On other occasions a fissure has been opened between a wall of the dyke and the country rock and infilled with lode material. A lode occupying such a position occurs at Redmoor Mine.

A variety of structural patterns may be developed when a lode meets an acid dyke and this was made the subject of a paper by Carne (1818) who noted most of the following patterns:—

a. The lode intersects the dyke and displaces it (e.g., Tolvaddon Mine).
b. The lode on entering the dyke shows no change (e.g., Weeth Copper Mine, Gwinear).
c. The lode, on intersecting the dyke, splits up into a few or numerous veins which are possibly controlled by the joints of the dyke, and these reunite on leaving the igneous body (e.g., Crenver and Abraham Mine).
d. The lode diminishes in width and value on passing through the dyke (e.g., Carn Brea and Rosewall Hill Mines).
e. The lode increases in width and value on passing into the dyke (e.g., Wheal Alfred).
f. The lode, on entering the dyke, increases in size and value and also sends off numerous small veinlets (e.g., Wheal Vor).

g. The lode, on reaching the dyke, is deflected so that it strikes parallel to the latter for a number of feet before passing through the igneous body and assuming its normal strike (e.g., Geevor Mine). By so doing the lode may appear to be faulted by the dyke.

Virtually all that has been written above concerning lode/acid dyke patterns applies equally well to lode/greenstone patterns although the latter have never been the subject of a paper.

4. Stockworks and closely-related bodies.

Small stockworks may develop in the hanging walls of lodes as a result of intense fracturing of the latter due to drag as they descend during normal faulting. That which occurred in the fissile arenaceous slate hanging wall of the Towanroth Lode at Wheal Coates, St. Agnes, is a typical example.

Large and economically important stockworks, and structures which though somewhat similar to the former differ from them in that the multitude of veins tend to possess a common strike direction, and which may therefore be called 'closely-sheeted bodies,' may develop by processes to be discussed later in country rock immediately overlying elevated cusps and in the apices of the cusps themselves.

An example of a true stockwork is that of the Fatwork Opencast Mine, near Indian Queens, Here a zone of tourmalinised slate hornfels, about 15 fathoms wide, and striking E—W., is penetrated by a host of short veins containing cassiterite, quartz and tourmaline which are also frequently observed traversing the rock in various directions.

An example of a closely-sheeted structure occurring in slate is to be found at Mulberry, Lanivet, whilst the swarm of parallel, greisen-bordered cassiterite- and wolframite- bearing veins of St. Michael's Mount is an example of one located in the apex of a granite cusp.

Stockworks and closely-sheeted bodies occurring in porphyry dykes have been worked in Cornwall. These have sometimes been formed as a result of the intersection of a dyke by a lode (as at Wheal Vor), but on other occasions (as at Wheal Jennings) (or Parbola) it appears that the dyke, having been shattered, was itself the channel-way for the mineralising solutions. At Wheal Jennings numerous cassiterite-bearing branches, striking mainly in one direction, die out almost immediately on passing out of the dyke into the killas.

V SPATIAL RELATIONSHIPS BETWEEN THE BATHOLITH, PORPHYRY DYKES, LODES, CENTRES OF MINERALISATION AND CROSSCOURSES

In this section it is proposed to describe the regional plan-patterns of the lodes, dykes, crosscourses, the centres of mineralisation and the intensity of mineralisation, then to consider the form of the batholith and the nature of its surface, and finally to discuss, in general terms, how these patterns may have developed.

1. The plan-pattern of the lodes, dykes and crosscourses.

Dewey (1948, Fig. 13) produced a map of South-West England on which a diagonal band about 10 miles wide is drawn: this purports to represent the mineralised zone of the region. The figure, however, is quite misleading as it does not indicate the true lode and associated dyke distribution pattern.

In order to appreciate the pattern in question a map (Fig. 2) has been included on which granite outcrops, metamorphic aureoles, lodes and crosscourses are indicated, and the following points emerge from a perusal of it and, in certain instances, of more detailed lode-maps in addition:—

a. In many mineralised areas a set of hypothermal lodes are associated with dykes whose strikes parallel those of the lodes. These are commonly intersected and displaced by crosscourses, which may be mineralised or barren, and whose strikes differ from those of the earlier lodes and dykes by about 90°. On occasion, however, the strikes of one or more of the hypothermal lodes of a given area may depart appreciably from the strike of the majority of their neighbours. Such lodes with anomalous strikes (the caunter lodes) are of a later age than those with which they are closely associated. The Reeves Lode of South Crofty Mine is a typical example: it intersects certain of the lodes with normal strikes and differs appreciably from them from a mineralogical point of view.

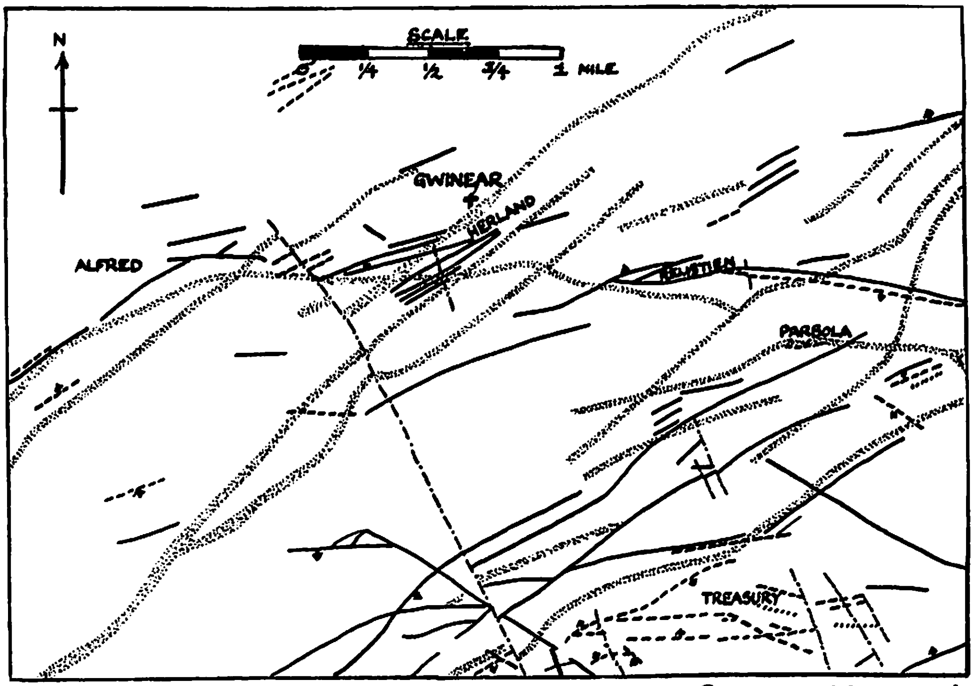

Fig. 3. Sketch map of a part of the Gwinear Area. Lodes full and broken lines: dykes stippled. (Reproduced from H. G. Dines' *The Metalliferous Mining Region of South-West England*, Vol. 1. Pub. H.M.S.O. London, 1956).

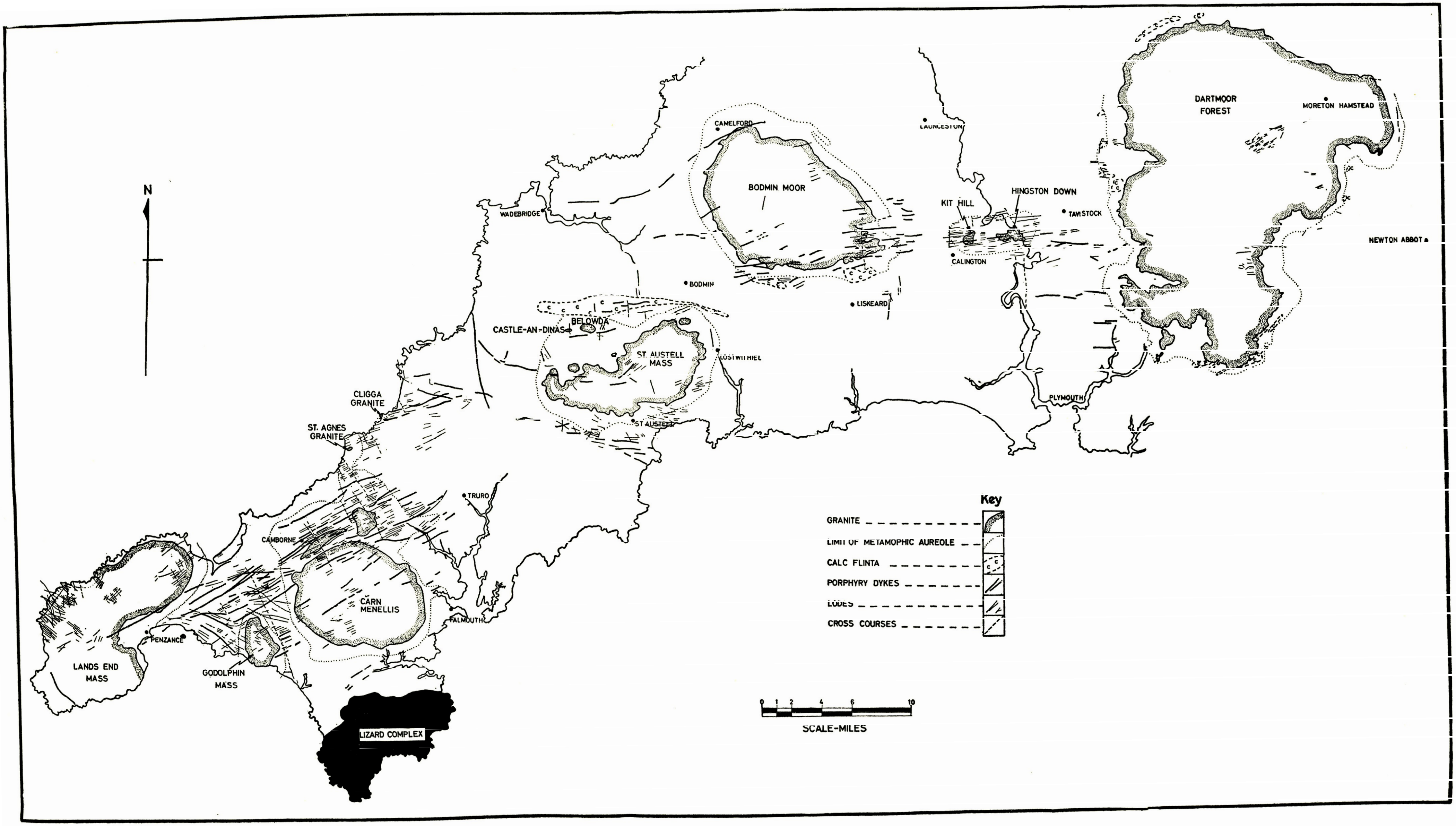

Fig. 2. Map of South-West England showing the distribution of the granite outcrops, metamorphic aureoles, lodes and dykes.

b. In certain areas two or more sets of hypothermal lodes occur with markedly different strikes: typical examples are the lode groups of Ding Dong (Land's End), Birch Tor/Vitifer (Dartmoor) and the Gwinear Area (where, as noted earlier, there are also dykes which strike in the same directions as each major set of lodes). (See Fig. 3.)

c. To the north of the St. Austell granite there are a number of hypothermal lodes which possess an anomalous, approximately north to south strike. The most notable of these is the wolframite/loellingite lode of Castle-an-Dinas. Others are the tin-bearing veinlets of the Mulberry ore-body, the Rock Hill lode, and the 'leader' of Park of Mines. In addition, the same general area contains the Watergate Bay porphyry dyke which also has an anomalous near north to south strike. It is probable that all these are closely related and developed comparatively early.

d. The lode/dyke pattern of the Land's End granite is also anomalous, so far as the South-West is concerned, in that it is crudely radial. In addition, the north-west to south-east striking swarm of branching veins of the Geevor/Levant area (which, as noted earlier, is characterised by a complex history of development) possesses a lenticular-net pattern, which can only be really appreciated when a detailed plan of the lodes is inspected.

e. Many of the dykes and lodes are near the granite/killas junction, and comparatively few occur near the centres of the larger granite outcrops. Although the shallowness of the lodes near the granite centres suggests that erosion may account for the general paucity of lodes there, it is believed that another more important control is involved which will be discussed later.

f. Certain marginal portions of the granite outcrops are devoid of lodes.

g. Vein-swarms occupy the apices of granite cusps (as at Cligga, St. Michael's Mount and Kit Hill) and also occur in the killas (as at Mulberry, Wheal Music and Wheal Fortune).

h. Many dykes and certain associated and approximately parallel hypothermal lodes are several miles from outcropping granite. This is true, for example, of some of the dykes and tin-bearing lodes of the Gwinear and Perranporth districts.

i. Often the distribution pattern of dykes and hypothermal lodes bears little or no obvious relationship to the shape in plan of the nearest outcropping granite. The Carn Brea area constitutes a notable exception: there the lodes and dykes strike approximately parallel to the long axis of the granite ridge.

j. Throughout the region, marked 'streams' of lodes and dykes occur. Thus, in the coastal strip between the Land's End and the Godolphin granites, a series of lodes and dykes swings round in an arc which is approximately parallel to the coastline. Another 'stream' flows across the southern margin of the Bodmin Moor granite, and thence via the granite cusps of Kit Hill and Hingston Downs, to Dartmoor. Other 'streams' are equally obvious on the map.

k. Finally, there is an approximate parallelism between the hypothermal lode/dyke streams and those portions of the arcuate Lizard/Dodman/Start thrust to which they are adjacent. On the other hand, the crosscourses are, when projected, approximately normal to the tangents of this thrust.

In addition to the relationships noted above it must be noted that, generally speaking, the strike of the hypothermal lodes tends to be coincident with one set of major joints in the granite, whilst the strike of the crosscourses does not depart far from that of a second set of major joints and from the fluxion in the granites (as indicated by the alignment of the feldspar crystals).

2. The centres of mineralisation pattern.

Fig. 4 is a plot of the tin fields of the south-west exactly as Dinas (1956, pp. 12-13) plotted them, and in addition, two series of lines have been drawn, one with an approximate north-east to south-west strike and the other with an east to west strike, through the centres of all the *small* tin areas. (The strike directions were chosen because they approximate to the two commonest lode trends in the region and the 'base lines' were drawn through the centres of the smallest tin fields because these points must be approximately coincident with the emanative centres of these areas. The positions of the emanative centres of the large tin-bearing areas are far less certain and in addition each of the large areas were probably fed from a number of sources.)

Many of the lines which have been drawn pass through several other tin areas, and this immediately suggests that the positions of these areas were determined by a set of controls which operated in the same way throughout the whole region.

It is convenient to delay further discussion of this pattern until later but it is pertinent to state now that in many cases it can be demonstrated that emanative centres are associated with fairly small, though pronounced, granite cusps which are often 'crowned' with swarms of small greisen-bordered cassiterite/wolframite veins. It would not be unreasonable to believe that when an emanative centre developed it was invariably in the vicinity of a cusp. However, erosion will have removed some of the cusps, and others such as those which must surely exist in the Gwinear area have never been exposed. The Kit Hill, Hingston Downs, St. Agnes, Cligga, and Carn Brea areas are all excellent examples of the association of emanative centres with granite cusps. It is also probable that a number of what perhaps may be termed 'secondary emanative centres' may occur in the vicinity of a single major cusp and these may be associated with secondary cusps. Thus at South Crofty Mine in the Complex Lode area of Robinson's Section and again in the so-called 3A, B and C lode zone there is a series of early flat-dipping felspathic wolframite-bearing veins with which are associated a number of later, rich, much steeper, cassiterite lodes. In the writer's opinion each of these rich areas marks the site of a secondary emanative centre which may be sited over a late granite cusp which has been emplaced within the earlier granite. This remains to be demonstrated, but because the Carn Brea/Carnmenellis mass is almost certainly a polyphase intrusive the above suggestion appears likely, and it also permits a reason to be put forward later as to why intense local fracturing should take place well inside the granite/killas contact.

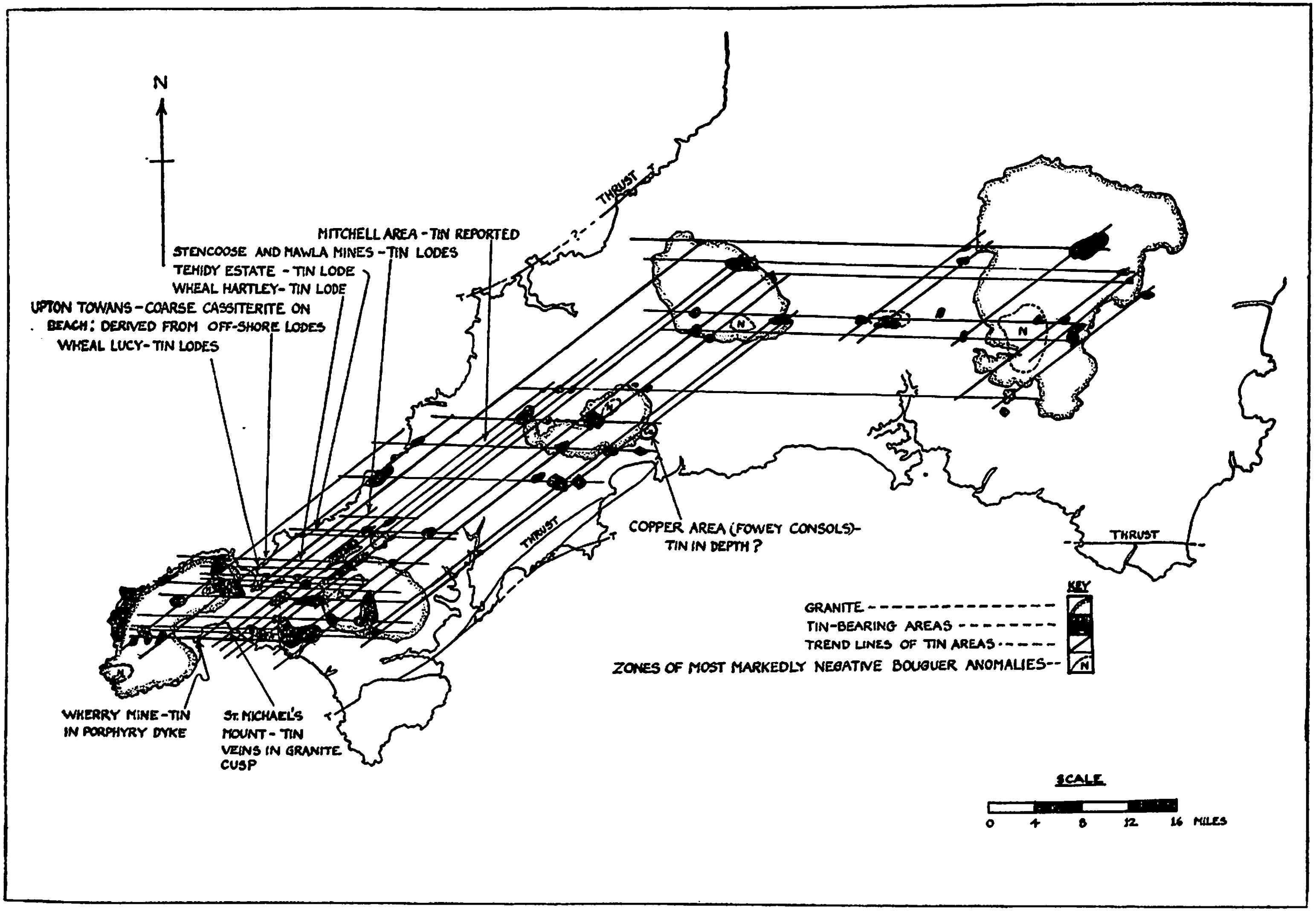

Fig. 4. Map showing the distribution pattern of the tin-bearing areas and of the zones of biggest negative Bouguer anomalies. The material on which this map is, in part, based, has been derived from Dines (1956, Figs. 3a and 3b) and from Bott, Day and Masson-Smith (1958, Fig. 2).

3. The intensity of mineralisation pattern.

Hypothermal mineralisation is most intense in the Godolphin/Carn Brea/Carn Marth/St. Agnes zone and decreases progressively to the south-west and north-east, so that on the Scilly Isles greisen-bordered veins and a solitary cassiterite-bearing veinlet are the nearest approach to lodes, whilst on the eastern fringes of Dartmoor hypothermal lodes are few in number and neither large nor rich. This distribution pattern, in which the most intense hypothermal mineralisation is roughly coincident with the centre of a large elongate granite mass can be matched elsewhere. If the lenticular mass of granite underlying Malaya is regarded as a single unit which happens to be joined to a similar unit which forms the backbone of Siam, then the distribution of tin with respect to the Malayan 'batholith' is remarkably similar to that occurring in the south-west. In Malaya the most intense tin mineralisation is within the centrally disposed Ipoh/Kuala Lumpur/Pahang Consolidated Mine triangle. The Kinta Valley deposits, lying approximately between Ipoh and Kuala Lumpur are equivalent to the Carn Brea/Carnmenellis/Godolphin fields, whilst the rich deposits in the vicinity of Pahang Consolidated Mine may be equated spatially with those of the St. Agnes area. The less intensely tin-mineralised areas of Kedah (to the north) and Johore (to the south) correspond to the St. Austell/Bodmin/Dartmoor and Land's End areas respectively.

The mesothermal intensity of mineralisation pattern is distinctly different from the hypothermal one. Although mesothermal veins are widespread they are usually comparatively small and sub-economic and the major lead areas are Newlyn East, the Perran Iron Lode district, Menheniot, the Tamar and the Teign Valley areas. Precisely why this lack of coincidence between the two patterns occurs is unknown though it could be used as a piece of evidence in favour of the theory that the hypothermal mineralisation is genetically related to the Permo-Carboniferous granite whilst the major part, at least, of the mesothermal mineralisation is related to the later Jurassic and/or Tertiary igneous phases.

4. The plan-form of the batholith.

It has long been thought that the exposed granite masses of the south-west are but portions of a single batholith which extends from the Scilly Isles to Dartmoor and which is a polyphase intrusive whose history of development is very complex and still only partly unravelled.

Consideration of the spatial relationships likely to exist between hypothermal lodes, porphyry dykes, etc., and the parent granite led the writer (Hosking, 1949 and Hosking and Trounson 1959) to postulate that the batholith possessed the crudely arcuate plan-shape shown in Fig. 5. Subsequently Bott and his co-workers (1958) established the form of the batholith by geophysical methods and showed that it differed but little from that postulated earlier by the present writer.

As noted earlier, Dearman (1963) has assembled strong evidence which indicates that the original plan-form of the batholith, together with the original regional plan patterns of the early lodes and dykes, were considerably modified

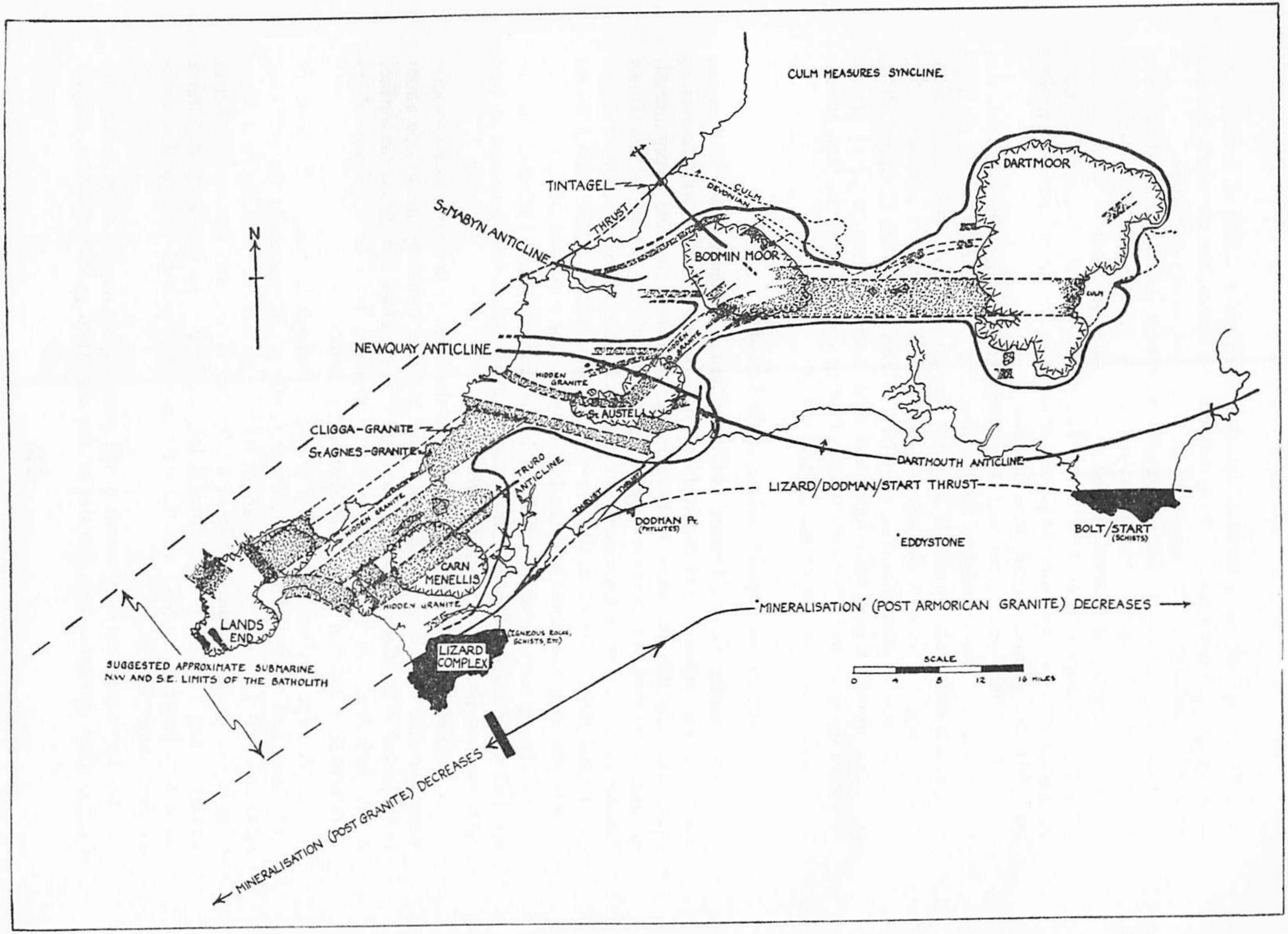

Fig. 5. Map of South-West England showing the postulated form of the batholith, the assumed positions of granite ridges, etc.

in mid-Tertiary times as a result of the development of a system of wrench faults along Armorican north-north-westerly tensional structures, and on which there has been a " cumulative dextral displacement of at least twenty-one miles."

Dearman assessed the effects of this dextral wrench faulting by " first extending the inferred and mapped lines of faulting across the map and then, starting at Land's End, applying a sinistral shift at each fault sufficient to bring adjacent outcrop boundaries into coincidence." This reconstruction eliminates the curve from the axis of the batholith and places the southern margins of the Bodmin Moor and Dartmoor granites in the same latitude.

The present writer agrees with Dearman's general thesis but considers that the magnitude of the cumulative displacement may well be far removed from the truth as a considerable amount of the early data on which he has based his work, must be suspect. He also disagrees completely with Dearman's assertion (p.282) that as a result of the removal of the effects of Tertiary wrench faulting " all the postulated granite ridges, early lodes and dykes connecting the exposed granites now have the same trend ": surely wrench faulting simply altered the plan position of the lodes, etc., without changing their strikes.

5. The nature of the original surface of the batholith.

In an earlier paper (Hosking 1949) the writer contended that the original surface of the batholith was characterised by a series of ridges with undulating crest lines and that the early lodes and dykes generally trended approximately parallel to the long axes of these ridges. The centres of early mineralisation (Dines' emanative centres) were associated with the ' high spots ' (cusps) on these ridges.

Considerable evidence in support of the original nature of the surface of the granite was then assembled and the following is only a portion of it.

a. The gravity survey of Bott and his co-workers (1958) indicated that the Kit Hill and Hingston Downs granite cusps are the high spots of an east to west ridge between Bodmin Moor and Dartmoor.

b. Flanking the Carnmenellis granite to the north is the north-east to south-west orientated Carn Brea granite mass. This has been shown by mining operations to be joined to the Carnmenellis granite and it is therefore a ridge on the surface of the batholith, which unlike those which originally lay over the centre of the Carnmenellis mass, has escaped destruction by erosion.

c. A ridge has been shown by mining operations to exist to the north of Carn Brea and Carn Entral. MacAlister (1903, p.774) has made the following remarks about it:— " The subterranean ridge of granite seen at Camborne Vean mine is also found at Dolcoath, South Crofty, East Pool, and, presumably, Wheal Tehidy, along a line bearing approximately E. 30°N. In nearly all its course the hollow between the ridge and the main mass is associated with parallel elvan dykes or lodes (Fig. 6).

d. The shape and large extent of the metamorphic aureole of St. Agnes and Cligga, when compared with the size of the associated granite outcrops, suggest

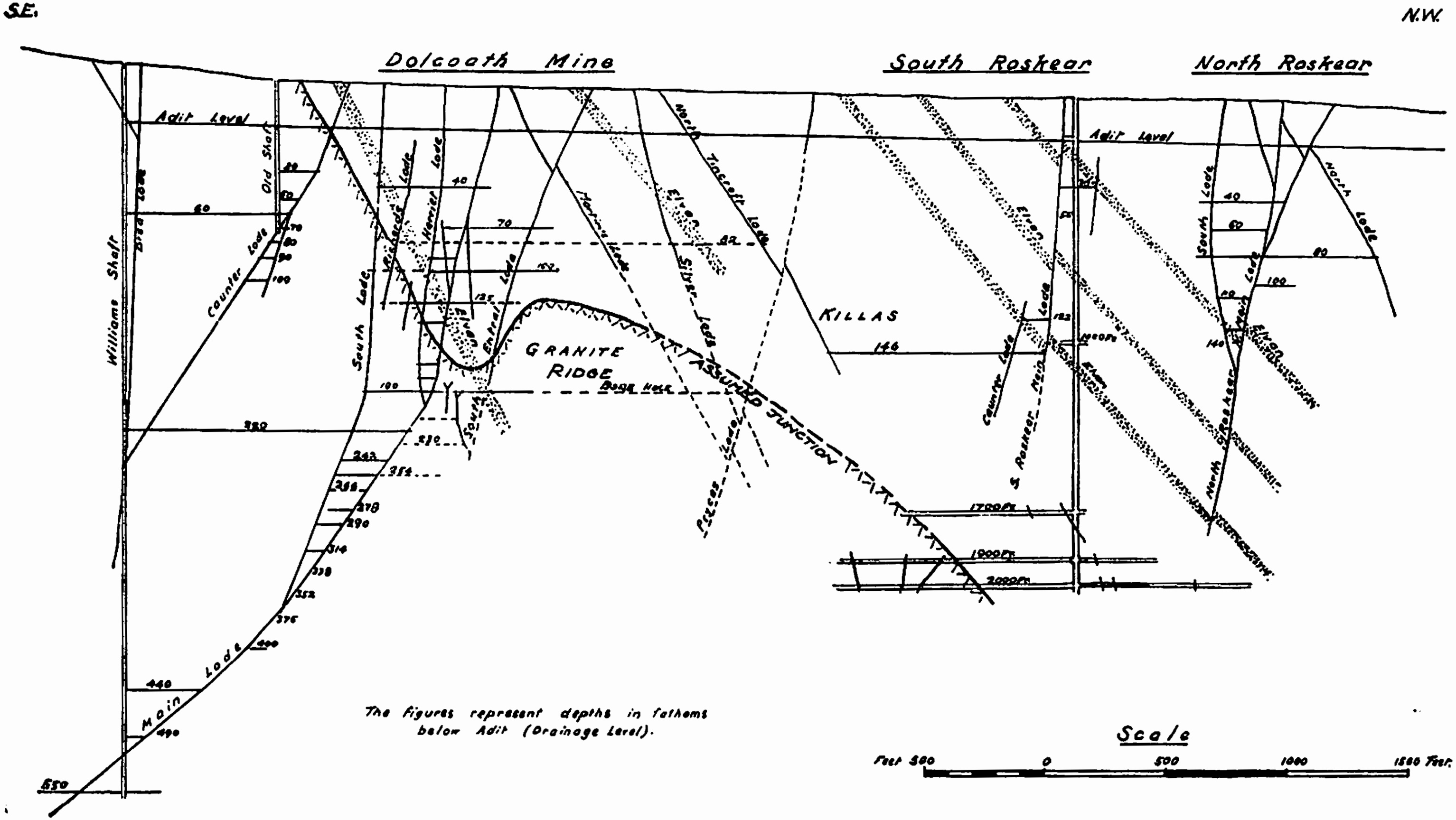

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Fig. 6. A section across the lodes of Dolcoath and the Roskear Mines. Based on sections by H. V. Thomas (Surveyor of Dolcoath Mine Ltd.) and by Davison (1929).

that the intrusive rock extends to the north at comparatively shallow depths. This is largely confirmed by the fact that cassiterite has been recovered from lodes in the sand-dune area to the north of Perranporth and at a distance of two and a half miles from Cligga—the nearest granite outcrop.

6. A tentative general history of development of the granite/dyke/lode/crosscourse patterns.

Because much is still unknown concerning the geology of Cornwall the following tentative general history of the development of the granite/dyke/lode/crosscourse patterns may well need to be substantially modified in the future: it will, however, have been worth writing if it does nothing more than emphasise the fact that much work still remains to be done before a really satisfactory history can be written.

It seems difficult to escape from the conclusion that the earlier rocks of the region were laid down in a geosyncline with a north-east to south-west strike and that the forces which carried the sides of the trough towards each other were responsible for the development of folds with north-east to south-west axes, for thrusts striking parallel to these folds and for certain wrench faults and tension fractures whose strike directions (as indicated earlier) varied between W.N.W.—E.S.E. and N.N.E.—S.S.W. It is also likely that on one or two occasions between Upper Devonian and, say, Middle Carboniferous times, folds and thrusts were developed with approximately east-west trends, as a result of approximately north to south directed forces, throughout the whole of the region north of the Lizard, Dodman and Start Peninsulas, and concurrently dextral wrench faults were developed along planes striking between N.W.—S.E. and N.N.W.—S.S.E. and which included earlier tension fractures which were rejuvenated. (This is contrary to Dearman's conclusion that wrench faulting did not take place along these lines until Tertiary times).

Following a general uplift of the geosynclinal deposits the region was invaded by a granite magma which was, in the writer's opinion, confined between two parallel thrusts. The southerly one is the Lizard/Dodman/Start thrust which may, as Dearman suggests (*op. cit.*, p. 282) have been considerably less arcuate than it now is, and the northerly one is that which extends through the Tintagel area. (The work of Bott and others (*op. cit.*) indicates that the south-east edge of the granite batholith is roughly parallel to, and broadly speaking bounded by, the Lizard/Dodman/Start thrust line, and it was this fact which suggested that its north-west edge might also be parallel to, and near, another thrust, and led to the tentative suggestion (Hosking 1962, p. 147) that a south-west extension of the Tintagel thrust might in fact be the boundary. In this connection it is pertinent to note that the Scilly Isles are immediately to the south of this extension.)

Bott and his co-workers (1958) conclude, as a result of their geophysical investigations, that the batholith has an irregular upper surface and that it developed from magmas which rose vertically in the south and then flowed north: in consequence it possesses an inverted L - shaped cross section with a very steep southern limb. These conclusions are supported by Exley's compositional studies of the south-western granites (1961) and by the writer's observation of a granite tongue locally fringing the north-western flank of the Carn Brea granite (Hosking 1962, p.148).

The work of Ghosh (1934) indicates that the Carn Menellis mass is a polyphase intrusive and this alone suggests that the batholith as a whole is one. However, the number of intrusive phases is still in doubt but studies of the minor and trace-element content of many granite samples from Carnmenellis (Hosking, K. F. G., Roberts, A. and Usman Hamid, unpublished studies) and of hundreds of stream-sediment samples from the same area (Hosking, K. F. G., Hosking, J. A. and Thomas, B. G., unpublished studies) give strong reason for believing that there the various phases are orientated along north-east to south-west lines (parallel to the dykes and hypothermal lodes) and that the crude ring structure which was suggested by Ghosh does not exist. (Fig. 7, which indicates the distribution of phosphorus in the minus-80-mesh (B.S.S.) fraction of the stream sediments, serves to show the north-east to south-west pattern which characterises the distribution of many elements in both the hard rock and sediments of the area, particularly in the lode-free south-east quarter).

In the writer's opinion the invaded folded sedimentary rocks acted as moulds for the ascending magma and impressed a series of approximately north-east to south-west and east to west ridges on the granite. Where the invaded rocks were domed as a result of the two fold systems intersecting, a granite cusp developed. Undoubtedly the mould was distorted to varying degrees by the ascending magmas, and it is reasonable to believe that the already developed wrench faults and tension fractures in the sediments had, as Dearman suggests (*op. cit.*, p. 280) a dip-slip component imparted to them, and, of course, their presence facilitated mould distortion.

The fact that cusps and centres of mineralisation occur at the intersections of certain north-east to south-west and east to west lines when the data are plotted on a comparatively small scale, and when any displacements due to post-lode faulting are ignored, suggests that the original pattern approximated to the present one, at least from the Land's End to the eastern margin of the Bodmin Moor. (The effect of working on a small scale, combined with the fact that a given line would, under any circumstances, intersect the larger tin-fields even if the latter were considerably displaced by Tertiary faulting, serve to minimise, on the map, the effect of distortion due to late movement and so permit the original pattern to be revealed.)

To the east of the Bodmin Moor it may be, as Dearman claims, that in pre-Tertiary times the Kit Hill/Hingston Downs ridge was east of the northern third of the Bodmin Moor granite and that the southern margin of the Dartmoor granite was in the same latitude as the southern margin of Bodmin Moor. Such changes do, of course, alter the original centre of mineralisation pattern appreciably in the north-east of the region but they do not necessitate a revision of the basic design unit, that is one in which cusps (and associated emanative centres) occur at the intersections of approximately north-east to south-west and east to west lines.

During the emplacement of the granite phases volatile-rich fractions collected in structural traps, as at Porthmeor (Zennor), and this resulted in the development of roof pegmatites which are small, mineralogically simple, and of no economic importance. Locally, also, the magma opened up joints and other planes of weakness in the adjacent hornfels thus causing the development of a series of apophyses which display internally complex patterns composed of normal-granitic, aplitic and pegmatitic units, and which, clearly, are characterised by a complex history of development. Minor 'granitic' bodies (aplitic, pegmatitic, quartz, tourmaline veins, etc.) were developed during and after each major granite 'invasion wave'.

Generally following the emplacement of the last of the granite magma, and after its superficial portions had consolidated, porphyry dykes were locally developed along the flanks of certain approximately north to south striking granite tongues, but more particularly along the north-east to south-west and east to west ridges. The Watergate Bay dyke, with its anomalous near north to south strike, may well have been formed particularly early as its strike parallels that of certain nearby lodes which are undoubtedly early. A dyke at Tremearne is also early as it is locally invaded by 'normal' granite apophyses. Locally, also, more than one generation of dykes may occur: certainly the mine plans of Polgooth suggest that one dyke pre-dates and another post-dates the tin lodes there. At Hawkswood Mine (as noted earlier) the porphyry dyke displaces an early wolframite-bearing lode.

Probably at a comparatively early stage small, isolated pockets of residuum collected in the granite cusps during their crystallisation, and concomitant with this process a gas pressure built up beneath their hoods to such an extent that it was locally capable of rupturing the hoods and overlying rock. (This is in accordance with the views of Emmons (1940, pp. 190-193 and 231-232.) The fracture patterns thus produced were, of course, also determined by the magnitude and directions of the regional stresses, as well as by inherent-planes of weakness (such as those due to contraction) in the affected rock units. However, the strikes of these early fractures are essentially the same as those of later developed, spatially closely related, major hypothermal lodes, so that regional stresses must have played a major rôle in their development.

Slumping under gravity, contraction, and lateral movements may all have combined to open these fractures sufficiently for the tenuous residuum fractions to move along them and to effect the development of swarms of greisen-bordered veins in the apices of the cusps or of mineralogically similar swarms in the rocks immediately overlying these granitic bodies. However, it is clear that the amount of adjustment needed to produce adequate channels for these mineralising agents was very small. Commonly, as noted earlier, the walls of greisen-bordered veins show no evidence of relative movement and during the present diamond-drilling of the Cligga area greisenised 'mineralised' zones have been intersected which are associated with nothing more than incipient micro-fractures (Hosking, unpublished studies.)

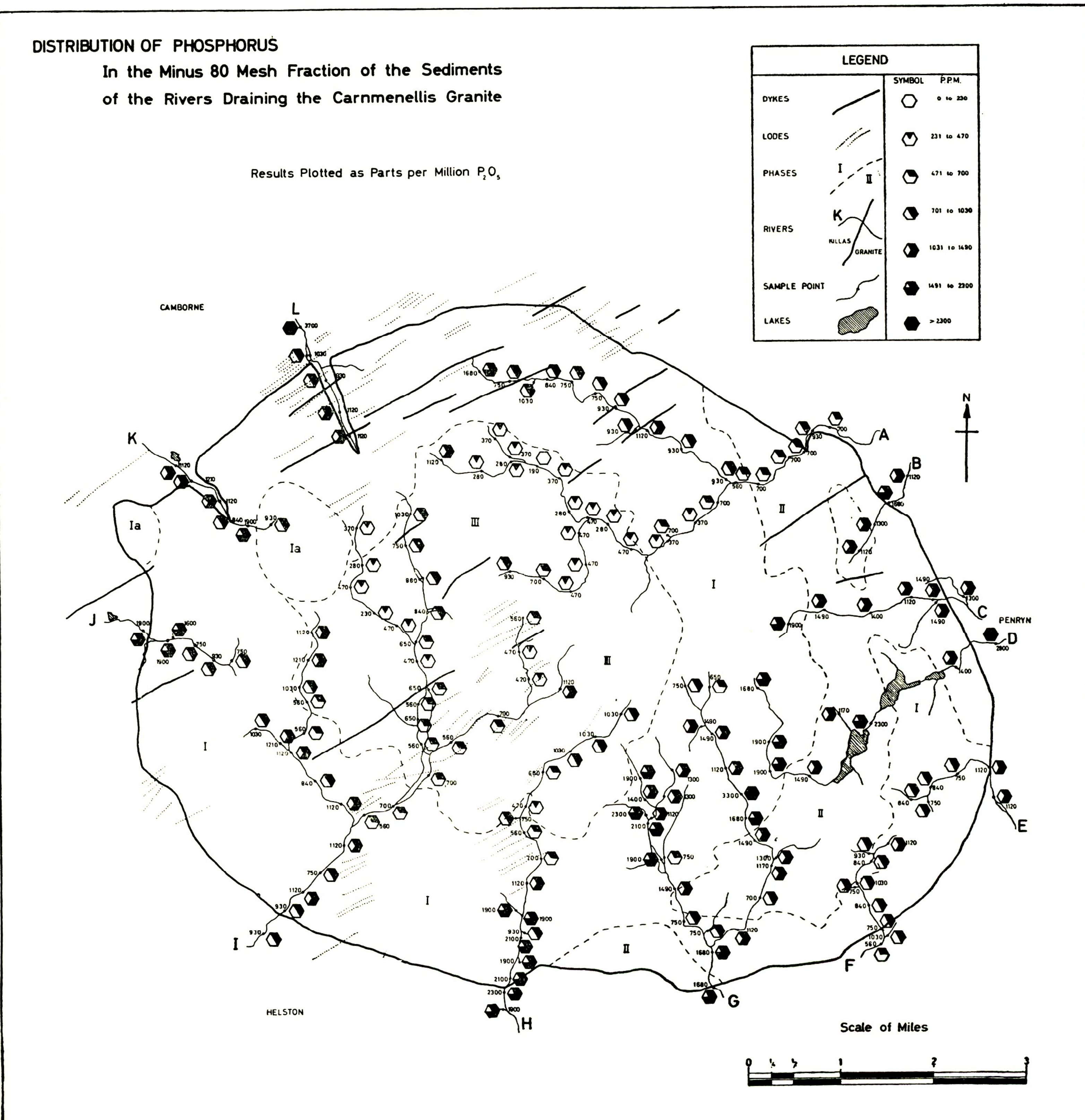

DISTRIBUTION OF PHOSPHORUS
In the Minus 80 Mesh Fraction of the Sediments
of the Rivers Draining the Carnmenellis Granite
Results Plotted as Parts per Million P_2O_5
LEGEND
SYMBOL
P.P.M.
DYKES
LODES
PHASES
RIVERS
KILLAS
GRANITE
SAMPLE POINT
LAKES
0 to 230
231 to 470
471 to 700
701 to 1030
1031 to 1490
1491 to 2300
> 2300
N
CAMBORNE
PENRYN
HELSTON
Scale of Miles
0
1
2
3

Fig. 7.

Whilst most of the swarms overlying cusps which have been recorded have, for obvious reasons, been in killas, they are probably not confined to it: the 3A, B and C swarm of South Crofty, which is noted earlier, appears to be one developed in an early granite phase.

That some of the swarms are associated with the first granite phase is suggested by the fact that the Conqueror Swarm of Wheal Fortune is intersected by granite apophyses.

Whilst vein swarms are the most characteristic products of mineralisation due to cusp residuum, on occasion, as at Castle-an-Dinas, virtually only a single lode results.

During the consolidation of the ' body ' of the batholith large pools of residuum collected beneath the high sports of the granitic roof (that is, beneath the cusps) and the gas pressure which increased as these pools accumulated locally became so great that it exceeded the pressure due to the overlying rocks and fractured them. Again, the fracture pattern in any given area was determined by the relative stresses, the direction along which the maximum horizontal stress was operating, the magnitude of the gas pressure and regional stresses, the direction along which the maximum horizontal stress was operating, the shape, relative sizes and physical characteristics of the rock units involved, the numbers of pre-lode faults occurring there, etc. The fractures were opened by contraction, gravity slumping and block movement associated with changes in the intensity and direction of the local and regional stresses. Although the occurrence of certain preferred strikes throughout the region bears witness to the importance of regional stresses during the phase of major hypothermal lode development, the marked differences between the three-dimensional patterns of, say, the Geevor, South Crofty and St. Agnes areas, indicate that local stress conditions were also exceedingly important, and emphasise the fact that the history of lode development in a given area cannot be deduced simply by considering those of broadly similar areas only a few miles away.

The lack of large and/or economically important pegmatites in the region is a matter of interest which can be explained if it is assumed that Emmons is correct when he states that fracture is due to the development of a gas pressure which builds up under the high spots of the batholith as the latter is consolidating. If then this gas pressure is sufficient to rupture the overlying rocks before the granite-forming components have been largely eliminated by the formation of feldspar, mica, etc., the residuum fraction which escapes along the fractures will lead to the development of pegmatites, and the pressure may never build up sufficiently at a later date to permit escape of lode-forming fractions. If fracture is delayed until the granitic components have been fixed the escaping residual fractions will cause the development of hydrothermal ore-bodies, and if the gas pressure never exceeds that of the confining rocks the residuum will only be able to effect deuteric alterations. Further discussion of the *mechanism* of ore-body development is deferred until later.

The nature of the ore-forming agents changed with time so that the period during which hydrothermal minerals were formed gave way to one in which mesothermal species were deposited. As noted earlier it seems certain that mesothermal species were deposited during two or three periods of mineralisation which were separated by large intervals of time. The relative importance (from a point of view of quantity) of each contribution is, at this point of time, just a matter of opinion, but will, nevertheless be referred to again.

The mesothermal species were, on occasion, laid down in the higher horizons of lodes which were largely infilled during the hypothermal phase: a typical example occurs at Tresavean Mine. Locally also, as in the St. Agnes/Perranporth area, mesothermal lodes strike parallel to those containing hypothermal tin and copper minerals, but in the region generally mesothermal mineralisation, as noted earlier, is associated with crosscourses, and the mesothermal zones tend to occur outside those zones in which hypothermal lodes are found. Despite this, there are many instances of mesothermal lodes intersecting hypothermal ones, so that galena and cassiterite, for example, virtually abut against each other: typical examples occur in Redmoor and Budnick Mines. Many examples are also known of hypothermal lodes which have been reopened late and in which mesothermal species have been deposited next to hypothermal ones: these will be described in some detail in a later section: typical examples, however, occur at Geevor and South Crofty mines.

It seems reasonable to believe that at least those mesothermal minerals which occupy the upper horizons of hypothermal lodes and those which constitute all or almost all the bulk of lodes which strike parallel to neighbouring hypothermal lodes are genetically related to the hypothermal lode minerals and to the Permo-Carboniferous granites. Perhaps also, for reasons which will be more apparent when primary zoning is discused, the mesothermal deposits occupying crosscourses, and far-removed from the tin and copper lodes, are of about the same age. On the other hand most or all of those which have been deposited within or adjacent to essentially hypothermal lodes may have been deposited largely, or entirely, in Mesozoic and Tertiary times. Considerations of the mechanism of primary zoning and the fact that extensive faulting took place in Tertiary times, support this hypothesis, the age determinations add further strong support. However, as noted earlier, as there is no evidence that the region was subject to more than very slight igneous activity in Mesozoic and Tertiary times it seems likely that the mineralisation associated with such activity would also be slight. It may be, therefore, that during these times mobilisation of early lode components followed by their re-deposition was the major process and not one in which significant amounts of 'new' material were deposited.

To summarise, then, it appears that fissures with hypothermal trends continued to develop when the ore-forming agents associated with the Variscan orogeny had so changed that they were only capable of depositing mesothermal species. However, it seems likely that long before this phase of mineralisation had ended the stress patterns dominating the region changed in such a way that fractures with hypothermal lode trends were closed and others, striking approximately at right-angles to them, were opened. In Mesozoic and Tertiary times, judging by age determination data, both systems were again opened. Perhaps much of the quartz in the barren crosscourses is of Tertiary age and also that of the little vein at South Crofty mine which intersects a crosscourse and strikes parallel to a neighbouring tin lode.

VI. TYPES OF MINERAL DEPOSIT: THEIR GENERAL CHARACTERISTICS

For the purpose of this paper the mineral deposits of South-West England under discussion are classified as follows:

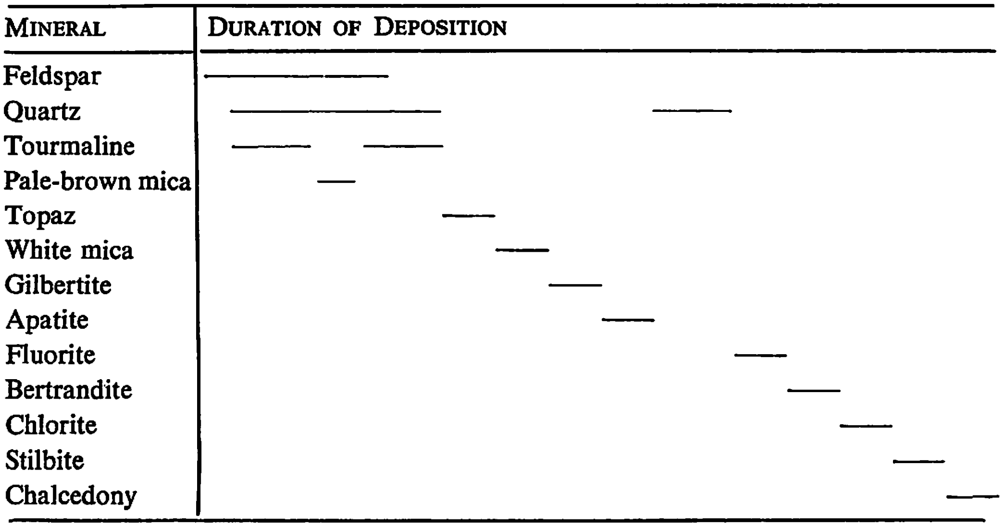
1. Pegmatites and metallized deposits with pegmatite affinities.
2. Greisen-bordered and other early, essentially feldspar-free, vein swarms.
3. Complex hydrothermal bodies.

1. Pegmatites and metallized deposits with pegmatite affinities.

Granite pegmatites are not uncommon but they are never large and of no direct economic importance. They cannot, however, be ignored when considering the genesis of the ore-deposits. They developed before, during and after the emplacement of the granite, and occur as schlieren in the granite, as marginal masses below structural traps and as lenses and veins (sometimes associated with aplites) in the vicinity of the contacts between the parent granite and the invaded rock. Their development has been varied and complex. Locally, for example, their pegmatitic character appears to be largely due to the growth of late "phenocrysts" of microcline microperthite as a result of potash metasomatism (Stone and Austin, 1961): elsewhere lenticular bodies appear to be the products of centripetal crystallisation from an early differentiated entrapped magmatic fraction (a crude zoning is sometimes apparent) followed, on occasion, by the system becoming open and further minerals being deposited from agents passing through. An example of the latter has been described from Trolvis Quarry, Carnmenellis (Hosking 1954). There early quartz and feldspar crystals behaved as baffles and later minerals were deposited almost entirely on the stoss side. In addition, the number of species and the intensity of mineralisation decreased from the bottom to the top of the drusy lenticular body. Finally, the last of the species to be deposited was chalcedony, which, if it really is a low temperature mineral, suggests that the formation of the body occupied a considerable period of time. The lack of dense and metallic species indicates that the pegmatite owes its origin to deposition from chemically distinct ascending fractions which were liberated from a differentiating early-isolated portion of the granite residuum. The paragenesis is indicated in Table 1.

A number of other felspathic bodies has been termed pegmatites but they lack sufficient feldspar to deserve the name. Webb (1946) describes a pegmatite from South Crofty Mine which is essentially a quartz replacement vein which developed in the grantite in such a way that the host-rock feldspars remained virtually intact in it.

TABLE 1: *Mineral Paragenesis of the Trolvis Pegmatite*



Other so-called pegmatites contain considerable amounts of arsenopyrite and wolframite, but cassiterite and other metallic species are comparatively rare. These may occur as isolated bodies or as vein swarms. The Complex Lode of the Dolcoath Section of South Crofty Mine is a good example of the first type. It is a steeply-dipping lenticular body consisting essentially of feldspar, quartz, wolframite, scheelite, cassiterite, and minor sulphides. The wolframite and arsenopyrite are strongly concentrated in the upper horizons, a not uncommon feature in such bodies, but the cassiterite, which post-dates the wolframite and arsenopyrite, does not show this characteristic to such a marked degree. It is quite clear that here one is dealing with an early felspathic wolframite/arsenopyrite lode which was subsequently fractured to a much greater extent than the surrounding country rock and within which migrating agents were impounded which were capable of depositing cassiterite, converting wolframite to scheelite, etc.

The so-called 3A, B & C zone of South Crofty Mine is a good example of the second type. Here numerous flat-dipping sub-parallel narrow veins occur which consist essentially of feldspar, quartz, wolframite and arsenopyrite. They are intersected by numerous steeply-dipping sub-parallel veins consisting of cassiterite, fluorite, chlorite and quartz. Why this felspathic vein swarm, and other similar ones in the mine, occur well inside the granite/killas contact is uncertain: perhaps as suggested earlier, they are situated within or above cusps of a later granite. The coincidence of cassiterite vein-swarms with the earlier felspathic ones is probably due to the fact that structurally weak zones are not appreciably strengthened by the development of felspathic veins within them. The paragenesis of the early felspathic veins of South Crofty is typified by that of the Complex Lode of Robinson's Section (Table 2. After Webb 1947).

TABLE 2: *Mineral Paragenesis in Early Felspathic Wolframite-Bearing Lodes of South Crofty Mine (After Webb, 1947)*

MINERAL	DURATION OF DEPOSITION
QUARTZ	————————————————————
FELDSPAR	———
Cassiterite (1)	——.......
WOLFRAM	———(Scheelite (2))
ARSENOPYRITE	———————
Chalcopyrite	———
Chlorite (3)	....
Pyrite	....
FLUORITE	....
Calcite	....

Essential minerals in capitals: occasional accessories in small letters: a dotted deposition range denotes irregular, local deposition.

(1). Cassiterite only in very small quantity in the vein; a possible accessory in the wall-rock.

(2). Scheelite is of very minor importance: occurs intergrown with wolfram.

(3). Only sparingly present except where the vein is cut by younger chloritic veins. The latter also frequently carry cassiterite in notable proportions.

2. Greisen-bordered and other early, essentially feldspar-free, vein-swarms.

Swarms of greisen-bordered veins commonly occupy the apices of granite cusps where they are confined to the uppermost few hundreds of feet. They may extend into the surrounding hornfels but only for a very limited distance. Most swarms consist of sub-parallel, very steeply-dipping planar veins which may be about a foot wide, but which are rarely above two inches, and which are usually bordered along both sides, but occasionally only along one, by greisen bands. Commonly the two greisen borders of a given vein are of about the same width, but sometimes (as at St. Michael's Mount) the widths are very different, and on rare occasions the greisen borders are discontinuous. The intervening granite is often appreciably kaolinised.

The Cligga swarm is atypical in that the parallel veins appear, in section, to be folded, a characteristic thought to be due to their development along contraction joints which parallel the now largely destroyed contact between the granite and overlying killas.

The strike of a given swarm coincides with that of the complex hypothermal lodes which invariably flank such metallised cusps. Field studies (Hosking 1953-54) clearly indicate that greisen formation predates that of the related veins though often, but not invariably, the fractures along which the greisenising agents moved were also used subsequently by the vein-forming ones. The geometry of the veins indicates that they owe their development to replacement rather than to the filling of fissures and it also establishes that on occasion (as at St. Michael's Mount) a given vein increased in strike length with time (Hosking 1953-4).

Quartz, wolframite and cassiterite occur in all the vein swarms and some of them contain sulphides, which, with the exception of arsenopyrite, are later than the species noted above: these include stannite, chalcopyrite and sphalerite. Sericite or gilbertite may occur as vein selvedges, and, on occasion, feldspar, tourmaline, topaz and apatite may be present, though they are usually in subordinate amounts. In some instances an early-developed vein was reopened to receive the late sulphides but on other occasions the sulphides occupy veins developed along late fractures.

At Cligga a crude mineral zoning is apparent: the cassiterite/wolframite vein system changes to one of tourmaline and quartz as it is traced towards the source of the ore-forming agents. However, other vein swarms possess the characteristics of telescoped ore deposits in that in some both early and late minerals occur in close association in a given vein and in others a given vein may, at a particular horizon contain early minerals only, whilst another, only a foot or so away at the same horizon, may consist largely, or entirely, of late-developed species; this is well seen at St. Michael's Mount and at the Cameron Quarry (St. Agnes). The paragenesis (Table 3) of the Cameron Quarry veins not only indicates the considerable

TABLE 3: *Mineral Paragenesis in the Veinlets of the Greisenised Granite of Cameron Quarry, St. Agnes*

MINERAL	DURATION OF DEPOSITION
SERICITE	
QUARTZ	
TOURMALINE	
APATITE	
CASSITERITE	
Chlorite	
Hematite	
Wolframite	
Arsenopyrite	
Pyrite	
CHALCOPYRITE	
SPHALERITE	
FLUORITE	

(1) The comparatively common species are in capitals.

(2) Most of the post-tourmaline species are preferentially concentrated in feldspar voids adjacent to incipiently mineralised fractures, but the latest generation of fluorite occurs with quartz in small crosscourse-type veinlets.

(3) Wolframite locally replaces cassiterite.

number of species occurring within a vertical distance of, say, 6 feet, but also that it is virtually the same as that of the large complex hypothermal lodes discussed later.

As noted earlier, swarms of sub-parallel veins and also true stockworks are encountered in the killas which possess mineralogical characteristics similar to those of the greisen-bordered veins, and which probably developed over cusps, perhaps in place of greisen-bordered veins, when fracturing was sufficiently severe to markedly affect the rock overlying the granite.

The Conqueror Branches of Great Wheal Fortune (Breage) is a typical example of the type under review. The veins which are narrow and commonly mica selvedged, contain cassiterite, wolframite, sulphides, topaz, tourmaline and quartz, while the wall-rock has been converted to a quartz/sericite rock in which tourmaline needles are often abundant.

3. Complex hydrothermal bodies.

This group comprises the hypothermal deposits containing cassiterite, arsenopyrite, chalcopyrite, wolframite, high-temperature sphalerite, etc., and the mesothermal which contain siderite, galena, low-temperature sphalerite, etc. In addition, the stibnite/jamesonite veins of North-East Cornwall, of uncertain parentage, but which possess certain epithermal characteristics, are also included.

The hypothermal deposits include the lodes proper, which are essentially mineralised faults in which minerals were deposited both in open fissures and in the adjacent wall-rock, and the carbonas, pipes and floors which are predominently the products of wall-rock replacement in the vicinity of very narrow ' feeder channels ' and which differ markedly from the ' normal ' lodes in form.

The ' normal ' lodes of the South-West are for the most part fault zones which have been repeatedly reopened during certain stages when ascending mineralising agents were active. Generally speaking a given lode was initiated by the development of a fracture with a variable dip and strike. Although displacement of the walls by lateral and reverse faulting occurred, in most cases most of the movement was due to normal faulting which caused open spaces to develop along the steeply dipping parts and constriction to occur along those which were comparatively gently dipping. Ascending ore-forming agents deposited mineral both in the open spaces and the adjacent wall-rock and displayed a marked preference for the steepest parts of the fault fracture—a feature which will be returned to later.

An economically significant lode only developed when the ore-forming fluids could enter the fault zone for a considerable period of time. This was achieved by repeated faulting which reopened early fissures which had been sealed by early-deposited minerals (often, at the same time fragmenting the early components) or by creating new channelways in the adjacent, and sometimes much altered, wall-rocks. Not only did this repeated faulting cause the structure of many of the lodes to be very complex (for typical examples see Cranshaw, 1920-21), but it was also responsible for the development (as noted earlier) of stockworks, etc., in the hanging walls beyond the confines of the ' parent ' lodes.

In extreme cases an inordinately large amount of ore-forming 'fluid' moved along insignificant fractures and by reacting locally with the wall-rock produced rich replacement deposits: the possible reasons why such intense wall-rock mineralisation occurred locally will be discussed later. Typical examples are the East Wheal Lovell pipes and the carbonas of the St. Ives mines which are briefly described below:—

E. Wheal Lovell pipes (Phillips and Louis 1896, pp. 144-145): These pipes, of which the largest extended from the 40 to the 110 fm. level, consist of a central fissure, never more than half an inch in width, filled with quartz and ferruginous clay, and surrounded by metallised altered granite, consisting of quartz, gilbertite and cassiterite, and minor amounts of fluorite, pyrite, chalcopyrite, bornite, chalcocite and siderite, which gradually faded away into the parent granite.

Carbonas: These are pipe-like or irregularly shaped bodies of stanniferous, highly altered granite with which are associated one or more, usually very narrow, feeder veins. At the Providence Mines (St. Ives) a vertical carbona, 30 × 15 × 4—36 feet in extent, consisting of quartz, feldspar, tourmaline and cassiterite, was connected to the Comfort Lode at the 105 fm. horizon by narrow veinlets and pipes (MacAlister 1907, pp. 115-116). At St. Ives Consols a great pipe-like carbona, lacking clearly-defined walls, and consisting of tourmaline, cassiterite, chlorite, fluorite, pyrite and chalcopyrite, occurred at the junction of the north-south-striking crosscourse with east-west veins. The trend of the carbona, unlike that of the normal tin-bearing lodes of the mine, was north-south. (MacAlister 1907, pp. 116-117).

The so-called No. 12 lode of South Crofty Mine is, in the writer's view, a small carbona: it is situated in a granite tongue in the vicinity of the intersection of the latter by a vein which, in the underlying hornfels, is narrow, steeply-dipping, and unproductive.

VII. PARAGENESIS, WALL-ROCK ALTERATION AND PRIMARY ZONING

The broad paragenesis of the major hydrothermal bodies, and the nature of the alteration of their wall-rocks, form part of Table 4, in which an attempt has been made to indicate the general order of deposition, etc., of the more important species occurring in all the types of mineral deposits under review. It must, of course, be appreciated that compromises have to be made in order to prepare such a table.

It is not proposed to deal with wall-rock alteration adjacent to mineral deposits in any detail. However, it is pertinent to make a few observations on this subject.

The type of alteration varies with time and with the nature of the host rock. The earliest deposits in the granite are commonly greisen-bordered, and even the complex hypothermal lodes may be fringed by greisenised rock. This phase of alteration is followed, in the order given, by tourmalinisation, chloritisation and haematitisation. Kaolinisation is locally important and may have developed during greisenisation and tourmalinisation. (At Cligga the granite is kaolinised between

TABLE 4: *A Generalised Mineral Paragenesis, etc., of the Mineral Deposits of South-West England*

Zone	Ore-Minerals		Economically Important Elements	Composition of Wolframite and Sphalerite	Trace Element Data*
	LATEST MINERALS				
7.	Barren: (pyrite).	Mesothermal and Epithermal Lodes Generally at right-angles to granite ridges.			
6.	Hematite. Stibnite. Jamesonite. Tetrahedrite. Bournonite. Pyrargyrite? Siderite. Pyrite: (marcasite).		Fe. Sb.		
5b.	Argentite. Galena. Sphalerite.		Ag. Pb. Zn.		
5a.	Pitchblende. Niccolite. Smaltite. Cobaltite. (Native bismuth: bismuthinite?)		U, Ni, Co. Bi.		Bi and Sn decrease in galena
4.	Chalcopyrite. Sphalerite. Wolframite: (scheelite). Arsenopyrite. Pyrite.	Hypothermal Lodes Generally parallel to granite ridges and dykes.	Cu	Fe increases in wolframite and decreases in sphalerite.	In, Mn, and Sn decrease, and Ge and Ga increase, in sphalerite.
3.	Chalcopyrite: (stannite). Wolframite: (scheelite). Arsenopyrite. Cassiterite: (wood tin).		Sn W As		
2.	Wolframite: (scheelite). Arsenopyrite: (molybdenite?) Cassiterite.				
1.	Cassiterite, Specularite.				
Greisen-bordered veins	Arsenopyrite. Stannite. Wolframite, Cassiterite. Molybdenite.	Veins often in granite cusps.			
Pegma-tites	Arsenopyrite, Wolframite. Cassiterite. Molybdenite.				
	EARLIEST MINERALS				

Gangue: Quartz. Chalcedony. Calcite. Dolomite. Barite. Chlorite. Hematite. Fluorite. Felspar. Mica. Tourmaline.

Wall-Rock Alteration: Greisenised granite. Quartz-sericite slate hornfels. Tourmalinised granite: capel. Tourmaline slate hornfels: capel. Chloritised granite: peach. Chloritised slate: peach. Haematitised granite. Haematitised slate. Kaolinised granite (?). Silicified granite. Silicified slate. Skarn-type rocks derived from greenstones and calc. sediments.

*See El Shazly, E. C., Webb, J. S., and Williams, D. Trace Elements in Sphalerite, Galena and Associated Minerals from the British Isles, (Trans. Instn. Min. Metall., 66, pp. 241-271.)

NOTE: Some of the components of Zones 3 and 4 may in part pre-date the cassiterite of Zones 1 and 2: this possibility is discussed in the text.

the greisen-bordered veins and there it is difficult, on mechanical grounds, to see how this could happen after the greisen had developed.)

Silicification accompanies all the above-mentioned types of alteration and locally it may be the dominant one.

Often, also, all the types of alteration occur at a given horizon, either more-or-less superimposed (in which case the earlier types are partly obliterated by the later), or side-by-side.

As lodes, in the granite, are approached which are heavily tourmalinised, chloritised or haematitised, the feldspar phenocrysts tend to become pink, then the groundmass shows progressive alteration to quartz with tourmaline, chlorite or haematite, and finally, close to, and within, the lode, the granite is converted largely or completely to quartz/tourmaline (capel), quartz/chlorite (peach) or quartz/hematite. The tourmaline of the early small veins, such as the cassiterite/tourmaline veins of the St. Austell china-clay areas, is to a considerable extent the coarse brown, variety, whereas that of the complex lodes is essentially blue, or zoned blue and brown, and in the form of minute needles.

Alteration of killas adjacent to lodes also varies with time. The earliest involves the conversion of the host-rock to an aggregate of quartz and sericite: this is followed by tourmalinisation (tourmaline slate hornfels), chloritisation and haematitisation. Silicification accompanies all the other types of alteration and is the dominant one in mesothermal lode zones.

When the ore-bodies form in calcareous sediments or basic igneous rocks (which are also lime-rich) a skarn suite of minerals develops in the walls and also constitutes the non-metallic gangue. In this environment garnetisation and axinitisation of the wall-rock are often particularly prominent.

Primary Zoning

In any given lode the major mineral components tend to become progressively younger as the body is ascended[1], consequently primary zoning is often clearly defined. The earliest and lowest zone is usually in part overlapped by the one immediately above it, and the upper typically possesses a greater strike extent than the lower. If more than two zones are present each succeeding zone overlaps and has a greater strike extent than the one immediately below it. In addition, the zones of hypothermal lodes are characteristically much more gently dipping than neighbouring granite/killas junctions. (Despite the fact that mine sections published during the last century clearly demonstarated this, it was often subsequently stated that in any given area the primary zones paralleled the granite/killas contact.) The longitudinal section of Dolcoath Main Lode (Fig. 8) which was published in 1893 by Burrow and Thomas (see 'References'.) admirably illustrates the more important aspects of a hypothermal lode in which primary zones have been clearly delineated by actual mining.

The distribution of major, minor and even trace metals (El Shazly, Webb and Williams 1956-57) in the various mining districts lends strong support to the view

[1]The possibility that this statement needs some modification is discussed later.

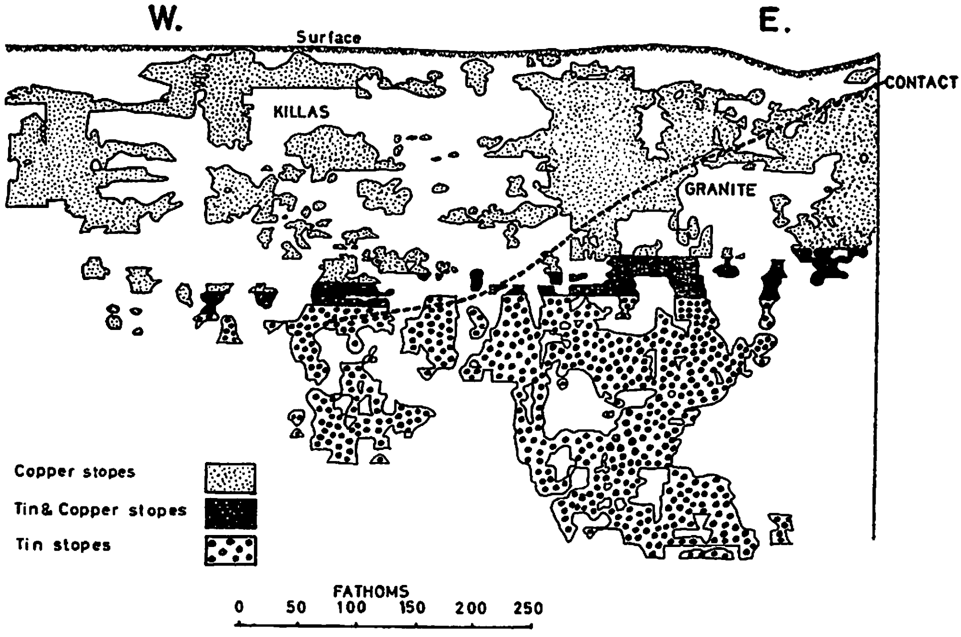


Fig. 8.
Longitudinal Section of Dolcoath Main Lode. (After Burrow and Thomas, 1893)

TABLE 5: *Maximum thickness of Primary Zones* (*Dewey* 1948, p.50)

Mineral Zone	Thickness in ft.
Zone of carbonates (iron, manganese, etc.) - - - - -	400
Zone of sulphides of antimony, etc. - - - - - - - -	200
Zone of sulphides of lead and silver, giving place in depth to zinc -	1,800
Zone of sulphides of copper intermixed with tungsten and tin for 700 ft. - - - - - - - - -	2,500
Zone of oxides of tin with tungsten in the upper parts - - -	2,500

that during all or most of the first and major period of ore-development (the one associated with the Permo-Carboniferous granite invasion) lode minerals were being deposited at progressively greater distances from the sources (the emanative centres) and so over progressively greater areas. The distribution of tin, copper and lead/zinc in the St. Agnes/Perranporth/Lambriggan area demonstrates this particularly clearly, and commonly an area occupied by tin lodes coincides with a part of a more extensive area containing copper deposits. (See Dines 1956, pp. 12-13.) However, in many areas erosion has in part obliterated the original distribution pattern.

The maximum thicknesses of the primary zones, as determined by Dewey (1948, p. 50) are noted in Table 5. It must be pointed out, however, that in most of the mines of the region the zones—particularly those of tin and copper—do not attain these thicknesses. It is also misleading in that it gives an impression of simplicity which does not exist. Zinc, for example, is quite as widespread in the copper zone as in the lead one, but in the former it occurs in high-temperature, iron-rich sphalerite in which ex-solution bodies of chalcopyrite are characteristic, whilst in the latter it is generally present in comparatively iron-poor sphalerite lacking ex-solution bodies.

It is often asserted that the temperature gradient which was established between the hot granite and the cool land surface was the factor primarily responsible for the deposition of minerals in zones, and that cassiterite, for example, was deposited in those portions of lodes near the emanative centre which lay between the two geoisothermal surfaces constituting the upper and lower limits of the zone in which the mineral in question would develop. The fact that the formation of lodes commenced before the last of the granite had been emplaced might be used in support of this theory as might the theoretical studies of Schneiderhöhn (1934) concerning the form, etc., of the geoisothermal surfaces developed in the vicinity of a hot intrusive.

That a given zone is more extensive in plan than any below it is, in Dines' opinion (1934, p. 286) due to the tendency for fractures to become progressively more extensive as the land surface is approached.

The fact that primary zoning is so clearly defined suggests that most of the lode development must have taken place in what, from a geological point of view, was a comparatively short space of time: particularly if the zoning were due essentially to the temperature gradient established between the hot granite and the surface. In other words, it suggests that lode development, for the most part, occurred in one comparatively short period which commenced during the final phases of development of the Permo-Carboniferous batholith.

That mesothermal species were also subsequently laid down in the original tin zone could mean that mesothermal mineralisation persisted, however, for a considerable period under conditions of regionally waning temperature. However, as noted earlier, the mesothermal species in the early hypothermal zones were certainly in part the products of distinctly later metallogenetic epochs and may have been entirely so.

The mineral distribution pattern is still more complex than what has been written above suggests because neither the early felspathic wolframite-bearing veins nor the greisen-bordered swarms fit into the regional primary zoning pattern. At South Crofty, for example, wolframite does not occur in the normal hypothermal lodes below the 260 fm. level, yet it, and arsenopyrite, are plentiful in the felspathic veins in the 335 fm. horizon where they are intersected by cassiterite/quartz/chlorite/fluorite lodes. Greisen-bordered swarms are units which are, in a sense, unrelated to the complex hypothermal lodes which commonly flank the cusps in which the former occur. The paragenesis of a given swarm is virtually the same as that of the complex lodes and there may be little difference in the kinds and numbers of species present. Furthermore, a given swarm may show some degree of zoning, as at Cligga, but this is quite independent of that displayed by neighbouring complex lodes. At Cligga, for example, complex zinc- and copper-bearing lodes occur in the hornfels immediately adjacent to that part of the cusp which contains quartz/tourmaline and cassiterite/wolframite/quartz veins. On occasion, also, branches of the complex veins have invaded the cusp and in part have been accommodated in it as a result of the early greisen-bordered veins being reopened. It is quite impossible to construct a geoisothermal model, in which the granite was the sole source of heat, which could account for this relationship.

The failure of felspathic veins and greisen-bordered swarms to conform may be due, in part, to fundamental chemical differences between those ore-forming agents which were responsible for the early ore-bodies and which were concerned with the development of the later complex hydrothermal deposits. Whether it may also be in part due to the time, nature and degree of fracturing is uncertain, but it is certain that these factors are capable of profoundly modifying the mineral deposition pattern which would develop were temperature the sole controlling factor: it is obvious for example, that cassiterite will only be deposited in a lode throughout the entire temperature zone in which it is capable of being deposited if adequate passage-ways for the tin-depositing agents exist throughout the zone. At South Crofty Mine, the upper and lower limits of tin deposition, when depicted on a transverse section, are markedly zig-zag and indicate that factors other than temperature played a dominant role in determining the precise sites of mineral deposition, and, as will be discussed later, the nature of the fissures was, in this case, a factor of major importance. Finally, the lack of conformity between the distribution of minerals in closely spatially associated but distinct types of deposit, as well as certain mineral associations noted in some of the individual ore-bodies, can in part be accounted for if it is assumed that the regional temperature gradient between the hot granite and the land surface was not the dominant controlling factor but that the gradient established along each fracture system as a result of hot ascending solutions loosing heat progressively to the wallrock was. This suggestion is in no way incompatible with the regional primary zoning patterns, as hot solutions derived from a deep source and ascending similar fractures in essentially the same rock type would result in zones of the type which occur—zones which are much flatter than associated cusp/killas contacts. Moreover, if it is held that a temperature gradient due to the loss of heat from ascending solutions to the walls of fissures was the dominant factor which determined where given minerals might be deposited, it is to be expected that there would be a lack of correlation between the disposition of species in the metallised felspathic veins, greisen-bordered swarms, and the complex hydrothermal lodes, as they were developed at different times and from different pools of residuum which themselves differed greatly in size and in disposition with respect to the contemporary land surface. It would also explain why hypothermal sphalerite may occur in essentially mesothermal lodes, as it does, for example, at Lambriggan. In addition, local fluctuations in the temperature of developing lodes would readily explain the various spatial relationships existing in similar ore-bodies between two species, each of which was represented by two generations. If the reopening of the lode for the reception of the solution from which the second generation was formed followed quickly after the first generation had been deposited the temperature at a given horizon would probably be higher than it was during the formation of the first generation: if there were an appreciable time lapse between the two stages the temperature would probably be significantly lower. Thus, in one lode it may be possible to find examples in which species A was deposited before B, whilst in a neighbouring lode, with a somewhat different history of fissure formation, B may locally have been clearly deposited before A. The following diagram (Hosking 1951, p. 319) further elaborates this theme.

Surge 1	*Surge 2 soon after Surge 1*	*Surge 2 considerably later than Surge 1*
$\dfrac{\text{Mineral B1}}{\text{Mineral A1}}$	$\dfrac{\begin{matrix}\text{B2}\\ \text{B1 A2}\end{matrix}}{\text{A1}}$ or $\dfrac{\text{B1 B2}}{\text{A1 A2}}$	$\dfrac{\text{B1}}{\dfrac{\text{A1 B2}}{\text{A2}}}$ or $\dfrac{\text{B1}}{\text{A1}}$ ...... $\dfrac{\text{B2}}{\text{A2}}$

VIII. FACTORS OTHER THAN TEMPERATURE WHICH DETERMINED THE DISTRIBUTION OF ORE

In the South-West there are countless examples of mineral deposits which are essentially confined to a given rock unit even though the temperate conditions would appear to have been favourable for the deposition of further similar ore beyond the confines of the unit. At South Crofty Mine, the No. 9 lode splits into sub-economic stringers on passing from the granite into adjacent killas and porphyry (Taylor 1963, pp. 749-758). The Cligga swarm dies out almost immediately outside the granite cusp. The veinlets of the Parbola tin-bearing stockwork are confined essentially to the porphyry dyke. The tin-ore of the Magdalen Mine (Ponsanooth) occurs solely in a greenstone mass which is intersected by a feeder channel.

Within the lodes rich parts (shoots) usually occur in the following environments:—

(*a*) *In the steepest parts.* Numerous examples have been noted, for example, at Geevor and South Crofty Mines.

(*b*) *At lode intersections.* Thus at Wheal Vottle (St. Agnes) where a vertical lode was displaced by a flat lode a rich bunch of tin-ore was found. " This rich part averaged perhaps four feet in thickness and gave about 15,000 tons of ore which assayed close on 50 lbs. of black tin (cassiterite) to the ton, while in the ground beyond the shoot, which has been pretty well explored, the lode did not average more than ten inches wide and assayed only 9 lbs. to the ton." (Collins 1912, p. 113.)

(*c*) *In structural traps.* In the felspathic, lenticular, steeply-dipping Complex Lode of the Roskear Section of South Crofty Mine wolframite is concentrated most markedly in the uppermost parts. At Geevor Mine in certain of the lodes, rich ore is confined to those parts which lie between pre-lode fractures (Garnett, 1961). Probably the canalisation of ore-forming agents into parts of lodes confined between earlier fractures is a much more widespread ore-control phenomenon than has been generally realised.

Although temperature may have broadly determined where a given mineral might be deposited, the site of deposition was much more strongly determined by the extent and nature of the fracture systems through which the ore-forming agents moved. Because of differences in the physical character of adjacent rock units each unit fractured differently from its neighbours when subjected to forces capable of developing fractures in all of them. Frequently the difference was such that fissures were constricted on passing from one rock unit to another, and it seems that such happenings commonly reduced the rate of flow of the ore-forming agents to a velocity at which they were capable of depositing meaningful amounts of lode material either within open fissures or by reacting with the wall-rock. This would account for the restriction of tin-ore at South Crofty to those parts of lodes which were within the main mass of granite, and for the restriction elsewhere of ore by porphyry dykes and greenstone bodies. It also suggests that the steepest parts of lodes are the richest, not because there the original fissures were wider, but rather because the rate of flow of the ore-forming agents was retarted, in part because of the increased width of the fissure, but more particularly because the flatter parts above were constricted. The development of rich intersections is also, in all probability, due largely to restriction in the movement of the ore-forming liquids by fault detritus, etc., though the development of chemically fresh corners, edges and surfaces during the fracturing may also have facilitated the deposition of ore in this environment (Hosking 1963-64). However, both at intersections, and elsewhere, local concentrations of ore in lodes may owe their development, to no small degree, to the precipitating action of an early mineral, or minerals, on the components of a later hypogene solution. It is probably not without significance that at Trugo (St. Columb) cobalt was obtained from a vein four to six inches wide *where it crossed a copper lode* (Collins 1912, p. 341) and at Wheal Ludcott fine specimens of ruby silver were obtained which were almost invariably accompanied by a considerable proportion of siderite " with which it seems to have some distinct relationship." (Collins 1903, p. 694.)

(*d*) *In zones of remobilisation.* At Castle-an-Dinas Mine (St. Columb), where the wolframite lode has been intersected by a large tongue of granite, the ore shoot haloes the post-lode intrusive! It seems difficult to escape from the conclusion that there the invading magma digested much of the lode and adjacent country rock and then the unwanted tungsten, iron and manganese were thrust out as a ' front ' into the fractured lode zone where they were redeposited. It is pertinent to add that minerals appear to have concentrated similarly elsewhere: thus at Kilembe (E. Africa) chalcopyrite has concentrated around the perimeters of pegmatite veins which penetrated the ore-body.

From what has been written above it will be apparent that one rock type is basically not more favourable than another so far as the deposition of ore is concerned: major tin deposits, for example, occur in granite (Dolcoath Mine), porphyry (Wherry Mine), dolerite (Magdalen Mine) and in hornfels (Wheal Vor). Even in the Chiverton Mines, where the lead/zinc ore is confined to those parts of the lodes which are within broad steeply dipping zones of 'soft shaly killas' which alternate with 'hard sandy killas and sandstone' (Collins, 1903) it is probable that differences in the manner of fracture of the two types of rock, rather than chemical or mineralogical differences, determined where the ore was to be deposited.

The composition of the wall-rock has, however, determined to some limited extent the composition of minerals in the lodes. Thus wolframite is the dominant tungsten species of lodes in the granite and hornfels, whilst scheelite is the dominant one of lodes in the greenstones and calcareous sediments. Furthermore, lodes in contact altered greenstones and calcareous sediments, unlike those in other rock types, commonly possess a gangue of skarn minerals.

The distribution of the various beryllium species (which are probably nowhere present in economic amounts in the South-West) appears to be determined by the nature of the host-rock: beryl, chrysoberyl, phenakite and bertrandite occur in pegmatites and early veins in the granite and hornfels, euclase has only been recorded from the greisen of Cligga, whilst members of the danalite-helvite-genthelvite groups are confined to lodes in the contact-altered greenstones and calcareous sediments. (See Kingsbury 1961, pp. 921-941; Hosking 1959-60, p.653.)

IX. THE SOURCE OF THE LODE METALS: THEIR MODES OF TRANSPORTATION AND DEPOSITION

A review of the mineral deposits of the South-West cannot be concluded without considering the source of the metals in these deposits, how the metals were transported to the sites of deposition, and how, and under what conditions, deposition of these metals occurred.

The source of these metals, as the source of the metals occurring in all the primary ore-deposits of the world, is controversial: so also is the granite with which the majority of the ore-deposits, at least, is held to be genetically related. The writer is of the opinion that the granite was formed by the deep-seated granitisation of sediments and associated basic rocks within a geosyncline and that it was then mobilised and invaded the overlying folded sediments in the manner suggested earlier. If this is so the granitised rocks were the sources of the metals now formed in the lodes.

Sullivan (1948) has postulated that the metals occurring in hypothermal lodes genetically related to granites were derived from basic rocks which had been granitised: in support of this he points out that the ionic radii of the 'ore-metals' are similar to those of ferrous iron and magnesium and hence they could proxy for them in the ferromagnesian minerals of the basic rocks to a very considerable extent. He also notes the comparatively high concentrations of tin, etc., which have been reported in such rock-forming species.

Others have suggested that the sediments were probably capable of supplying the metals which would be mobilised during their granitisation, and Webb (1947,

p. 209) notes that cassiterite has been recorded in the Devonian sediments of Western Europe and suggests that deposits of Devonian age may have been the source of the lode tin of the region under review.

As noted earlier, the major granite outcrops of the South-West are situated in the argillaceous rather than the arenaceous areas and virtually all the greenstone swarms are in close proximity to them. Trace-element analyses of the pre-granite rocks of the region, which are at present being carried out at the Camborne School of Mines, have not yet yielded sufficient data to determine, with a fair degree of certainty, whether such rocks could, by being granitised, have supplied some or all of the metals occurring in major amounts in the lodes and in trace amounts in the acid intrusives. However, such analyses as have been completed indicate that the argillaceous sediments outside the metamorphic aureoles in lode-free areas are surprisingly high in many of the ' lode metals ' (Table 6) and alone, or in conjunction with the greenstones, could well be the sources of the lode-tin, -copper, etc., of the region.

It has been often assumed (see Sullivan 1948) that most granites can only contain very modest amounts of the ' lode metals ' because the ionic radii and charges of the latter are such that these metals cannot be accommodated to any marked extent in the lattices of the major granite minerals, and so, as the granite is consolidating, the ' lode metals ' concentrate in a residuum. At the same time a gas pressure builds up under the ' high spots ' of the roof and this may, as noted earlier, initiate the development of channelways along with the lode metals may escape.

Sullivan (1948) was aware that certain granites could hold significant amounts of lode metals, and he suggested that if a granite contained dominant amounts of hornblende the species might accommodate so much tin that none would be left in the residuum to form lodes. He did not mention the fact that biotite, which is commonly a major granite component, was also capable of accommodating appresiable quantities of tin and also of many other lode metals. Had he realised this his views concerning the genesis of mineral deposits related to granitic intrusions would surely have been modified—perhaps in the way discussed later.

Barsukov (1956), however, appreciated that biotite might play an important part in the genesis of at least some of the lodes genetically related to granites, and is of the opinion that the tin of lode cassiterite is not derived primarily from a tin-rich residuum but from this mica. He thinks that ascending hot solutions, rich in sodium and fluoride ions, cause albitisation of the feldspars and convert the biotite to white mica in the vicinity of channelways and at the same time they mobilise most of the biotite tin as $Na_2(Sn(OH,F)_6)$. The solution containing this complex tin-bearing salt migrates to higher horizons where, under conditions of changing pH, progressive hydrolysis takes place in the following way: —

$Na_2(Sn(OH,F)_6)$—Na_2SnF_6—Hydrate of stannic acid—Cassiterite.

The hydrofluoric acid liberated during hydrolysis reacts with feldspars forming secondary micas, topaz, fluorite and quartz.

TABLE 6: *The Trace Element Content of Samples of Killas from Barren Areas† outside the Metamorphic Aureole of the Carnmenellis Granite.**

Sample No.	PARTS PER MILLION										
	Sn	Be	Cu	Pb	Zn	Ni	Co	Mo	W	As	P_2O_5
3	30.0	0.25	16.0	10. 0	140.0	72.0	14.0	1.0	30.0	20.0	935.0
4	7.5	1.0	60.0	25.0	200.0	60.0	10.0	1.0	6.0	30.0	700.0
5	12.5	1.0	50.0	50.0	160.0	72.0	24.0	2.0	18.0	70.0	700.0
6	100.0	0.75	200.0	360.0	480.0	80.0	30.0	1.5	8.0	130.0	465.0
9	7.5	0.25	60.0	45.0	400.0	72.0	34.0	2.5	14.0	25.0	935.0
11	1.5	0.5	32.0	15.0	232.0	68.0	20.0	1.0	8.0	5.0	186.0
12	30.0	1.0	12.0	15.0	184.0	64.0	14.0	3.0	30.0	1.0	700.0
13	2.5	1.5	20.0	10.0	120.0	60.0	10.0	2.0	4.0	2.5	935.0
14	4.0	0.25	90.0	45.0	200.0	72.0	20.0	3.0	3.0	5.0	700.0
14A	4.0	0.25	50.0	35.0	208.0	68.0	20.0	1.0	4.0	3.0	935.0
17	1.5	1.0	25.0	20.0	184.0	60.0	10.0	1.5	4.0	5.0	465.0
18	1.0	1.5	30.0	5.0	200.0	72.0	14.0	0.5	8.0	4.0	700.0
19	4.0	1.0	50.0	35.0	184.0	68.0	14.0	1.5	3.0	1.0	465.0
20	2.5	0.25	120.0	25.0	200.0	132.0	16.0	1.0	3.0	1.0	700.0
23	10.0	0.5	70.0	10.0	200.0	60.0	24.0	1.0	3.0	0.5	935.0
24	1.0	0.25	30.0	5.0	184.0	68.0	36.0	0.5	6.0	2.0	935.0
25	4.0	0.25	40.0	15.0	184.0	80.0	30.0	1.0	3.0	5.0	700.0
26	12.5	0.25	60.0	40.0	192.0	72.0	20.0	2.0	3.0	1.0	465.0
27	10.0	2.0	35.0	25.0	140.0	50.0	10.0	1.5	5.0	2.0	745.0
28	<10	1.0	40.0	35.0	140.0	60.0	20.0	0.5	6.0	6.0	930.0
29	<10	1.0	35.0	75.0	180.0	40.0	10.0	1.0	3.0	20.0	280.0
34	10.0	1.0	60.0	25.0	160.0	50.0	5.0	1.0	2.0	30.0	280.0
35	20.0	1.0	50.0	25.0	280.0	160.0	30.0	1.5	2.0	50.0	280.0
36	10.0	1.0	50.0	15.0	360.0	80.0	5.0	1.0	6.0	8.0	375.0
37	10.0	2.0	60.0	85.0	280.0	60.0	10.0	0.5	8.0	<1	745.0
38	10.0	1.0	50.0	30.0	140.0	90.0	15.0	1.5	4.0	<1	930.0
39	10.0	2.0	90.0	75.0	800.0	80.0	10.0	4.0	8.0	5.0	375.0
41	<10.0	2.0	130.0	200.0	500.0	120.0	13.0	1.0	4.0	50.0	375.0
42	10.0	2.0	55.0	80.0	320.0	40.0	10.0	1.0	3.0	30.0	745.0

*Hosking, K. F. G., Roberts, A. L., and Usman Hamid. (Unpublished Studies.)

†The areas have been termed 'barren' because no lodes have been recorded in them. Certain of the samples are so high in metals that it is likely that the areas from which they were taken are mineralised: note particularly sample no 6.

(All analytical methods used were of the rapid colorimetric type.)

The results of recent studies by the writer, which are discussed below, have failed to lend support to Barsukov's hypothesis, but enable an alternative one to be presented. Briefly, determination of the minor and trace-element content of biotites and 'muscovites'[1] from samples of granite taken from lode areas, dyke areas and areas which are devoid, so far as is known, of lodes and dykes, on the Carnmenellis Mass, yielded the results in Table 7. Whilst a full discussion of these results will not be attempted here it is pertinent to note that in all the environments the biotites possess a much higher concentration of ore-elements than the muscovites with which they are associated. It is also of importance to appreciate that copper, zinc, nickel and cobalt almost invariably occur in much higher concentration in the biotite than in the muscovite of a given sample of granite (the occasional anomalous result may be due to imperfect separation of the material for analysis). On the other hand, the muscovite from a given specimen of granite normally contains appreciably more tin, and often more beryllium, than the biotite associated with it.

The 'muscovites' are probably developed by direct late crystallisation from interstitial magmatic fractions, by reaction between late entrapped differentiates and biotite and feldspar, and what is of major importance when the question of ore-genesis is under discussion, by reaction between biotite and ore-forming agents liberated as a result of roof fracture from the 'pockets' of residuum which had accumulated beneath the 'high-spots' of the batholith. That muscovite tended to develop at the expense of biotite during hypothermal lode development in Cornwall was long ago hinted at by Davison (1926, p. 584) when he stated " that the granite in areas without lodes differs from that in lode areas: (a) by the rare occurrence of tourmaline; (b) by the usual occurrence of biotite; (c) by the comparatively small amount of muscovite; while the granite in highly-mineralised areas always contains much tourmaline, usually little or no biotite and much white mica ".

The results in Table 7 clearly indicate that there is no reason for believing that the conversion of biotite to muscovite leads to a mobilisation of the tin in the former as Barsukov suggests: indeed, they suggest that when such a conversion takes place there is an addition of this element (and probably also of beryllium). It must, of course, be conceded that the tin in the muscovite may occur as minute cassiterite crystals, and, indeed, Barsukov has demonstrated that such tin as occurred in late-developed 'muscovite' near certain Russian tin-lodes did occur in this way.

That muscovitisation of granite is accompanied by the addition of tin has been demonstrated by the writer (Hosking; unpublished studies) during a study of the small granite cusp near Cameron (St. Agnes). There, as greisenisation increases so also does the tin content of the rock. However, locally where silicification of the greisen has occurred the tin content of the rock proper falls markedly (Fig. 9) but in the silicified zone casiterite locally occupies voids after feldspar. Whilst it is not suggested that the visible cassiterite was derived solely from the tin which was mobilised in the immediate vicinity during silicification, it suggests that some, or all,

[1]The term muscovite is used here in a collective sense and embraces primary white mica, sericite and gilbertite.

TABLE 7: *A Comparison of the Metal Content of Biotite with that of accompanying Muscovite in Samples of Granite, close to and distant from Porphyry Dykes and Lodes, from the Carnmenellis Mass, Cornwall**

	Sample Type and Number	PARTS PER MILLION								
		Sn	Be	Cu	Pb	Zn	Ni	Co	W	As
NEAR LODES	B1	15	15	100	15	1,600	70	14	70	2.5
	M1	50	12	<1	15	110	<2	<1	60	<1
	B2	7.5	10	25	60	960	60	10	30	10
	M2	30	20	<1	15	100	<2	<1	25	<1
	B3	7.5	10	12	50	960	46	20	16	1.5
	M3	60	10	<1	7.5	110	<2	<1	35	<1
	B4	20	20	20	25	1,200	50	10	400+	5
	M4	50	10	4	25	100	<2	<1	25	10
NEAR DYKES	B5	15	12.5	20	50	880	46	14	240	3.5
	M5	40	30	<1	15	80	4	<1	12	<1
	B6	7.5	7.5	15	50	920	70	10	2	2.5
	M6	50	8	<1	110	130	<2	<1	50	5
	B7	25	7.5	8	40	840	40	10	40	2
	M7	60	15	<1	75	80	<2	<1	70	<1
DISTANCE FROM KNOWN LODES AND DYKES	B8	100	10	12	65	960	50	8	2	7.5
	M8	34	60	3	35	130	6	<1	20	<1
	B9	10	12.5	20	160	1,240	70	12	12	0.5
	M9	50	15	<1	600	160	<2	<1	20	<1
	B10	10	1	20	40	600	40	8	40	1
	M10	70	24	20	100	180	<2	<1	15	<1
	B11	30	12.5	160	50	920	70	10	160	10
	M11	50	10	<1	25	70	<2	<1	10	<1
	B12	20	15	20	25	800	30	4	50	30
	M12	50	30	4	50	130	<2	<1	60	<1
	B13	20	8.5	15	50	920	50	12	2	2.5
	M13	50	16	<1	15	70	<2	<1	60	<1
	B14	100	20	70	150	4,000	50	14	400+	10
	M14	54	12	<1	50	110	<2	<1	35	<1
	B15	40	15	25	50	1,800	54	10	40	15
	M15	40	10	2	25	110	<2	<1	70	<1
	B16	7.5	1	10	15	920	60	14	50	6
	M16	30	16	6	15	40	1.5	<1	8	<1
	B17	5	1	12	15	800	56	12	40	30
	M17	40	12	<1	25	80	2	<1	16	<1
	B18	28	0.5	15	25	720	64	10	30	10
	M18	20	14	<1	40	90	4	<1	16	<1
	B19	7.5	1	16	50	880	56	12	20	3
	M19	20	34	<1	—	80	2	<1	18	<1
	B20	15	0.5	15	25	800	56	20	30	0.5
	M20	30	32	<1	25	100	4	<1	8	1
	B21	5	2	20	40	840	60	24	40	2
	M21	30	40	<1	25	130	4	<1	16	<1

*Hosking, K. F. G., Roberts, A. L. and Usman Hamid (unpublished studies).

(B = Biotite : M = Muscovite) (All analytical methods used were of the rapid colorimetric type).

of the mineral may owe its origin to tin liberated by silicification of muscovite in depth and then transported in solution to the precipitation site.

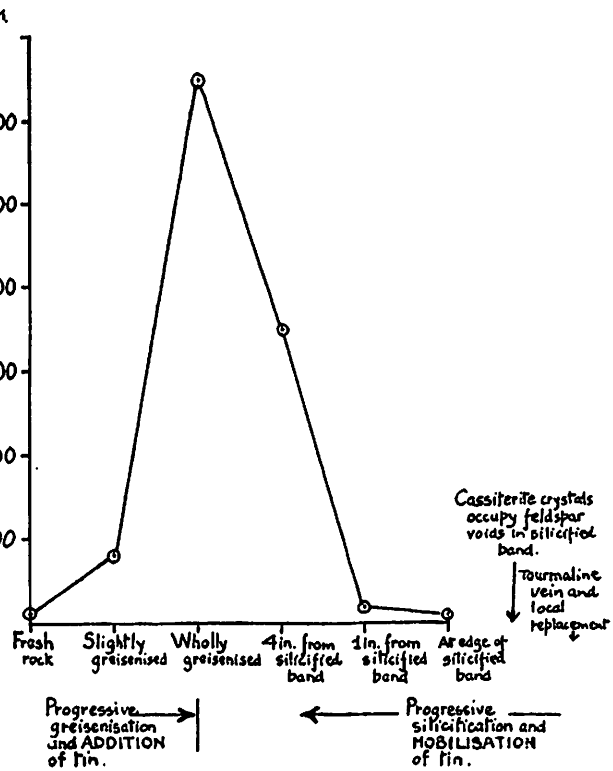


Fig. 9. Changes in the tin content of the Cameron Quarry (St. Agnes) granite during greisenisation and subsequent silification.

It is, therefore, tentatively held that some, or all, of the tin in all the Cornish lodes has been obtained from the muscovites (which in part, at least, developed from biotites) by a process which, besides mobilising the tin, promoted silicification of the mica. Table 7 also suggests that when biotite is converted to muscovite most of the copper and zinc (and several other elements) is lost. What happens to these mobilised elements? It is not possible that they migrate into the lode fractures and are precipitated at points where conditions are favourable? If this does happen it follows that some, at least, of the copper- and zinc-bearing species of the lodes may have been deposited *before* the cassiterite. That is to say, the general view that during the early phases of hypogene mineralisation tin was deposited in the deeper lode horizons and this was followed by the deposition of copper and zinc in the higher horizons, may not be entirely correct. It is, however, certain that some copper was deposited after the tin, as at Geevor Mine, for example, shattered cassiterite cemented by chalcopyrite is not uncommon. How much of this later copper has been derived from biotite by late mobilisation and how much has come directly from the residuum is unknown. At present it is also quite impossible to determine what proportions of all the other lode minerals have been obtained from the micas and from the residuum. Furthermore, only guesses can be made concerning the nature of the agents which promoted the mobilisation of metals in the micas and which transported these, and any metals from the residuum, to the various zones of precipitation. A summary of the writer's views concerning the initial phases of the genesis of the primary ore-deposits of the South-West occurs in Fig. 10.

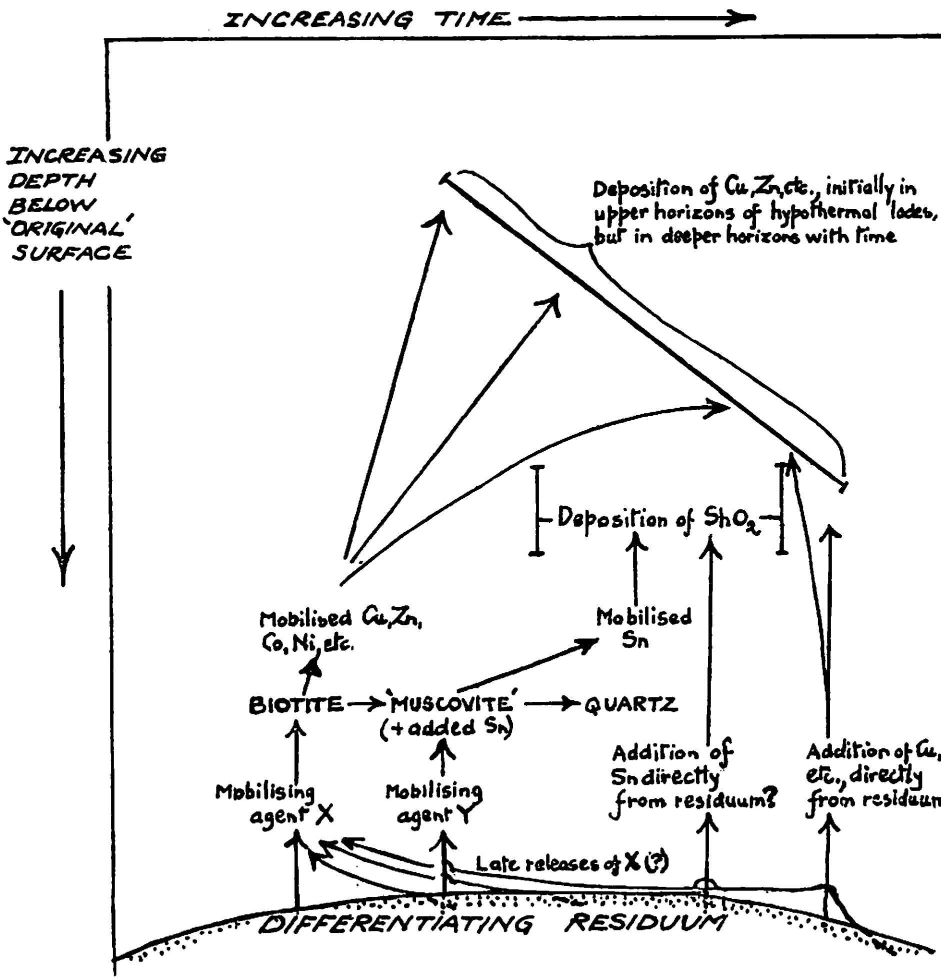


Fig.10. Suggested initial phases of the genesis of the hypothermal ore-deposits of the South-West of England.

It is not known if gases played any part in the ore-forming process, but if they did not then the solutions involved in the early phases of lode development, at least, must have been exceedingly tenuous as it can be demonstrated over and over again that they were capable of moving through knife-edge partings with apparent ease. It is, however, reasonably certain that regardless of the manner of transportation of the ore-forming elements from their sources to the zones of precipitation, deposition of the ore-minerals was from solution as the content of their vacuoles is characterised by a small gas to liquid ratio. The vacuole liquid is chloride-rich and so it is difficult to escape from the conclusion that chlorides may have place an important rôle in the genesis of these ores.

The temperatures of formation of even the early hypothermal minerals were probably not particularly high. Smith (1949, pp. 624-625) using the decrepitometric method obtained the following temperatures of formation for certain of the Cornish lode minerals:—

1. A vuggy intergrowth of tourmaline, cassiterite and quartz from St. Austell

Mineral	*Temperature of liquid when vacuoles filled*	*Corrected temperature assuming minerals were formed at a depth of 2 miles.*
Tourmaline	345°C.	390°C.
Cassiterite	345°C.	390°C.
Quartz	329°C.	370°C.

2. A coarse intergrowth of quartz, wolframite and chalcopyrite from South Crofty Mine

Quartz	293°C.	345°C.
Wolframite	242°C.	265°C.
	Chalcopyrite not recorded.	

3. An intergrowth of coarse chalcopyrite and quartz from Tincroft Mine

Chalcopyrite	261°C.	280°C.
	Quartz not recorded.	

Temperatures established by the decrepitometric method must be suspect because there is always the possibility of error due to loss or gain of vacuole liquid between the time when the minerals were deposited and the present. However, the above temperatures, when considered relative to one another, accord very well with what might be extected if the hypothermal minerals of the South-West developed, as is generally thought, under conditions of waning temperature. However there is the distinct possibility, as Schneiderhöhn's studies (1934) suggest, that the earliest phases of mineralisation took place under conditions of increasing temperature, and Smith's determinations are far too few to give a true picture. It would, for example, be of considerable interest to know the temperature of formation of the wolframite in the felspathic pre-tin lodes of South Crofty Mine.

From an absolute point of view Smith's temperatures may well be low as sphalerite containing exsolution bodies of chalcopyrite is extremely common in the South-West, and often it can be demonstrated that it post-dates spatially related cassiterite (both the 'normal' variety and wood-tin): if the experimental work of Buerger (1934, pp. 525-530) can be relied on, this sphalerite was deposited within the range 350-400°C.

That both early and late minerals which crystallised in lode fissures generally developed as a result of ascending solutions carrying material to the precipitation centres is proved by the fact that in the overwhelming majority of cases examined by the writer preferential deposition took place on the underside of crystals projecting into the fissures: this is indicated by the asymmetric development of projecting quartz and cassiterite crystals, by variations in the widths of growth bands (the widest being on the stoss side), and by the deposition of later minerals largely, or entirely, on the under surfaces of early crystals which behaved as baffles to the rising solutions.

Variations in the widths of given growth bands of quartz and other crystals also indicate that when such minerals were formed by replacement of country rock in the vicinity of a lode fracture system they were commonly fed by solutions with uni-directional flow, though the latter, not unnaturally, often departed markedly from the direction of flow in the adjacent major lode-fissures.

By contrast, local distribution patterns of lode minerals sometimes indicate that they developed by processes other than those described above. At Geevor Mine, for example, the writer has found dolomite crystals "sitting" on the upper surfaces of quartz crystals projecting into a druse. Though it is not absolutely certain it seems likely that the dolomite crystals developed during the cooling of a solution which was entrapped, and which, at the point in time when this happened, was almost saturated with calcium, magnesium and carbonate ions. Furthermore, in several of the lodes of St. Agnes almost perfect concentrically zoned spherules of wood-tin are found 'suspended' in quartz, and sometimes the spherules are covered by acicular crystals of cassiterite whose long axes are normal to the spherules' surfaces. It is difficult to escape from the conclusion that these interesting bodies depended for their development on the centripetal migration of tin-bearing ions through a silica gel.

Finally, examination of numerous thin and polished sections of the lode material of the region demonstrates that early-deposited species were commonly partly replaced (and probably, frequently completely replaced) by later species. Such replacements clearly indicate that some or all of the replaced species must have been mobilised and were either transported to higher horizons and used in the development of further lode species, or were dispersed in the micro-fractures, etc., of the country rock. Furthermore, the improbable replacements which are seen in primary lode material make it quite impossible to formulate any really comprehensive laws—in spite of what has been written to the contrary—which are applicable to hypogene replacement. The following are a few of the many unusual replacements noted by the writer (unpublished studies):—

(a) Wood-tin by chalcopyrite (West Wheal Kitty Mine).

(b) Cassiterite by wolframite (Cameron Quarry, St. Agnes).

(c) Wolframite by fluorite (South Crofty Mine).

(d) Arsenopyrite by sphalerite (Gwithian Area).

X. CONCLUSION

Short of writing a book it is quite impossible to do justice to all aspects of the subject with which this paper has been concerned. Some sort of compromise was obviously necessary, and the policy of the writer has been to give limited space to a particular topic, such as wall-rock alteration, which is likely to be dealt with at some length by those writing companion papers, and to deal comprehensively with present-day views concerning the genesis of the mineral deposits—particularly those which are not widely known.

He has also endeavoured to high-light some of the numerous questions which still lack unique answers as it is still all too commonly believed that little work of importance remains to be done on the ore-deposits of the South-West.

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