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"The Geology and Mineralization of Geevor Tin Mine, Cornwall".

A Thesis submitted for the degree of
Doctor of Philosophy
in the Faculty of Engineering
of the
University of London.

by

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ABSTRACT

Geevor Mine is situated on the northern flank of the Land's End Granite in the St. Just mining district of West Cornwall. Steeply-dipping, NW-SE lodes, with an average width of 2 ft., are confined to the granite. The latter is overlain by metamorphosed 'killas' and a conformable 'greenstone' series which possesses an overall North-West dip. Their previous folding controlled the emplacement of the granite, and their structure was further distorted during the intrusion stage. Tin, as cassiterite, with copper as a by-product, is produced from nearly twenty lodes, many of which have now been completely exploited.

A greater degree of fracturing, comprising primary and secondary granite joints initiated by a continuance of the horizontal maximum stress operating during intrusion, allowed the increased vertical stresses associated with mineralization to be accommodated by movement along pre-existing joints. Elsewhere in Cornwall new fissures, now equivalent to the lodes, were created.

Preliminary movement comprised block faulting, the limits now being defined by 'post-mineralization' faults and fault zones, and occasionally by a marginally-mineralized lode. Individual blocks were eventually subjected to wedge faulting, each wedge being defined by the lodes. The corresponding movements, both normal and reverse faulting, may be evaluated from displacements exerted upon numerous small dykes.

Complete lode mineralization was attained by a series of phases, commencing with wall-rock alteration, and separated in time from late quartz-rich phases by the cassiterite- and sulphide-bearing associations. The extent of distribution of each phase product was influenced by strong structural and temperature controls, demonstrated by constructing contour diagrams.

Post-mineralization movements along the earlier limits of block faulting created an additional form of 'cross-course' or 'guide', which was infilled with quartz associations, as opposed to the other which appears only as planes of complex movement.

"The Geology and Mineralization of Geevor Tin Mine, Cornwall".

Volume I

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"It is a mettall growing for the moste part amonge the hard and infrangable rocks, in the Moares and mountaynes the owre thereof being an obdurate stone spred in the veynes of the mountaynes, whereof the workes and maner of working is of two sortes, Streame workes and Loade workes. The Streame are in the brookes, in the valleys amoung the hills. The Loade workes in the mountaynes. The Streame workes are shallowe and more easie: the Loade workes deepe, paynfull and dungerous."

..... Carew's "Survay of Cornwall". (1602)

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Fig. (F) Plan of the Underground Workings of Geevor and North Levant Mines, 1925: Scale, 1 inch to 100 feet.

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1. INTRODUCTION

1/1. Scope of the Present Study.

Gaunt stone fingers pointing to the sky are all that the casual traveller in the South-West of England sees of what were once the never silent winding and pumping engines of the now disused mines. Apart from the endless waste tips they are all that remain to remind the visitor of the existence of one of the world's greatest mining districts. Only two operating mines at the time of writing are left to carry on the tradition of Cornish mining; a tradition that has been carried by the "Cousin Jacks" to every corner of the world where ore is mined. One such mine is that operated by Geevor Tin Mines, Ltd. Six miles North-West of Penzance (Lat. 50° 9', Long. 5° 41'), the property lies on the coast in the mining district of St. Just. High steep cliffs form the Northern boundary to the area, while in other directions are the bare undulating hills and moorlands of the Land's End Granite.

The writer first visited Geevor Mine during 1957, but this thesis represents the results of his work which commenced in July 1958 and continued until October 1961. It has also been borne in mind by the writer that one of the prime reasons for research in the field of economic geology is to increase the understanding of the genesis of a deposit so as to be able to predict hitherto unknown areas of mineralization for underground exploration and development. Very little work of a geological nature has been carried out at Geevor Mine in recent years and it is now the only remaining accessible mine in the

St. Just area. With this in mind the writer decided that in the time available most new information would be gained by making a complete underground examination of the workings. After one year's work upon the mineralization and allied subjects it became apparent that such studies must be based upon a more complete understanding of the structural history of lode formation than was at that time available. Thus, before progressing further an attempt had to be made to establish the role played by structural influences. The initial structural studies during the latter part of 1959 proved so rewarding that the entire emphasis of the work was changed in July 1960 towards an investigation of the effects of structural control upon the degree, location, and extent of the tin mineralization.

Since no workings are forever accessible the writer hopes that the present thesis may form the basis for future more detailed work upon the mineralogy and other specific aspects of the geology of the Geevor Mine. An effort has been made to make the maximum possible number of underground observations and a total of 35 weeks has been devoted to studies underground. In short, the writer considered that as a mining geologist, a large proporation of his time could be most profitably spent 'in the mine'.

Specimens obtained and lodged both in the Royal School of Mines and the Geological Office of Geevor Mine are available for laboratory research, even though the workings from which they were collected are no longer accessible. It is for this reason that the thesis may appear to be too

heavily biased towards a study of the structural control of mineralization rather to a meticulous study of specimens in the laboratory. Nevertheless the present work has involved an examination of 650 hand specimens, 215 thin sections, 103 polished specimens, and 83 bulk lode samples, with the aim of deciphering the different successive phases of mineralization and determining their distribution.

Although the work has centred upon Geevor Mine it is hoped that the knowledge gained there may be usefully applied to the whole of the St. Just mining district, and that it may be of some assistance to exploration, development, and the day-to-day working of the mine.

"If I am in the wrong, my errors may set the minds of others at work, and may be the means of bringing both them, and me, to a knowledge of the truth."

Thomas B. Macaulay (1836).

1/2 Layout of the Thesis

The Thesis is presented in the form of three volumes, the contents of which are as follows:

Volume I - The Text

Volume II - Figures

Volume III - Photographs

All three contain a number of folded maps, plans, and diagram

The Text is naturally divisible into two sections. One is concerned with the South-West of England, especially the Land's End Granite, and the other deals with the Pendeen-Botallack area and Geevor Tin Mine. The first section provides a summary of the structure of the South-West, a subject to which new ideas are constantly being added. Mineralization has been dealt with briefly since the majority of the information was published by Henwood (1843), Collins, (1912), Hosking (1949 & 1951) and Dines (1956). The greater proportion of these subjects were discussed by Webb (1947) in his PhD. Thesis entitled "The Origin of the Tin Lodes of Cornwall", and the present writer acknowledges his frequent reference to, and dependence upon, this major work.

Many results of this investigation are applicable only to Geevor Tin Mine. Some of the more general conclusions, however, concerning the tectonic history and structural, temperature and petrological control of the tin-copper mineralization are relevant to the whole of the Cornish mining district. Before comparisons could be made it was therefore necessary to summarize the existing theories and knowledge.

1/3 Acknowledgements

With the increasing and essential integration into industry of the specialist, the latter is too frequently criticized for his apparent lack of understanding of the whole 'operation' and his failure to view his own sphere of work in perspective. Too often it is an example of the management's short-sightedness and ignorance of the potential value of a detailed study, and the inability to appreciate another approach. This results in a failure fully to utilize the services of the specialist. When understanding and tolerance do exist it is to the mutual advantage of all concerned and to the benefit of the operation as a whole.

For this reason the writer has found it a particular pleasure to be able to work with Mr. D.H. Batchelor, Manager of Geevor Mine. Both he and Mr. G.W. Simms, Chairman of the Board, have provided every possible assistance and encouragement. The other members of the Board of Directors and all the mine staff have been ready to give of their time. The late Mr. J.H. Bennetts, Manager, Mr. A. Bennetts, Chief Surveyor and Mr. H. Grenfell, Underground Manager, have been especially helpful through their knowledge and experience of the mine. A special note of thanks is accorded to Mr. J. Trembath, Chief Sampler, who has acted as a completely reliable assistant and generously given of his time and energy throughout the course of the investigation. Assistance has also been provided by Messrs. R. Cox, R. Taskis and R. Falcon-Steward.

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Photographs of hand specimens of typical Geevor ore have been produced with the advice and patient assistance of Mr. J.A. Gee, to whom thanks are gladly acknowledged.

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1/4 History of Geevor Mine

The commencement of the Cornish Mining industry is lost in legends, and there are many familiar theories that the Cassiterides of Herodotus were the rocky Cornish coastline or the Scilly Isles. The oldest reliable records show that tin mining was an organised venture in the 11th and 12th Centuries, but it is most probable that there was a very ancient commerce in tin between the Mediterranean and South-West England for a long period. The Phoenicians and the Romans, especially during the 3rd Century A.D., appear to have conducted a considerable trade, as described by Greatheed (1822), Barham (1828), Whitley (1912, 1914, 1915), Hamilton Jenkin (1948), Rowe (1953) and others.

The very first workings for tin in the St. Just area were most probably in alluvials which were traced back to the primary deposits. The first tin ore reputed to have been won by the Romans by underground mining of the lodes came from Ding Dong in the centre of the Land's End Granite. Their attentions must have turned at a very early stage towards the St. Just district where the lodes could be observed outcropping on the cliffs. Because the average lode strike is normal to the coastline, the area is one of the few parts of Cornwall where cliff outcrops of the lodes are at all numerous. Adits from the high water mark could de-water over 300 feet of ground, and thus one of the greatest of their mining problems, drainage, was overcome by natural means. The history of mining in the St. Just area, of which the main Setts are shown in Fig.(13),

has been briefly dealt with by Dines (1956) who writes as follows:

"The area is an ancient one from the mining standpoint and many of the mines, after commencing as individual concerns, have been amalgamated into groups which, in turn, have changed from time to time, so that some of the mines have passed from one group to another. According to published records, the chief tin producer was the Levant group with an output of over 26,000 tons of black tin, and the Botallack group that yielded over 15,000 tons was second, while other important tin mines were the Wheal Owles group, Geevor Mine, St. Just Amalgamated or St. Just United and Boscaswell Downs Mine. The Chief copper producers were also Levant (over 130,000 tons of copper ore) and Botallack (over 124,000 tons), but the only other outstanding copper mines seem to have been Pendeen Consols and Boscaswell Downs. Arsenic, also, was raised chiefly at Levant and Botallack and a small amount also from Wheal Owles and Geevor Mine. The area seems to have been at the peak of its productivity in the latter half of the 19th Century. Mines that have been active during the 20th Century are Geevor, Levant, Botallack, Hermon, Bellan, Boscaswell Downs and Pendeen Consols; the last two due to an unsuccessful re-opening. The only mine active to-day is Geevor, in which, though the mine is on the coast, the tin lodes, so far, have only been exploited in granite country."

The first reliable record of workings in the Geevor sett is provided by a date cut into the wall of Level 3 near the Carne Shaft. Fig. (16) and Fig. (9) show the location of the Level 3 adit, extending from the Carne Shaft to the coastline, which appears to be the first exploratory adit above the present Geevor Lodes. Connected to the adit were several shafts, including Thorn's, Mexico, and Roberts Shafts. A number of small lodes were located as shown and very selective stoping was carried out from closely spaced levels.

The adjacent North Levant Mine, the lodes of which are shown in Fig. (14), was active before 1910, and Wheal Carne, operating from the Carne Shaft under the name of Maitland, was producing between 1836 and 1856. Fig. (C) indicates the extent of the proved lodes by that time, and their

relation to the whole of the St. Just district is indicated by Fig. (E). Access to the present lodes of Geevor Mine was first gained via the Carne Shaft to a depth below collar of 668 feet on the dip of the North Pig Lode. Development to the North-West necessitated the sinking to 805 feet below collar of the Wethered Shaft upon which work commenced in 1909. Geevor Tin Mines, Limited was formed in 1911, as described by Gregory (1925), and took over the property then being worked by North Levant and Geevor Limited. The lodes located between the Carne and Wethered Shafts included the North Pig, South Pig, Jumbo, Caunter, Black, Blue and Mundic Lodes, the positions of which are depicted in Fig. (16). These were developed on several main and intermediate levels, with additional travelling ways providing access to the surface.

In 1912 the 40 tons per day mill was replaced by a four-stamp mill capable of treating 100 tons per day. However, development was continuing more rapidly to the North-West and it soon became apparent that the future development of the mine lay in this direction. Cann and Sevier (1927) described how the Victory Shaft was consequently collared in 1920 at a point approximately 1660 feet to the West of the Wethered Shaft, as shown in Fig. (B). The plan of Geevor and North Levant Tin Mines, reproduced as Fig. (F), shows the extent of the workings of both the Geevor Mine and the abandoned North Levant Mine in 1925, by which time the following lodes had been located and developed; South Pig, North Pig, New, North, No.2 Branch, No.1 Branch, North-West Branch, Hanging-Wall Branch, and Footwall Branch.

Ore was raised in both shafts until 1944 when hoisting was discontinued in the Wethered Shaft, and the aerial ropeway used for transporting ore to the mill below the Victory Shaft was closed down. Sevier (1945) summarized the continued underground development of the mine and the lodes have now been worked from 15 levels on the Victory Shaft, the latter having been sunk to the equivalent of Level 16. The datum heights of all the levels of Geevor Mine are given in Table (2).

Both a practical mining definition and a geological definition of a tin lode embrace the structural and mineralogical character of the mineralization. The practical definition, however, takes into account the average grade of the ore and the extent, both laterally and in depth, of the economic ground. The term 'Prospect' is applied to those lodes which comply with the geological definition but have not been, or do not appear likely to be, major producers of tin. The lodes of Geevor Mine, many of which have now been completely worked out, are shown in Fig. (30) and are as follows:-

Coronation Lode
North Lode
North Pig Lode
South Pig Lode
New Lode
Wethered Lode
Borehole Lode
Caunter Lode
No.1 Lode
No.2 Branch Lode
No.3 Branch Lode
'A' Lode
'C' Lode
'D' Lode
Footwall Branch Lode
North Levant Lode

The Hanging-Wall Branch Lode was largely unproductive and was employed mainly as a cross-cut. The No.1 Branch Lode, between the No.2 Branch and North Pig Lodes, has been omitted from Fig. (30) due to the complexity of the workings in its vicinity. Cronfell Lode has also been omitted,

since its discovery in 1961 post-dated the construction of the diagram. Of the several prospects which occur, only the following, being the more important, have been illustrated:-

Wethered No.2 Branch Lode
North-West Branch Lode
Prospect No.1
Prospect East
Prospect South

Exploration in the vicinity of the Wethered Shaft disclosed several small lodes in the upper levels, the positions of which are given in Fig. (16).

The lodes are confined, with the exceptions illustrated in Fig. (27), entirely within the granite and follow a roughly parallel strike in the NW-SE direction. They are separated, as shown by the sections in Fig. (29), by distances of between 50 and 500 feet. Apart from a small number of local variations they dip to the South-West at an average angle of 70 degrees, but varying between 55 degrees and vertical. Some lodes, such as the North Pig, Borehole and Grenfell, consistently dip to the North-East for considerable lengths. Where the lodes intersect, as they frequently do, the angle of intersection in plan is in the order of 35 degrees, as illustrated in the plan of the workings on Level 12 in Fig. (31).

The width of the lodes, including both the infilling and the frequent intense wall-rock alteration, varies between 3 feet and one or two inches, with a mean value of around 18 inches. The mean length over which the lodes carry economic values is in the order of 1,000 feet, with a maximum of 3,000 feet. This is in excess of the total vertical

extent, as defined in the same manner, which varies between 300 and nearly 1,000 feet. Any lode which has not been proved to exist over more than one or two levels is regarded as a prospect.

There is a gradual increase in the depth of the economic mineralization towards the North-West and the granite contact. This feature is most clearly seen in the longitudinal section of the North Pig and No.2 Branch Lodes, provided in Fig. (23). Dines (1956) has adopted this characteristic of the Geevor lodes to illustrate the zoning effect upon the mineralization of an adjacent sloping granite surface. This results in the deepest workings on Level 15 being confined, to date, to the North-West of the Victory Shaft, and, in particular, to the Coronation, No.2 Branch and No.1 Lodes.

The present workings of Geevor Mine are shown in relation to those of the surrounding disused mines in Fig. (H), which also indicates all the known workings in the Pendeen-Botallack area. Transverse sections through the area, along the lines given in Fig. (19), are provided in Figs. (20), (21) and (22). These figures, in common with the majority included in the thesis, were constructed in December 1960, and do not show the results of recent (1961) development within Geevor Mine. A more complete description of the lodes, both of their structure and mineralization, is provided in later sections.

PRODUCTION RECORD

Table (1) — GEEVOR TIN MINES, LIMITED

	Tons of Ore Milled	Tons Black Tin Produced	Recovery (lbs)
From 22nd Feb. 1911 - 30th June 1912	14,455	147.5	
" 1st July 1912 - 30th Sept. 1913	24,546	258.0	
12 months ended 30th Sept. 1914	25,246	376	
" " " 30th Sept. 1915	25,487	353	
15 months ended 31st Dec. 1916	28,683	444	
" " " 31st March 1918	26,313	416	
Year ended - 31st March 1919	25,919	439	
" " - " " 1920	28,324	432	
From 1st April 1920 - 31st Mar. 1922	23,508	331.302	
		17.661	
		26.103	
Year ended - 31st March 1923	11,957	190.768	
1924	30,594	380.0	
1925	38,861	530.128	
1926	40,706	436.8	
1927	35,340	495.197	
1928	46,908	609.35 (65%Sn)	
1929	49,920	739.638	
1930	57,873	810.85	31.36
1931	25,954	376.18	32.46
1932	5,736	91.05	35.55
1933	38,785	632.61	36.5
1934	55,907	742.45	29.74
1935	61,892	783.438	28.35
1936	56,606	876.84	34.70
1937	57,912	920.66	35.60
1938	60,850	821.10	30.22
1939	65,949	1033.5	35.10
1940	64,392	851.0	29.60
1941	70,812	862.5	27.28
1942	60,351	701.5	26.03
1943	65,479	831.61	28.44
1944	65,181	681.02	23.40
1945	49,618	577.29	26.06
1946	44,943	552.608	27.54
1947	45,537	530	26.07
1948	49,839	641.6	28.84
1949	53,866	627.9	26.11
1950	49,634	638.6	28.82
1951	53,978	734.0	30.46
1952	55,020	740	30.12
1953	55,027	600.29	24.43
1954	54,930	682.34	27.82
1955	54,957	634.69	25.87
1956	55,404	652	26.36
1957	63,281	702	24.85
1958	63,829	683	23.97
1959	63,484	683	24.1
1960	65,662	648.48	22.12
	2,169,455	27,967.059	28.876

Table (2)

Geevor Tin Mines, Limited

Total Surface Area

Geevor Sett, including Levant ground, acquired in 1933	317.040	acres
Boscaswell, acquired in 1936	280.135	"
Calartha, " " "	35.195	"
Pendeen, " " "	31.773	"
Portheras, " " "	31.968	"
Trease, " " "	28.188	"
	724.299	acres

1/5 Mining Methods

With a present average level interval of 100 feet the lodes are developed by 6 x 7 foot drifts, employing a 32-hole burn cut on the strike of the lode. At intervals stope raises are driven to the level above and 6 foot interdrives over the stope width leaving a 6 foot floor pillar connect the raises. At 20 ft. centres chute connections, later serving as drawpoints, are driven from the level below to the interdrive. Shrinkage stoping commences from the interdrive by overhand benching, retreating from the original raise with a stope width of 40 inches. As described in 'Mine and Quarry Engineering' (1955) the overhand stoping continues until the back has attained a point approximately midway between the two levels and the working faces have been taken back at least 100 feet on either side from the original stope raise position. At this stage underhand benching starts to retreat from the raise, the 4 foot pillar left under the level above being holed at 20 foot intervals.

Owing to the narrow stoping width of 40 inches the above stoping method has been developed in order to reduce the time the ore remains in the stopes and thereby prevent ore consolidation. Ground support by timber stulls is small and dilution is not a serious problem. The 40 inch stoping width is the minimum practical working width by which the entire lode, which is considerably narrower, may be extracted.

In 1954 the timber headframe and original steam hoist of the Victory Shaft were replaced respectively by a galvanized rolled steel headframe and a 450 h.p. double drum electric winder (Mine and Quarry Eng., 1955).

Although at present hoisting from the skip loading station below Level 14, the hoist has been designed for hoisting from an ultimate shaft depth of 2,500 feet with a maximum rope speed of 25 feet per second. The shaft dimensions are 15 feet by 6 feet within the timbers and an output of 58 tons per hour will be possible from this deep horizon. Underground transport is by trains of 1 ton side-tipping Hudson cars hauled by 18-inch gauge battery locomotives. Ore hoisting in the Victory Shaft is from one horizon and the broken ore is transferred through worked-out stopes by control chutes, gates and grizzlies to a station 55 feet below Level 14.

All ore hoisted in the Victory Shaft is treated in the Geevor Mill with a flowsheet comprising crushing, grinding, washing, flotation, vanning, tabling and so forth. Further details are provided by A.D. Bennetts (1945), (and Mine and Quarry Eng., 1955) but the flowsheet has since been improved.

The mine possesses an underground labour force varying seasonally between 100 and 150, and working a day-shift only. With an average yearly development footage (including cross-cutting, rising and winzing) of approximately 8,000 feet, the following production figures for the year ended 31st March, 1961 may be regarded as typical of recent years.

Tonnage hoisted through the Victory Shaft ..... 68,432 tons

Ore milled after hand sorting ..... 65,151 tons

Tons of black tin produced (65%Sn.) (dry wt.) ..... 657 tons

Average recovery per ton milled ..... 22.26 lbs. B.T.

(Black tin = SnO_2)

Past production details are provided in Table (3) and are supplemented by Annual Reports of Geevor Tin Mines Limited, complete copies from 1911 being held at Pendeen.

Table (3)

Geevor Tin Mines, Limited

Levels and Datum Heights

	Feet	Total Depth Feet		Reduced to Ordnance Datum Feet	
Wheal Carne Shaft			≠	549.75	
From Surface to Shallow Adit	174.73	174.73	+	375.02	
" Shallow Adit to Dug-Out	77.75	252.48	+	297.27	
" Dug-Out to 2nd Level	94.76	347.24	+	202.51	
" 2nd Level to 3rd Level	111.76	459.00	+	90.75	
" 3rd Level to 4th "	70.00	529.00	+	20.75	
" 4th " " Intermediate	71.09	600.09	-	50.34	
" Intermediate to 5th Level	61.50	661.59	-	111.84	
" 5th Level to Sump	7.00	668.59	-	118.84	
Wethered Shaft			≠	424.54	
From Surface to 3rd Level	350.00	350.00	+	74.54	
" 3rd Level to 4th Level	64.52	414.52	+	10.02	
" 4th " " 5th "	145.95	560.47	-	135.93	
" 5th " " 6th "	79.24	639.71	-	215.17	
" 6th " " 7th "	154.07	793.78	-	369.24	
" 7th " " Sump	12.00	805.78	-	381.24	
Victory Shaft			+	322	above
Collar to 3rd Level	260.00	260.00	+	62	"
From 3rd Level to 5th Level	150.00	410.00	-	88	below
" 5th " " 6th "	80.00	490.00	-	168	"
" 6th " " 7th "	100.00	590.00	-	268	"
" 7th " " 8th "	75.00	665.00	-	343	"
" 8th " " 9th "	100.00	765.00	-	443	"
" 9th " " 10th "	100.00	865.00	-	543	"
" 10th " " 11th "	109.60	974.60	-	652.6	"
" 11th " " 12th "	114.75	1089.35	-	767.35	"
" 12th " " 13th "	116.88	1206.23	-	884.23	
" 13th " " 14th "	114.95	1321.18	-	999.18	
" 14th " " 15th "	112.45	1433.63	-	1111.63	
" 15th " " 16th "	116.01	1549.64	-	1227.64	

Ordnance Datum is that of Liverpool subject to correction for that of Newlyn.

2. GEOLOGY OF SOUTH-WEST ENGLAND

2/1 General Geology

Following upon the work of Hill (1901) on the general geological setting of the mineralization of South-West England, Reid and Flett (1907) provided a firm foundation for further stratigraphical and petrological work in the area. Their work was supplemented by that of many of their contemporaries in the Geological Survey, notably by Ussher (1912, 1913), Reid, Barrow et al (1910, 1911, 1912), Ussher, Barrow et al (1909), Reid and Scrivenor (1906), Hill and Macalister (1906) and Barrow (1906). Hendriks (1937) and Stubblefield (1939), basing their work upon that of the Geological Survey, radically revised the earlier results. As Webb (1947) provided a comprehensive summary of the prevalent views held at that time, the writer proposes to give no more than a brief précis of the general geology of the region.

Although sedimentary rocks of Ordovician age were once erroneously included in the Cornish succession it is now generally agreed that, with the exception of the Lizard Complex, the earliest strata exposed in Cornwall are of the Devonian age. Hendriks (1937) assigned them to the Lower Devonian, and it was usually considered that the so-called Mylor division is of this age. Recent work by Lacy (1960) in the Land's End area has shown, however, this hypothesis is open to question. The youngest strata in the South-West of England are the Carboniferous Culm measures of Devon.

The sedimentary strata, known locally as 'killas', were deposited near the northern perimeter of a Hercynian geosyncline and are mainly poorly fossiliferous clay-slates. They have been intruded by acid and basic rocks, the latter occurring both as pillow lavas and as injected sills, originally of doleritic type. Both the 'killas' and the basic rocks, known as 'greenstones', have been influenced by the Hercynian Orogeny, although to varying extents and with differing results. Some confusion has been caused by the nomenclature given by various authors to the orogenic periods affecting ... South-West England. This arises through the terms being applied both to time periods and to folding with a definite trend direction. Several writers have used the terms Hercynian, Armorican, and Variscan, the latter having been further sub-divided. The writer prefers the definition provided by Stille (1924).

The 'killas' and 'greenstone' were folded and thrust by the Hercynian Orogeny, the climax of which was the intrusion of Permo-Carboniferous granites. Granite is visible as several major and minor exposures extending from the Scilly Isles to Dartmoor, and is doubtless continuous at depth, as indicated by the recent work of Bott, Day and Masson-Smith (1958) and as suggested previously by Hosking (1949).

Regional metamorphism of the area is at a maximum in the south, towards the Meneage thrust zone, and decreases to the north. Adjacent to the granite contacts metamorphism of the 'killas' has produced hornfelses, phyllites, and slates, and converted the 'greenstones' into complex hornfelses. An acid dyke stage followed the intrusion of the

granites. Aplites, pegmatites and quartz porphyry dykes, known locally as 'elvans', were intruded into both the granite crusts and the country rocks. Fracturing of the rocks and movement along previously developed fracture planes provided channel-ways for fluids which effected pneumatolytic alteration of the wall-rocks and finally for the passage of ore fluids. This phase culminated in low temperature modifications, and the whole episode resulted in the development of mineral lodes centred around focal points in the granite surface, as indicated by Dines (1933).

Extensive marine and aerial erosion of the region continued until Pliocene times, exposing many of the granite masses and mineralised areas. The Tertiary period is represented by sands and gravels such as those exposed upon St. Agnes Beacon, by raised beaches and alluvial tin deposits of Pleistocene age, and by alluvium, head and peat such as those on the coast at Prah Sands. A series of raised beaches indicates several phases of elevation, depression and tilting of the land. Further general information, together with a comprehensive list of references, on the geology of South-West England is provided by Dewey (1948).

2/2 Stratigraphy

Until the beginning of the 20th Century work on the stratigraphy of S.W. England had tended to consist of detailed studies in unconnected areas, until Hill and Macalister (1906) provided the first overall succession. Their results were revised by Green and Sherborn (1912) who considered that, as previously stated by Green (1904), the majority of the beds previously designated as Ordovician and Silurian, were Lower Devonian (1913). Miss Hendriks (1937), after her earlier paper (1931), summarized all previous opinions and work and completely revised pre-existing views. She proposed the name 'Gramscatho Beds' for those which had previously been represented as 'Manaccan', 'Grampound', 'Ladock', 'Falmouth', 'Porthscatho', and part of the 'Veryan', etc. Evidence was given that the 'Gramscatho Beds' lay above the Lower Devonian rocks (Meadfoot Series). The 'Mylor Beds' in the Land's End area were assigned to the Lower or Middle Devonian, and Lower Palaeozoic rocks were thought to be represented by lenticles of limestone and quartzite torn up from depth by the Lizard thrust movements, so as now to lie in the Meneage crush-breccia. The map of Cornwall based on Miss Hendriks' new interpretation is reproduced as Fig. No.(4).

The age determination afforded by fossils discovered in the crush rocks was questioned by Stubblefield (1939), who suggested that some of them should be referred to the Lower or Middle Devonian. Miss Hendriks (1939) contributed further to the discussion and later summarized some of the still outstanding problems, besides comparing the stratigraphy of

Cornwall and of Bohemia (1949). She provided a synthesis of her views in the form of a diagram showing the relations and developments of the Devonian rocks of South Cornwall (1949). A short summary of existing views, including those of Stubblefield, was written by Dewey (1948), to whose paper the reader is referred for further details and references. Controversies continue in the light of new evidence supplied by several workers, including Stubblefield (1958) and Lacy (1958).

The sedimentary rocks of South-West England are essentially a series of clay-slates with sandy and calcareous beds, grits, shales, cherts, limestones and sandstones. The slates vary in colour from buff to grey, green to purple, and are poorly fossiliferous. They have been described by Miss Hendriks (1949) as "dull and monotonous" and for further detailed information the reader is referred to her descriptions (1937, 1949).

The strata are interbedded with several series of pillow lavas and many basic masses occur either as intrusive sills or flows. The whole basic group has been referred to as 'greenstones', but it represents a complex suite of widely differing original types which have been metamorphosed to varying degrees. Some correlation has been attempted between separated 'greenstone' masses, as described by Reid and Flett (1907), Evans (1917), and other workers, but care has to be exercised. To the economic geologist the 'greenstones' are of importance because their study helps to elucidate the overall structure of an area. They may also exert an influence upon the mineralization, either by structural or other controls.

2/3 Structure

(a) General Structural History

An understanding of the structure of the mineralized areas of the South-West is dependent upon an interpretation of the overall structure which extends into Somerset and even South Wales. All the early workers recognized the fact that the area had been thrown into a series of roughly East-West folds which were later complicated by thrusting. Most of the old interpretations of the structural history were dependent upon a reliable stratigraphical account, and until this was available they consisted of the recognition and elucidation of relatively small-scale structures in the 'killas' over small areas, coupled with a vague overall interpretation based upon the mapping of the Geological Survey. Evans (1926) recognized that the area, in common with large parts of Western Europe, had been subjected to roughly North-South compression during the Hercynian Orogeny, a term which he defined as follows:-

"By some authors it has been used to signify mountain folds with an approximately east-and-west strike, the 'Armorican' of others; and by other authorities faults and folds with a north-easterly and south-westerly trend, sometimes termed 'Variscan'. By still others, including Marcel Bertrand, it was used to designate the earth-movements extending in their more intense manifestations from later Carboniferous to early Permian time. This is the sense in which I (Evans) shall employ it, and not as denoting any particular direction. It will, therefore, include both the Armorican and Variscan chains of Suess. To the word 'Caledonian' have also been assigned several different meanings. I have employed it, not as meaning a particular strike of folding, but a period of disturbance extending over late Silurian and early Devonian times."

The Culm Syncline, depicted in Fig. (4), passes in an East-West

direction through Central Devon. Its axis is composed, as described by Ussher (1829) and Owen (1950), of Carboniferous Culm Measures. To the North of the syncline marine Devonian rocks with Old Red Sandstone intercalations outcrop between Barnstaple and Minehead. To the South the Devonian slates, sandstones and limestones are folded in a roughly East-West direction, as discussed by Miss Hendriks (1937) and Dewey (1948). The structure is complex and is described by Webb (1947) as involving "tight isoclinal folding, synclinoria and anticlinoria, and complex imbricate structure". Miss Hendriks (1937) ascribed the latter to "a series of almost strike thrusts, which cause repetitions of the sequence and of a crush zone belonging to an earlier (Variscan) phase or period of movement." She attributed the great Lizard Thrust, previously given a late-Carboniferous age, to late-Devonian or early Carboniferous Variscan movements, which were also responsible for the unconformity between the Culm Measures and horizons of the Upper Devonian.

Fig. (4) shows the dependence of structural theories upon the correct elucidation of the stratigraphical history of the area. Miss Hendriks (1937) provided a comprehensive account of the stratigraphy and structure of the area, upon which the work of later writers has been based. She made many comparisons between the South-West of England and Central Bohemia, summarizing her views as follows:-

"Earth movements ascribed to the Variscan folding are first indicated in South Cornwall in the middle Gramscatho and in central Bohemia after Stage H. The main movement in both areas began towards the end of the Devonian period (earlier than in the neighbouring regions of central Europe), the earliest stages of the Variscan folding being accompanied by immense volcanic manifestations of similar type

(Bohemian diabases and keratophyres), with lateral compression from the South-East, and serpentine intruded in and just above a great thrust. The serpentine, also, is closely associated in both areas with limestones belonging to two areas: to the Upper Devonian and Stage E of Bohemia. It is closely followed in central Europe, as at the Lizard, and with a similar strike between NNW. and NNE., by gabbro and granite-gneiss. Lastly, in both areas the serpentine occupies the inner part of a region the periphery of which is marked by granite belonging to a later (and apparently unrelated) cycle. In South Cornwall and central Bohemia not only the rock and faunal facies, but the tectonic and igneous events also correspond."

Numerous writers have recognized that both the trend of fold axes and the attitude of the cleavage in the 'killas' imply compression in a roughly North-South direction, with local variations between N-S and NW-SE. Evans (1926), in a purely theorectical discussion, suggested that early Hercynian compression in a roughly N-S direction had acted upon an area which possessed a slope from the South to the North, with the result that the early folds tended to be recumbent towards the North. With increasing compression, the strata were impressed with a slaty cleavage dipping to the South. When no further relief by folding was possible, fracturing along thrusts took place. According to Evans the earlier movements were accompanied by basic intrusions invading both Devonian and Carboniferous strata, and culminated in the intrusion of granites and the emplacement of associated mineral veins. The granite magma was considered to have previously lain beneath Pre-Cambrian rocks to the South and to have been moved by the thrusting into the periphery of the distorted geosyncline.

(b) Age of the Folding

Folding in the South-West is not of a simple nature, and the fact

that there may be fold systems of more than one age has been recognized by all writers. Some confusion has existed in the past owing to the varying nomenclature given to the different fold trends. The folds may be classified into separate systems on the basis of either their age or their direction. The writer prefers to adopt the various terms such as Hercynian, Variscan, Caledonian and Armorican, for stating age relationships only and to denote the trend directions of folding directly. Miss Hendriks' (1937) concluding views on the structural history of Cornwall are epitomized in the following extract:

"In crossing Cornwall from North to South, from Pentire Head to the Dodman, or from North-East to South-West, from Davidstow to Mullion Island, the major synclines are deepest on the Northern side of the Watergate-Dartmouth anticline. The depth in the extreme South is less, owing to the pinching out of the southernmost syncline by the great Variscan overthrust on its flank. This was part of the movement which determined the earlier deformation of the area (including the metamorphism of the Lizard schists and Variscan serpentine magma, intruded at depth during the folding that preceded the Armorican movements and determined the trend of the later Devono-Cornish chain). Then followed uplift of the folded structure, the later deformation being associated with the intrusion along the anticlines of the post-Carboniferous granites".

Miss Hendriks (1937) referred the folding in the South-West to the Hercynian orogeny. Dewey (1948), in summarizing the structural history of South-West England, postulated that the area had suffered two major orogenies which left evidence of their action as follows:-

"Earth movements affected the region during two principal periods. The earlier movements brought about folding along axes directed N.E. and S.W. and pre-Devonian rocks retain the effects of these movements. Similar lines of folding affected wide regions in North-West Europe and are well seen in Scotland; for this reason the direction of folding

has been termed Caledonian. If the movements ceased in early Palaeozoic times the folds appear to have controlled later emission of igneous rocks, for the granite-masses and the elvan dykes are distributed along a similar trend-line, while the mineralized fissures of West Cornwall pursue the same direction."

He continued:

"Rocks of Devonian and Carboniferous age were next deposited; some in circumstances of quiet subsidence, others under stress with resultant vulcanicity, the whole area slowly sinking beneath the ocean on the South but rising to shore levels in the North. Towards the close of the Carboniferous period, however, great masses again disturbed the whole district; rocks were folded along East and West lines by pressures acting at right angles to this direction and locally with sufficient force to overfold and even to overthrust lower upon higher parts. Folds of similar direction affect Brittany and have therefore been termed Armorican from the ancient name for North-West France."

Miss Hendriks (1937) had previously ruled out on stratigraphical grounds the possibility of the area having been influenced by an early orogeny, such as the Caledonian, stating the case as follows:-

"Two periods of movement have long been recognized in South Cornwall, ascribed to the pre-Devonian and post-Carboniferous Hercynian periods respectively. The former being untenable on account of the Upper Devonian age of the beds involved, there remains only a late Upper Devonian to early Carboniferous (Variscan) period in which the earlier movement could have occurred."

Miss Hendriks (1959) is more concerned in her latest paper with a revision of her previous (1937) views and does not discuss the ages of different fold trends.

Robson (1945) gave a general summary of the structure of the region and described the effects of two orogenic periods; the Caledonian which he defined as Siluro-Devonian, and the Armorican which he defined as

Post-Carboniferous. He assumed that "the Grampound grits are unconformable with the western series (Mylor-Varyan)" and that "the base of the Grampound grit is a major stratigraphical and structural division." He considered that "all rocks south are Lower Palaeozoic and of Caledonian structure, and that all rocks north are Upper Paleozoic and Armorican in structure." The major anticlinal axis extending from Godolphin to Truro, the minor synclines between the Godolphin Granite and the Land's End Granite, and the anticlinal axis extending from the region of St. Ives to Land's End are all described. On the basis of the stratigraphy and the dominant NE-SW trend of these structures Robson considered that they are a result of Caledonian compression. To the East the Devon synclinorium, the Davidstow-Gunnislake anticline, the St. Mabyn syncline, the Newquay-Dartmouth anticline, and the Meadfoot syncline have an E-W trend which he considered to be due to "the Armorican compression with the buckling of the Culm geosyncline".

Webb (1947) summarized all the previous views and concluded that:-

"Though much detail still remains to be filled in, it is probably best to refer the tectonics of Cornwall to the Variscan period, and mainly to the Asturic phase. This phase was preceded by the Bretonic and Sudetic movements of variable intensity. Intrusion of the tin-bearing granites took place at the close of the Astric phase and may have been followed by minor Saalic disturbances."

Prentice (1958) listed three distinct tectonic styles that can be recognized in South-West England, as follows:-

(a) the Lizard unit; metamorphosed rocks of the Lizard, Dodman and Start Point, south of the Lizard Thurst-zone,

(b) the Killas unit; where fold axes and cleavage planes are near to horizontal,

(c) the Autochthonous Unit, in which the fold axes are near vertical and cleavage poorly developed."

He considered that the main folding in the Autochthonous unit is late or post-Westphalian and that the Killas and Lizard Units may have suffered from an earlier phase of orogeny. In conclusion he suggests that the 'orogeny' began in late Namurian times in the south of the region, and that the Culm deposits were laid down in the foredeep of the mountain chain.

The known stratigraphy and structure in the South-West was recently reviewed by Simpson (1959) who stated:-

"It is very improbable that a major orogeny occurred in this area (South-West England) before the end of the Ammanian, for at least some indication of it should then be present in the stratigraphy of the South Wales and Bristol areas. The earliest relevant orogenic phase discoverable in these areas is the Malvernian, and although the deformation produced in them by this episode is not great it is quite conceivable that the intensity of deformation increased southwards into the main sedimentary trough. However, the main phase of deformation to the north is the post-Upper Coal Measures thrusting which carried Carboniferous Limestone on to Upper Coal Measures north of the Mendips, and is usually referred to as Asturic."

He continues:

"In the present state of our knowledge we cannot say whether there has been only one major orogenic phase covering the whole of the Palaeozoic area of West Somerset, Devon and Cornwall, or two, an earlier limited to the Southern part, and a later replacing it to the north. Thus there are three possibilities to be investigated .....

(1) Malvernian orogenesis alone.
(2) Asturic orogenesis alone.
(3) Malvernian orogenesis in the south, Astric in the north."

George T.N. (1961) considered the available evidence and adopted the following views

"Deformation during the Hercynian orogeny, mainly expressed in the Upper Palaeozoic rocks of North-Western Europe, had antecedants linking the induced structures with the waning pulses of the Caledonian. The stratigraphy of both Devonian and Carboniferous sediments bears clear signs of the physical environments in which the rocks were laid down, and of the initiation of movement in proto-Hercynian times. The lower Devonian rocks commonly rest with only minor breaks upon the Silurian; and the last major event of the Caledonian revolution may be regarded as of mid-Devonian age."

The subject has been recently discussed further by Owen (1961) and Butcher (1961).

(c) The Lizard Thrust

The Lizard Complex is a major problem in itself. It has been thoroughly described by Flett (1946) who gives a comprehensive account of past and present theories concerning both the Lizard thrust and the origin of the various rock types exposed in the Lizard area. The thrust, frequently a discussion point in the literature, has been assumed to be synonymous with the Start thrust. Teall (quoted by Reid in 1907), for instance, said:-

"It seems probable that this disturbance (Dodman), is connected with that of the Start on the East and of the Lizard on the West; and it is worthy of note that a line joining these disturbances is approximately parallel to one joining the centres of the principal masses of granite in Cornwall and Devon."

Recent work, however, has indicated that the thrusts present at the Lizard and the Start are not identical. Geologists in the past

have always been handicapped by the limited exposures of the thrusts on land and any theory concerning their continuity has been conjectural. Geophysics is now being utilized to a greater extent in this field, and recent work by Allan (1961), in which a nuclear spin magnetometer was utilized to produce a magnetic contour map of parts of the Western English Channel, has tended to disprove some of the early ideas. Allan, whose views were largely supported in discussion by W.F. Whittard concluded thus:

"The supposed Lizard-Dodman-Start metamorphic thrust does not appear to be continuous and the Lizard complex terminates quite abruptly a few miles out to sea. The New Red Sandstone deposits have been banked up against the foot of the Hercynian mountains here. The Start metamorphic rocks are also shown to terminate a few miles out to sea, where again the coincidence with the New Red Sandstone boundary is most marked."

The Lizard-Start thrust has been discussed in many papers in connection with the line of granite outcrops, the mineralized lodes and the post-mineralization faulting, but some of the ideas must be reconsidered in the light of this new geophysical evidence.

Miss Hendriks has recently (1959) revised her ideas on the age of the Lizard Complex and now considers that "the age of the nappe movement and the intrusion of the serpentine can be approximately dated as latest Devonian or possibly early Carboniferous." This hypothesis has not been disproved by recent isotopic ages from the Lizard determined by Dodson (1961) and Miller and Green (1961).

(d) Conclusions

The foregoing conspectus briefly outlines current views on the large-scale structures in the South-West of England and the age of the orogenies to which they may be attributed. No writers are in complete agreement concerning the ages of the phases of compression and some base their classification merely upon the trends of the fold axes, employing the directions given by Ager (1961) and Umbgrove (1947). Two main fold trends are present; a dominant NE-SW trend in the South-West and a dominant E-W trend in the North-East. These may be related to compression from the South-East and from the South respectively. The general view is that they are not of the same age, the South-East compression being earlier than the other. Moreover, it is uncertain whether the first compressive force operated during a late stage of the Caledonian Orogeny or at an early stage of the Hercynian Orogeny. Simpson (1959) commenced his recent paper on this subject by stating:

"When a few years ago the writer (Simpson) of this article started to try and discover what was known about the stratigraphy and structure of South-West England it became clear that whereas a great deal of information was available, particularly on the maps and in the memoirs of the Geological Survey, yet much confusion existed and practically no valid generalization could be made."

Although a correct interpretation of the major structure of the South-West is of the utmost importance in deciphering the structural control of mineralization, it is not within the bounds of this thesis to discuss the subject in greater detail. Incidentally, the writer feels that

greater progress might be made if workers were to spend more time on field studies, especially in West Cornwall, than upon theorectical interpretations of the field results of past geologists, supplemented by the concoction of ill-defined geological nomenclature!

Important structural results are likely to be obtained in future by detailed studies of the minor structures over large districts. This approach would be most appropriate in an area such as the Land's End district where the total exposure of aureole rocks is small and stratigraphical divisions are rare, if not absent. Such work over a restricted area would be of use only in the interpretation of the major structures within that particular district, but if a project were designed to cover most of the South-West by subdivision into minor areas, the results obtained would undoubtedly be of far-reaching importance.

A new field of study which will have an important application in the South-West is that initiated recently by the University of Bristol and the Institute of Oceanography. By means of asdic and bottom-sampling apparatus they have been successful in carrying out a geological survey of the Bristol and English Channels. Stride (1960) produced some remarkable details of folding on the sea-bed around the coast of the South-West, and with information obtained from inclined echo-sounder recordings Donovan and Savage (1961) have prepared a preliminary geological map of the Bristol Channel. Details of the sea-bed petrology may be obtained by bottom sampling and diving, as

described by the present writer (1960). Similar work has already been completed by some organizations, notably by Boillot and Calvez (1961) who have produced a geological map of the sea-floor covering 700 sq.km. off the northern coast of Brittany.

A complete off-shore survey in the South-West, employing the methods described by the present writer (1961), would yield most valuable information concerning not only the major structures of the off-shore areas but also of the land peninsula, the interpretation of which is often vitiated by the dearth of continuous exposures such as commonly exist on the adjacent sea-bed. A close survey within the 2 mile limit could employ all the standard methods of bottom-sampling, including direct observation by divers. Beyond this limit geophysical and asdic techniques, described by Taylor-Smith (1961) and Fedynskiy (1959), would play a more important part.

A start has already (1961) been made upon an off-shore airborne geophysical survey of the South West, which will be correlated with the results obtained on land by Bott, Day, and Masson-Smith (1958). It is hoped that this airborne investigation which, as described by Bott (1961), has proved so successful in other parts of the country, will be of special application in the Land's End district. Although the traverses will not approach close to the shoreline, they may be expected to supply further information regarding the form of the Land's End Granite at depth. Such information is essential for a correct understanding of the structures, especially jointing and faulting, found within both the granite and its aureole, particularly along the North-Western coastline.

2/4 Granites

(a) General Description

Extending discontinuously at the surface for 120 miles from Dartmoor to the Scilly Isles, the granites cover all the moorlands and are the source of the tin-copper mineralization. The latest dating methods have confirmed that the intrusion of the granites took place in Permo-Carboniferous or Permian times as the culminating episode of the major Hercynian movements. Their relation to the granites of France has been described by Read (1949). The immediate association between the mineralization and the granites was noted by many of the early writers, such as Davy (1818), Carne (1822. T.R.G.S.C.), Carne (1828 & 1865) and Hill (1902). Since the first detailed account of the area by the Geological Survey it has been possible to view the Cornish granite suite as a whole, and many workers have concentrated on petrological and structural studies of the various outcrops. The major publications for each granite outcrop, according to Webb (1947), are listed below:

Dartmoor: Ussher (1912, 1913)
Reid and others (1912)
Brammall and Harwood (1923, 1926, 1932).

Kitt Hill and Gunnislake: Reid and others (1911)

Bodmin: Reid and others (1910, 1911).
Ghosh (1927).

St. Austell: Ussher, Barrow and Macalister (1909)
Richardson (1923)

St. Agnes and Cligga Head: Scrivenor (1903)
Reid and Scrivenor (1906)

Carnmenellis (Carn Brea and Carn Marth): Hill and Macalister (1906)
Ghosh (1934).

Land's End and Godolphin: Reid & Flett (1907)
Hall (1930)

Scilly Isles: Barrow (1906)
Osman (1928)

Lundy Island: Dollar (1941)

The various granite outcrops show a remarkable similarity in both mineralogy and structure. Containing quartz, orthoclase, subsidiary plagioclase, biotite, muscovite, tourmaline, and many accessories, they may be classified as potassic or soda-potassic granites. Detailed descriptions of the mineral assemblages were given by Brammall and Harwood (1923), Ghosh (1927, 1928, 1934), Osman (1928) and in various publications of the Geological Survey. Chemical analyses were also provided by the above writers, especially Ghosh (1934) and Phillips (1875). The joint systems in each of the granites are remarkably similar and may be related to a common flow direction which resulted in a parallel alignment of the major joint directions, as demonstrated by Exley (1959).

Owing to these similarities the contemporaneous origin of the granites was postulated at an early stage. Mining development disclosed that all the granites had an associated period of mineralization and that there was a possibility of their uniting at depth. The suggestion of a common source of the granites was made by de la Beche (1839), and re-stated by Ussher (1892) and Collins (1912). Further information, dealing with such matters as the varying widths of the metamorphic aureoles and specific areas of metamorphism and mineralization, was summarized by Davison (1925, 1926). Hosking (1949) discussed the relationship between

granite emplacement and mineralization and in 1959 produced a sketch-map of the South-West which is reproduced by the writer as Fig. (3). This depicts the presumed form of a granite batholith. Recent geophysical work by Bott, Day and Masson-Smith (1958) has confirmed previous views concerning the form of this "batholith".

For some years during the 18th century arguments for and against the intrusive nature of the granites were often repeated, but the evidence of exposures certainly favours an intrusive origin and is against granitization in situ. Strike deflections and the tilting of strata adjacent to the granite contacts have been recorded from many localities by Ussher (1912) and Brammall (1926), as well as by workers in the Land's End area. Granitic material penecontemporaneous with the main granite masses is common in the aureole rocks and flow structures in the granites cut across planar structures in the adjacent 'killas'. Xenoliths, some in various stages of assimilation, are present near the contacts and all the granites display orientation of the feldspar phenocrysts indicative of flow alignment. The fundamental problems raised by the granite controversy are not the concern of this thesis, and the writer is content to assume that the granites were essentially intrusions of a partly-liquid mobile magma. Nevertheless, various concepts of magmas and migmas may be adopted to explain individual conditions.

The exposed granites are variably coarse-grained and porphyritic. Significant differences in grain size and composition, which are evident

in most of the exposures, are due in nearly all cases to the presence of more than one intrusion. Many early papers listed in the References mentioned fine-grained granites which could not be classed as dykes, and the Geological Survey workers mapped later intrusions of a fine-grained variety of granite within exposures of essentially coarse-grained granite. Brammall (1923, 1932), Ghosh (1927, 1934) and Richardson (1923) demonstrated that there were frequently more than two intrusions and that each successive intrusion was progressively more acidic. The contacts between successive facies are both sharp and grational and indicate that there was often a very short time interval between each individual intrusion. The mineralogy of the granites is similar within successive intrusions exposed in one outcrop, thus raising many interesting questions concerning the nature of the original magma, most of which have been outlined by Webb (1947). The granites are badly exposed inland and much of the interpretation of composite intrusions has to be based on isolated and widely separated outcrops. If the South-West granites were better exposed it is likely that the composite nature of the separate intrusions would prove to be much more complex than is now realized. Recent workers, such as Bagchi (1947) on the Land's End Granite, Subbarao (1960) on the Godolphin Granite, and Exley (1959) on the St. Austell Granite, have extended the knowledge of composite intrusions and of the changing conditions which took place during the time interval between the intrusion of the first and last granite in any one major outcrop.

(b) Localization of the Granites

The NE-SW and E-W trend of folding in the country rocks of the South-West is reflected in the areal disposition of the granite outcrops from Dartmoor to the Scilly Isles, as shown in Fig. (2). The NE-SW arrangement is illustrated by the Land's End and St. Agnes granites, and by the Carnmenellis, St. Austell and Bodmin Granites, while the E-W alignment is shown by the Dartmoor and Bodmin granites, and by the Carnmenellis and Land's End Granites.

A long-standing hypothesis is that the granites were intruded near the intersections of pre-existing antiforms of two different trends. On this basis of the possible intersection of NE-SW and E-W trending major folds Robson (1945) based his theory of the localization of the granite intrusions, maintaining that the least resistance to intrusion occurred at the intersections of Caledonian and Armorican anticlines. Robson (1945) outlined the position of these antiforms and concluded:

"The development of this great fold system promoted the invasion of huge batholithic masses of alkali granite each of which appears to have been guided and centred by an anticline and likely enough superimposed on the deeper Caledonian folds. The disposition of the intrusive domes (E.N.E.-W.S.W.) does suggest that they were 'directed' by the coincidence of two systems of anticlines giving a course of least resistance."

Hosking (1949) elaborated on this theme and postulated the presence of granitic ridges at depth between the various outcrops. He considered that the localization of these ridges was controlled by extensions of the antiforms, at the intersections of which the granite attained its greatest heights. Hosking (1949) correlated the trends of the ridges

with periods of earth movement, stating:

"These ridges would appear to be controlled in the west largely by the effects of Variscan earth movements, and in the east largely by Armorican earth movements."

The geophysical results of Bott, Day and Masson-Smith (1958) confirmed Hosking's earlier hypothesis, which was presented in greater detail by Hosking and Trounson (1959) before the geophysical results were available. These two authors presented a plan, reproduced here as Fig. (4), showing the limits of the granite batholith and the positions of the sub-surface granite ridges. They summarized their views as follows:

"It is considered that the disposition of these ridges (of granite) was determined largely by the moulding action of minor anticlines which were present in the country rock invaded by the granite, and which were generally parallel to the Lizard Start Point thrust. Doubtless the same forces caused the development of the thrust and the anticlines. Further 'moulding' anticlines were developed by the rucking of the sedimentaries due to the emplacement of certain closely-spaced large granite knots in the major anticlines."

The present writer is prepared to accept that the emplacement of the granite ridges was controlled by E-W and NE-SW antiforms and that the intrusions of granite above the main ridges are located at the intersections of the two major antiforms. Caution must be exercized, however not to attribute major antiforms to particular orogenic periods merely on the basis of their trends.

(c) Associated dyke and vein phases

Associated with all the granite intrusions are complex dyke and vein phases which are of both pre- and post-granite age and may be classified

according to their relative age and mineralogy. Ghosh (1934) postulated a detailed succession for the Carnmenellis granite, involving successive granite intrusions, followed in turn by acidic dykes and the mineral lodes, while Webb (1947) outlined an analogous general sequence of events for the whole of the South-West. The various phases may be summarized, in order of decreasing age, as follows:-

(1) Pre-granite veins and coarse-grained granite.
(2) Fine-grained granite.
(3) Porphyries, pegmatites, and aplites.
(4) Quartz-tourmaline veins.
(5) Mineral lodes.

The pre-granite veins include quartz, quartz-feldspar and some quartz-tourmaline varieties. Many of them, especially those of quartz, follow the complex folding of the 'killas', and all are cut off abruptly at the granite contact. Contemporaneous with the coarse-grained granites are granite veins near the contact, together with contact granitic phases such as pegmatites and aplites, and contact tourmalinization. Many of the above features appear to be reproduced by the succeeding fine-grained granite phase, which itself formed granitic veins in earlier coarse-grained granite. The porphyries form a series of fine-grained dyke rocks, often with porphyritic crystals of potash feldspar, quartz, and pinitized cordierite, set in a fine felsitic groundmass. On occasions they are not readily distinguished from aplite, especially when they occur in granite. The porphyries are known locally as 'elvans', but this term has possibly been applied in past literature to embrace both porphyries and other dyke rocks.

All the granites are accompanied by genetically related pegmatites and aplites, which are irregularly and sporadically disturbed. These often occur together and appear to be penecontemporaneous in age, many sills consisting, as do those at Porthleven described by Hall (1930), of banded pegmatitic and aplitic material. The field associations and variations in mineralogy and texture of the two types arouse many problems concerning their genesis, as discussed by Webb (1947).

The aplites consist essentially of feldspar and quartz with varying amounts of muscovite, and as Webb (1947) states, they may be classified as muscovite-aplites, aplogranites, or leucocratic microgranites. Their frequent high tourmaline content may be due either to penecontemporaneous tourmalinization or to tourmalinization of the feldspars during the mineralization phase.

Confusion has often arisen regarding the relative age of some mineral lodes and aplite dykes. The writer believes, however, that this confusion can be largely attributed to the incorrect interpretation of observed phenomena.

Quartz-tourmaline and quartz veins are frequently found within the granites and grade into the mineralization phase. Brammall and Harwood (1925) and Scrivenor (1903) devoted considerable attention to the relationship between the colour of the tourmaline and its age and genesis; Webb (1947) also contributed some information on this score. In general the primary tourmaline of the granite and some aplites is orange in colour, whereas the tourmaline in quartz-tourmaline veins and that formed by the replacement of feldspars is blue.

(d) The Age of the Granite

Lambert and Mills (1961) outlined the setting of the granites of the South-West within the Hercynian orogenic belt, stating that a major eugeosyncline developed during the Devonian and Carboniferous, and that in the later part of the Lower Carboniferous, the Upper Carboniferous, and possibly, the Permian, the area suffered folding, metamorphism, and major igneous intrusion. These authors reproduced Hendriks' (1937) stratigraphical and structural map and stated that the "shale-greywacke-volcanic series are folded into a major east-west structure in which Devonian to Lower Westphalian strata are preserved." continuing:

"These granites (South-West) are therefore post-lower Westphalian. Approximately 60 miles North-East of Dartmoor, however, lies a further group of Devono-Carboniferous sediments. These sediments include coal measures of Lower Stephanian age (quoting Moore L.R. and Trueman A.E. 1937) overfolded on East-West axes, the highest strata containing ..... The overfolding is of a type similar to that of Devon and is probably of the same age. There is therefore a strong probability that the granites are post-lower Westphalian." and "The upper limit of stratigraphic position is provided by continental deposits conventionally referred to the Permian and the Trias. The British Permo-Triassic deposits are largely unfossiliferous; There is little reason why the Dartmoor granite should not be of any Permian date; in general, however, earth movements seem to have been largely complete before the Upper Permian (Zechstein). Accordingly we conclude that the granites of South-West England were probably emplaced in the highest Carboniferous or early Permian times."

Considerable attention has centred recently upon the age determinations of granites, and most of the work concerning the U.K. was summarized by Lambert & Mills (1961). Their work commenced as an investigation into the ages of British granites. The first results, based upon the K-Ar total volume method, were reported by Mayne, Lambert

and York (1959) in support of their proposed extension of the geological time scale. The time-scale originally compiled by Holmes (1947) contained some discrepancies which became apparent as a result of Moorbath's work (1959) on the ages of several British lead deposits, the geological setting of which had been previously reviewed by Dunham (1952). Lead ores of recognized Caledonian and Hercynian ages fall into two distinct groups, within each of which the model ages and geochemical ratios are strictly comparable. The ages obtained were older than those indicated by Holmes' geological time-scale. Consequently, Kulp (1959) and Holmes (1960) revised the time-scale to give the Caledonian Orogeny an age of 390-420 m.y. and the Hercynian Orogeny an age of 260-290 m.y., carrying the beginning of the Cambrian back to about 600 m.y.

This revision was criticized on general grounds by Davidson (1959) and by Kulp et al. (1959). Independent re-determinations of the age of micas by the K-Ar and Rb-Sr methods by Kulp et al. (1960), confirmed that the values obtained by Mayne for the Caledonian granites were probably too high. The above subjects were also dealt with by Faul (1959), Faul & Tilton (1957), and Read (1961), who quotes Wager & Moorbath (1960), and Holmes (1959). Aldrich & Wetherill et al. (1958) described the methods of such determinations.

Using K-Ar determinations upon biotites, Kulp et al. (1960) ascribed to the Dartmoor Granite (Haytor Rocks) an age of 271 $\pm$ 5 m.y. and to the Land's End Granite (Botallack Cove) an age of 250 $\pm$ 15 m.y. Their work was repeated by Faul, who obtained an age of 290 m.y. for the Dartmoor Granite. Mayne (1959) recalculated previous estimates of

305 m.y. and 340 m.y. for the Dartmoor and Land's End Granites respectively, and arrived at 298 m.y. and 330 m.y. instead. The differences apparent in these determinations are greater than one would expect from experimental errors only.

Lambert & Mills (1961), employing Rb-Sr age determinations upon biotites, produced an apparent age of 285 $\pm$ 8 m.y. for the Dartmoor Granite (Haytor Rocks) and of 270 $\pm$ 9 m.y. for the Land's End Granite (Botallack Cove). These results compare more favourably with the estimations obtained by other techniques. For instance, Moorbath (1959) stated that galenas from the South-West yield a model age of 280 m.y. (quoted by Lambert & Mills 1961) and Darnley (1959 & 1960) determined an age of 290 $\pm$ 7 m.y. for uraninite from the lodes of Geevor Mine.

Holmes (1959) adopted the view that the granite intrusions and mineralization occurred during Mid-Morganian time, whilst Kulp et al. (1960) suggested that the granites are probably of very late Stephanian or Permian age. Lambert & Mills (1961) stated in conclusion that:

> "the mean Rb-Sr age of 285 $\pm$ 8 m.y. gives the best estimate for the age of the Dartmoor Granite and should be close to the absolute age of the intrusion. The Land's End Granite could be contemporaneous within the limits of experimental error, but the available evidence seems to suggest that it may be somewhat younger."

They concluded that the Permo-Carboniferous boundary should be placed within the interval 285 $\pm$ 10 m.y.

Although most of the publications quoted by the writer are post-1959 the accuracy with which determinations are currently being made has

improved considerably. It seems a logical step to extend the work to composite granite intrusions and to the associated mineralization in more than two of the main granite exposures. It is possible that later granite intrusions exert an influence upon both the structural pattern within a pre-existing granite and upon the mineralization phase itself in composite granites. This is a subject which deserves investigation in the future by all available methods.

Thanks to improvements in electronic methods thermoluminescent techniques of age determination have recently received attention by Komovskiy & Lozhnikova (1959). They have demonstrated that with still further refinement the method could be used for the relative age determinations of granites, since their results are in fair agreement with those obtained by Afanas'yev (1955) who used the K-Ar method on granitic intrusives of Hercynian and Caledonian age from the North Caucasus region.

2/5 Granite Structures

(a) Form of the Granite

The underground continuity of the South-Western granites was suggested by Sedgwick and Murchison (1837) to account for the continuous belt of mineralization as outlined later by Dewey (1925). All successive writers have agreed with this interpretation and Rastall (1931) considered the "exposed granites to be cupolas on a large batholith of considerable depth separated by a relatively thin sedimentary cover."

The gravity and magnetic surveys by Bott et al (1958) showed that:

"the roof regions of the remaining granites (all except the Dartmoor granite) are only partly exposed, the sub-sedimentary extensions characteristically lying to the North of the exposures. The walls may be locally vertical but more usually slope steeply or moderately steeply outwards. The gravity results suggest that the southern wall is usually the steeper."

The total anomalies obtained suggest that the granite continues to depths of 10 and 20 km; about half the width of the roof. The floor of the batholith is consistently deeper to the south, and in many ways "the granite belt is geometrically asymmetrical." In conclusion Bott et al (1958) stated that:

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

forcible intrusion with stoping, the magma rising in the south."

It has thus been established that the various granites are continuous below surface to form parts of the same batholith.

(b) Flow Direction

One of the standard works on structures in igneous rocks is that of Balk (1937), who drew freely from the numerous papers of Cloos. Most references to the subject are provided by Balk (1937) and Sherbon Hills (1955). Of the various flow structures, platy flow (schlieren) and linear flow structure are common in the South-Western granites. The granite contacts are rarely visible, and parallelism of the feldspars near the margins of the intrusions is the only indication of the flow banding believed to be due to the more or less viscous flow of magmas. The feldspar phenocrysts exhibit a form of Plane parallelism, the largest faces (often the 010 planes) being oriented in parallel planes, and the longest axes of the crystals being aligned roughly in the direction of flow of the magma. It must be emphasized, however that use of orientation of feldspar phenocrysts to determine the flow direction of the magma has to be applied with caution. Balk (1937) and Cloos have frequently illustrated the development of eddy currents and many other features which may be wrongly interpreted by the observer unless a sufficiently large area at each locality is selected for examination.

(c) Cross-Joints

Joint patterns in a granite mass may be simply classified as either primary or secondary. The former may be further subdivided into cross, longitudinal, diagonal and primary flat-lying joints. Balk (1937) defined cross-joints as "those that are arranged perpendicular to primary flow lines, or nearly so." They are usually longer and straighter than other joints and are among the earliest fractures to form in a congealing igneous mass. Early aplitic dykes commonly follow the cross-joints, and in the case of many massifs, these joints and the dykes that follow them, continue for a distance (sometimes more than a mile) beyond the contacts of the intrusion.

Flow lines represent the direction of maximum lengthening in the congealing melt, and according to Balk (1937), "the direction of maximum compression that affected the consolidating magma lies within the plane of the cross-joints, normal to the flow lines," the joints being developed as soon as the elastic limit was exceeded in the deformation of the newly frozen rock. Cloos (1921) considered that "the cross-joints appear as a continuation of the viscous elongation, through other forcible means." In his earlier publications, according to Balk (1937), Cloos "assumed that this compression was caused by some 'tectonic', regional force, not directly connected with the intrusion of the magma," a view which he later modified. Balk (1937) considered that:

"the force responsible for the yielding of the magma in a definite direction, and also for the complementary cross-joints, is the force of the intrusion. This does not preclude the possibility that other fractures are due to regional compression. Each area must be judged on

its own evidence, and generalizations are not possible."

The identification of cross-joints depends upon the previous recognition and interpretation of flow-lines and "if flow-lines are not visible, cross-joints, in the strict sense, cannot be determined, although corresponding fractures may exist." The existence of aplite dykes within joints is not proof that those dykes occupy cross-joints. If, in a granite massif, the flow-lines form an arch or dome, the associated cross-joints are arranged in a fan-system. When the cross-joints are occupied by dykes this effect may be easily observed, the dykes usually dipping towards the centre of the massif. As Balk (1937) stated "the apex of an arch of flow structures commonly coincides with the apex of a joint fan, but the joint fans are likely to spread less than the pitch of the flow-lines or the dip angles of the flow-layers require."

(d) Longitudinal Joints

Longitudinal joints are normally classed as primary joints, although their exact mode of origin is not definitely understood, and it is normally impossible to prove that some may not have developed subsequent to consolidation of the magma. They are normally steep joints and are best developed where the flow-lines lie flat, when they strike parallel to their trend. According to Balk (1937), longitudinal joints "differ somewhat from cross-joints in their general appearance. Many of them are rougher, lacking the clean-cut, smooth surfaces of the cross-joints". They tend to develop in zones in which they are closely

spaced, and their early age is "demonstrated by aplites, pegmatites, quartz veins, or basic dykes, which follow them."

Longitudinal joints are dependent upon the flow direction, and "adjust their strike to variations in the trend of the flow-lines." It is possible that some of them may be secondary because flow lines "introduce an element of mechanical weakness into the fabric rock." Balk (1937) considered that in contrast to the movement associated with cross-joints, displacements along longitudinal joints are not common. He cited many examples to illustrate the greater frequency of dykes along cross-joints than along longitudinal joints, as well as the fact that longitudinal joints remain closed during the time of dyke injection into cross-joints.

(e) Diagonal Joints

The term 'diagonal joints' was limited by Balk (1937) to denote "steep joints that strike at angles of approximately 45 degrees to the trend of the flow-lines", and were "referred to a predominantly horizontal stress." True diagonal joints are more common in sediments and metamorphic rocks than in igneous rocks and when present in the latter they may be filled by dyke material. They exist as two complementary systems, of which one may be locally supressed, and they commonly approach the direction of the cross-joints. Balk (1937) considered that the "diagonal joints are shear planes, which predominate over cross-joints if the mass of the rock is hemmed in so that it is prevented from slipping sideways, whereas cross-joints develop if the

compressed mass is lubricated and free to glide." It is common to find that a dyke occupying a cross-joint or longitudinal joint will possess diagonal-joints when the surrounding granite possesses only cross-joints and longitudinal joints.

According to Balk (1937) "joints in the quadrant that is bisected by the cross-joints are far more conspicuous, perhaps more numerous also, than joints in the other quadrants." Cloos (1921) pointed out that longitudinal and diagonal joints may be of primary and secondary age; whereas, cross-joints are of primary age only." Later (1925) he restated this view as follows:

"Any number of later joints may share the direction of longitudinal joints, since they follow the direction of good parting; but the cross joints which run parallel to the direction of poorest parting, represent the total number of joints formed during one stage only. They cannot develop again, unless by a recurrence of exactly the same conditions."

By 'conditions' Cloos (1925) inferred the same orientation of principal stresses.

(f) Flat-Lying Joints

Both the longitudinal and diagonal joints are steep and are affected by variations in the trend, rather than the pitch, of the flow-lines. The last set of primary joints, the flat-lying joints, differ from the previous three types in that they dip at low angles. They appear to form readily if the surface of the mass is flat, as for instance, according to Balk (1937), "along the apex of large domical bosses (the flanks of which may, nevertheless, be steep) or along the surfaces

of flat sheets and laccoliths." In such cases; "Low dip of flow layers facilitates their development, but is not necessary, nor do the joints always embrace gently pitching flow lines. Volume changes in the intruded mass, differences in load, and other factors have been advocated as the cause of flat-lying fractures." Flat-lying primary joints are in evidence in granitic masses where flat-lying pegmatites, aplites, and micro-granites, tend to develop.

(g) Joints in the South-Western Granites

Various terms are used to define the joints described above. Cloos (1922) summarized the terms as follows:

(1) Q-joints, cross-joints, hardway planes, and 'toughway'.

(2) S-joints, longitudinal joints, rift planes, the 'cleaving way'.

(3) L-joints, primary flat-lying joints, bedding or sheeting planes, 'floors'.

When describing granites of the South-West most writers have provided details of the joints. Osman (1928) on the Scilly Isles, Brammall (1926) on the Dartmoor Granite, and Ghosh (1934) on the Carnmenellis Granite, described the joint systems and flow lines present within the respective granite.

The Carnmenellis granite, which has been subjected to the most thorough and most recent examination, may be cited as a standard example. All the granite exposures exhibit minor differences which are complicated by the composite nature of some of the intrusions. Where porphyritic feldspars are evident a flat-lying mineral parallelism is made

conspicuous by the alignment of the large feldspars, with their clinopinacoids arranged in sub-horizontal planes. Flat aplite and microgranite dykes are often found in association with the primary flat-lying joints. Flow lines indicate a locally variable magma flow from the south or south-east to the north or north-west, corresponding to arching of the granite masses.

The approximate southerly compression which caused the folding and eventual thrusting of the country rocks culminated in the intrusion of the granites. During the intrusion the country rocks appear to have yielded preferentially in the direction of the intrusion, and with the advent of the consolidation stage the northerly directed compressive stress seemed, if Balk's and Cloos' interpretation of the origin of cross-joints is correct, to have been replaced by a roughly east-west compression.

The development of the cross-jointswas followed by that of longitudinal, diagonal and flat-lying joints. Exley (1959), in a generalized sketch, showed that the flow direction in the Dartmoor and Bodmin granite was from south to north, with attendant E-W cross-joints and N-S longitudinal joints. In the St. Austell and Carnmenellis granites the flow direction swings round to the NNW, with a corresponding deviation in the joint patterns. With the same general NNW flow direction in the Land's End Granite the main joint directions are NE-SW and NNW-SSE. In the Scilly granite the flow direction is NE and the joint directions trend NE-SW and NW-SE.

Jointing in the early granites is always distorted by stresses attending the injection of later magmas in a composite intrusion. Nevertheless, as discussed by Dewey (1925), it is possible to recognize that in general the cross-joints are parallel to, and the longitudinal joints perpendicular to, the mineralized zones of the South-West.

3. MINERALIZATION

3/1 Introduction

With a few exceptions the primary tin-copper deposits may be assumed to be genetically related to the South-Western granites. The main E-W or ENE-WSW lodes, which occur in both the granite and the country rocks, have been the most important producers of ore. They were formed as a result of both the infilling of fissures and the alteration of the adjacent wall-rocks. The lode system reveals a complete mineral sequence from hypothermal cassiterite and wolfram, through chalcopyrite and sphalerite, to comparatively low temperature minerals such as calcite and siderite. North-South fractures, which in many cases fault the E-W lodes, were infilled with mesothermal minerals; chiefly sphalerite, galena, fluorspar and barytes.

A full account of the mineralogical and structural characteristics of the mineral lodes is beyond the purview of this thesis. The reader is therefore referred to a complete description of the mineralization given by Hosking (1951) and illustrated with specific examples. Information on the individual mines of the area is provided by Dines (1956) and by private plans and reports still in existence. Both Henwood (1843) and Collins (1912) gave reliable first-hand geological information on many of the mines, and particulars of various properties have been published by the Royal Geological Society of Cornwall. General descriptions of the wolfram deposits have been contributed by Rastall (1918), Davison (1920), Dewey & Dines (1923), and Polkinghorne (1953), while the occurrence of

uranium ores was described by Pearce (1878), Dines (1930), and James (1945). Analogous descriptions of other ores have been written by Collins (1903), Dewey (1920, 1921 & 1923) and Davison (1932).

The first major work on the mineralization was De la Beche's (1839), which was quickly followed by that of Henwood (1843) who provided a valuable record of the mineralogical and structural details of many of the mineral districts and individual lodes. His observations were utilized by Collins (1912) and later writers in summarizing the characteristics of the mineralization. Other important papers are those by Cronshaw (1921) on the Camborne district, Weston-Dunn (1923) and Davison (1924).

Studies of the general geology, paragenesis, and structural history of the lodes were made by Le Neve Foster (1878), Thomas (1882), Thomas (1886), Flett (1902), Lees (1914), McLaren (1917), and Vokes & Jeffery (1954), the Dolcoath Main Lode being a frequent subject of investigation. Other notable descriptions were given by Le Neve Foster (1875 & 1876), Rowe & Foster (1887), Davison (1923) and James (1944). The mineralogy of the lodes was described by Davison (1924) and Hosking (1951), and a complete list of the minerals found in Cornwall was published by the Royal Geological Society of Cornwall (1948) and by Kingsbury (1952).

A concentration of the lodes into mineral zones on both a regional and local scale was recognized by the earliest workers in the South-West. The more likely occurrence of tin lodes in granite and separated by a zone of impoverishment from copper lodes in the country rocks was appreciated

by the miners and applied in exploration. Dewey (1922 & 1925) recognized the existence in plan and section of tin, copper, lead-zinc and iron zones, and provided the first comprehensive account, outlining their correlation with depth changes. The relation of the zones to the upper surface of the major granites was indicated by Rastall (1923), and further information was summarized by Davison (1927).

Cronshaw (1921) appreciated that the mineralization had consisted of several distinct phases. He listed ten, commencing with quartz, feldspar, wolfram and arsenopyrite, and concluding with calcite. The ore fluids of the individual phases were considered to have differed considerably in composition owing to the progressive differentiation of the ore fluid at its source. Weston-Dunn (1923) preferred to explain the vertical and lateral mineral zoning by differentiation of the ore fluid during its ascent of the lodes. Both explanations were considered to be valid by Webb (1947) who outlined the mineralogical and spatial features of the separate zones. He suggested that not only was the ore fluid at any one time "undergoing extramagmatic differentiation during the course of its ascent up the lode fissure", but also that "the ore-forming fluid leaving the source was not identical throughout the period of lode formation."

The production history of many of the mines indicates that not only were the different mineral zones never completely represented but also that they were not necessarily parallel to the granite surface. This led Dines (1933) to postulate both vertical and lateral migration of the ore 'fluids' from certain restricted emanative centres, resulting in the upper

zones having a wider lateral distribution than the lower ones.

One of the prominent features of the lodes is the evidence they reveal of several phases of mineralization and movement. Variations in the time intervals between successive phases and changes in the prevailing conditions, especially temperature, resulted in the telescoping or absence of some of the accepted mineral zones. Any hypothesis that those minerals occurring in the deepest horizons of the lodes are the oldest and that with decreasing depth the minerals present become relatively younger is rendered suspect. Broad agreements between zonal sequences and mineral paragenesis are possible but detailed correlations should be restricted to the distribution and characteristic minerals of the individual phases. The sequence of mineralization was discussed by Hill & MacAlister (1906), Cronshaw (1921) and Hosking (1951).

Swarms of greisen-bordered veins often occur in the small cusps beneath the peaks of the major granites, and Hosking (1956) concluded that they were formed under completely different circumstances than the 'normal' tin-copper lodes. One of the more important deposits, at Cligga Head, was described by Scrivenor (1903) who provided a detailed account of the environment of mineralization. The economic geology and history of this deposit were related by Cox (1961) and Dines (1956) respectively, and its relationship to mineralization in the St. Agnes-Perranporth district was discussed by Knuckey (1957). Descriptions of similar occurrences include those of Hemerdon Wolfram Mine by Cameron (1951), St. Michael's Mount by Hosking (1953), and Carn Brea by Robson (1946). The deposit of Castle-an-Dinas Wolfram Mine bears some similarities to those listed above

although its origin is not identical, as noted by Davison (1935), Kear (1951), and Young (1957). The characteristics of the greisen-bordered deposits and their relation to the more important 'normal' mineralization were described by Hosking (1951 & 1959).

The geological setting of the South-Western tin-copper mineralization within the British Isles was outlined by Finlayson (1910) and Dunham (1952), and comparisons between the British cassiterite deposits and those of other countries have been made by MacAlister (1908), Ferguson & Bateman (1912), Singewald (1912), Jones (1925) and Fawns (1905).

The tin-copper lodes are essentially fissure veins. They have been formed as a result of both infilling of the open fissure and alteration of the surrounding wall-rock, often to such an extent that the latter is sufficiently mineralized to warrant its extraction as part of the 'lode'. Variations in the extent of development of these features and in the relative representation of the several separate mineralization phase, result in the widely different characteristics of the lodes of individual mining districts and mines.

Classifications of the lode structures were originally given by Collins (1893), Hill & MacAlister (1906), and MacAlister (1908). A general summary was provided by Dines (1956), who included the majority of the information under the individual mines, and a comprehensive account of the structural features of the lodes was given by Hosking (1949) who described characters such as replacement, banding, brecciation, vughs, and sheeting. He presented a precis of the major features such as lode intersections, branching, faulting, and lode-dyke intersections, mentioning

their economic aspects.

A change occurs in the structures of a lode according to the mineral zone in which it is situated or its position with respect to the granite surface. Lodes in the deeper portions of the tin zone consist essentially of sheared granite surrounded by intensely altered rock. A narrow, central, infilled fissure is frequently present and the width of the 'lode' is large in comparison with the width of the fissure. Parallel fractures, each with associated wall-rock alteration, are common. Details of the structures of individual lodes were provided by Henwood (1843) and the numerous other writers listed in the References.

Increases in the complexity of the lode structures in the intermediate zone and extending into both the tin and copper zones were noted by Cronshaw (1921) and Weston-Dunn (1921). They considered that the maximum structural intricacy occurred in the vicinity of the granite contact. In this area MacAlister (1908) regarded brecciation to be the most common feature, each phase of fragmentation, having been accompanied by a separate phase of mineralization. Webb (1947), in describing the lodes of the intermediate zone, considered that those in the killas had suffered a greater brecciation and frequently contained large fragments of wall-rock. In comparison, those in the granite tended to be composed of "numerous parallel stringers which may have been brecciated."

With increasing distance from the granite the lodes become structurally more simple and Webb (1947) summarized the changes as follows:-

"(a) a decrease in complex repeated brecciation.
(b) a less confused aggregate of ore-minerals.
(c) a decrease in wall-rock ore-mineralization.
(d) a tendency towards ore-deposition in simple fissures."

In the deeper tin zones the lodes were considered by Webb (1947) to consist ideally of a leader (usually quartz), the lode material (usually infilling), and the mineralized granite. He compared the main features of each component from the lodes of Geevor and South Crofty Mines.

The localized wall-rock alteration may be divided, especially in the granite, into zones which have been outlined by Webb (1947) and Hosking (1951). They are predominantly zones of chloritization, tourmalinization, greisenization, sericitization, silicification, kaolinization, and reddening of the granite. Additional mineralogical descriptions were provided by Bagchi (1947) and Rao (1952).

The common minerals with which cassiterite is normally associated have led to many theories concerning the manner in which the tin was conveyed in the mineralizing solutions. Daubree (1879) suggested that it was transported as a fluoride and later writers such as MacAlister (1903) and Davison (1935) proposed boron and silicon as 'carriers'. Barsukov (1956) and Little (1960) have recently contributed to this subject and the latter concluded that "of the previously suggested methods of tin transportation, alkali-stannate and alkali thio-stannate solutions are in accordance with the inclusion data. Additional possibilities are alkali-chloro- and fluo-stannate solutions."

A subject of great controversy, as Hosking (1951) described, is "whether cassiterite and allied minerals were deposited as a result of interaction between gases (or liquids above their critical temperatures) or were deposited from the solution". Many writers described various cassiterite deposits as being either hydrothermal or pneumatolytic on the basis of their apparent relative ages and mineral associations.

Webb (1947) divided the whole mineralization period into three stages. The first was the epipegmatitic which resulted from fluid residua arising out of pegmatite crystallization, and to which may be attributed the deposition of the quartz-feldspar-wolfram-arsenopyrite veins which are so well developed at South Crofty Mine. The dominant vertical stress and the initial pressure release instituted the ascent of the residual fluids under vapour pressure. This pneumatolytic stage was gas-rich and carried halides, boron and tin. Webb (1947) considered that it was responsible for the deposition of the majority of the tin in association with tourmaline and chlorite, largely by replacement.

He considered that the loss of volatiles and heat during the pneumatolytic stage lowered the vapour pressure and that later solutions, comprising the hydrothermal stage, were forced up by the weight of the overlying fractured rock. These were less tenuous than those ascending during the pneumatolytic stage and the characteristic minerals, principally quartz and sulphides, were carried mainly in the colloidal state. The bulk of the hydrothermal solutions were deposited in regions overlying the tin zone and resulted in the formation of sulphide-bearing, infilling,

quartz veins. Webb (1947) concluded that the pneumatolytic and hydrothermal phases were closely connected and that the former was of a comparatively short duration. At the source the excess volatiles were rapidly lost in the pneumatolytic phases and the residual hydrothermal solutions soon became the dominant ore fluid.

Despite recent laboratory research this matter remains unproven. Smith (1949) developed a technique for the measurement of the temperature of formation of cassiterite and associated minerals which showed that they were formed below temperatures in the region of 350° C. Recently Little (1960) applied the inclusion technique to further cassiterite ores and concluded that "since under the conditions of deposition, these water solutions had the property of liquids rather than gases, the deposits (excepting most pegmatites and the Mexican Volcanic class) are more properly classified as 'hydrothermal' than 'pneumatolytic'," if the terms are used according to the definition given by Smith et al (1950). Little decided that his work indicated "that most hydrothermal tin deposition occurs in the 300 to 500 deg. C. range, although the temperature may be as high as 600 deg. C." He also gave numerous other measurements of the deposition temperature of associated minerals, especially quartz and sulphides, from Cornwall.

Webb (1947) considered that the last siliceous solutions arose along the cross-courses, the features of which were described by Hill & MacAlister (1906) and Dines (1956). Other post-mineralization features include faults, flucans, slides, and guides or trawns as they are known in some

districts, most of them differing in age and origin. The exact use of the terms defined by Henwood (1843), Hill and MacAlister (1906), and Collins (1912), varies according to the district. Faulting was especially troublesome in the St. Agnes district and was described by Williams (1917), Hawkins (1822), le Neve Foster (1877), Davies (1879) and Fern (1920).

3/2 Regional Distribution of Mineralization

Henwood (1943) made the first comprehensive study of the mineralization in the South-West and noted the average strike of the lodes and its variation from district to district, shown in Fig. (2). Among the early workers were Pryce, De la Beche, Carne, W. Smyth, le Neve Foster, Symons, Hunt, Collins and members of the Geological Survey, including Hill, MacAlister, Scrivenor, Flett, Davison and Cronshaw. The principal mining districts may be classified according to the granite mass which with they are associated.

In Devon the lodes were worked on the West of Dartmoor near Calstock and Tavistock, and on the East in the Christow valley. The two small granite bosses of Kit Hill and Kingston Downs were the centre of an important mining district, as were also the Bodmin and St.Austell Granites in the south-east. The main concentration of mines was around the Carnmenellis and Carn Brea Granites, and extended towards the Granites of St. Agnes, Cligga, and Godolphin. On the northern flanks of the Land's End Granite lie the mining districts of St. Just and St. Ives, while on the Scilly Isles a few controversial earthworks have been doubtfully attributed to the activities of ancient tin miners.

An overall summary of the distribution and characteristics of the mineralization was provided by Dewey (1925), who emphasized that the general disposition of the lodes follows the outline of the land mass itself. Eastwards from the Land's End Granite the belt of mineralization curves round from the South-West, through West-South-West and finally

assumes an East-West direction in the Dartmoor region. He noted the linear form of the mineralized tract, which commences in the Land's End Granite and extends for more than 100 miles to the Eastern side of Dartmoor, describing it thus:

"It is a narrow tract, being more than 10 miles wide, and it cuts indifferently through rocks of various ages.... Neither structure nor topography affects its course, while within the narrow belt the lodes trend in all directions, and were formed at different periods. A rough parallelism from the centre to the margins of the tract is observed, the tin and copper ores lying centrally, while those of zinc, silver-lead, antimony and iron successively approach the margins ....."

Within the mineralized tract itself, the lodes show marked variations in their distribution in plan. The present writer will not attempt to describe these interesting features, since they have already been fully discussed by Hosking (1949). His summary of the salient features is as follows:

" (1) In any given area, some fissure lodes and dykes strike along parallel lines, but there is always a set of fissures intersecting these at a fairly large angle."

" (2) Many veins and dykes are associated with fringes of the granite outcrops, but comparatively few are encountered in the centres of these outcrops. This barrenness may be due to some extent to the removal by erosion of once existing lodes, as suggested by Emmons."

"Certain marginal portions of the granite outcrops are practically, if not entirely, devoid of fissure veins, and this, for example, is true of the Southern portion of the Land's End Granite and the South-Eastern portion of the Carn Menellis granite."

" (3) Many dykes and some parallel tin-copper lodes are quite far removed from any visible granite. This is true of the dykes and tin-copper lodes of the Gwinear district and of the tin lodes near Perranporth."

" (4) In many cases the lode-dyke pattern bears little or no relationship to the shape in plan of any granite outcrop with which it appears to be associated. Two notable exceptions occur:- The lodes of the Land's End Granite show a roughly radial arrangement, the fact noted by Emmons and utilized by him as an example of the radial development of lodes associated with circular granite intrusions. The elongated boss of Carn Brea has lodes and dykes striking parallel to its long axis. This also, according to Emmons, is just the pattern which would be expected."

" (5) Throughout the country very marked 'streams' of lodes and associated dykes can be seen ....."

In a later paper Hosking (1959) epitomized the characteristics of lode pattern in plan as follows:

" (a) In any mineralized area a number of lodes strike approximately parallel to the porphyry dykes and there is usually a later set of lodes and barren fissures which intersect the earlier at an angle of approximately 90 degrees. Usually the lodes parallel to the dykes contain the earlier hypothermal minerals (cassiterite, wolframite, chalcopyrite, etc.), while the others contain a mesothermal suite (e.g., galena, sphalerite, pitchblende). The mesothermal lodes and barren cross-courses frequently fault the earlier lodes."

" (b) To the North of the St. Austell granite there are several cassiterite-wolframite lodes which possess an anomalous N-S strike. The most notable of these is the Castle-an-Dinas wolframite/lollingite lode."

" (c) Many of the dykes and veins are near the granite/killas junctions and comparatively few occur near the centres of the large granite outcrops. Although the shallowness of the lodes near the granite centres suggests that erosion may account for the general paucity of the ore-bodies there, the authors (Hosking and Trounson) believe that this is not the main reason.

" (h) There is an approximate parallelism between the majority of the lode/dyke streams and those portions of the arcuate Lizard/Dodman/Start Point thrust to which they

happen to be closest. On the other hand, the late mesothermal lodes and barren cross-courses are, when projected, approximately normal to tangents to this thrust."

In all the districts there are divergencies from the average lode trend, and areas occur where the average lode trend is markedly different from the general East-West strike. Henwood (1843) tabulated the average lode strikes of the different mining districts, illustrating the divergencies that exist. As Hosking (1959) has shown, 'streams of lodes' within Dewey's (1925) mineralized tract tend to 'flow' away from the general trend, which swings from E-W to WSW-ENE as the tract is followed westwards along the peninsula. Examples of such divergencies are present around the St. Austell and Godolphin Granites, but the most important are in the St. Just area of the Land's End Granite, where the average lode trend is NW-SE.

3/3 Age of the Mineralization

De la Beche (1839) and Dewey (1925) suggested that all the lodes of the South-West are essentially contemporaneous, although other writers, including Carne (1818), Collins (1912 and Henwood (1943) have evolved elaborate orders of formation for different veins. There is no doubt that locally there are differences in age between the formation of individual fissures and between perids of mineral infilling, though the interpretation of age relationships is often complicated by repeated movements and mineralization phases. Nevertheless, according to Webb (1947), it is "highly probable that the vast majority of the Cornish tin-copper lodes are essentially contemporaneous, in view of:

" (a) the similar mineral association of the lodes,
(b) the undoubted consanguinity of the various granites,
(c) the fact that around each particular granite the lodes were formed during similar stages of the cooling history of the granites."

Hosking (1949, 1959) and many previous writers, including Evans (1925, 1926) have commented on the general East-West strike of the hypothermal lodes, as contrasted with the North-South strike of the mesothermal lodes and cross-courses. Attention has been drawn by some writers to the occurrence of 'caunter Lodes', which are defined in the Geological Survey Memoirs as connecting two parallel lodes. There seems to be no reason to suppose that these lodes are very different in age from the main lodes, and although there are examples of caunter lodes shifting the main lodes, the reverse has been recorded from the same localities.

Any age difference between the caunter lodes and the lodes of the main trend appears to be no greater than that between individual lodes of the main trend. Webb (1947) considered that "they (the caunter lodes) probably represent local complexities in the fracture pattern, all being formed during one period of disturbance."

The first phases of mineralization, commencing with metallised pegmatites, took place soon after the intrusion of the granites. The ensuing East-West tin-tungsten-copper lodes were followed by the North-South lead-zinc-iron lodes which marked the close of the main stage of mineralization. The age of the granites has been determined as being approximately Permo-Carboniferous, while the succeeding mineralization extended into the Permian.

Hosking (1949) outlined the views which were generally accepted until 30 years ago concerning the sequence of mineralization, but noted several exceptions to this order.

In most of the mining area any attempt to determine the age of the mineralization on stratigraphic evidence is vitiated by the fact that the sedimentary country rocks cut by the lodes are older than the granite. The mineralization associated with the Dartmoor Granite, as pointed out by Darnley (1960), is later than Carboniferous rocks of Namurian age, but it differs in character in many ways from that of the remaining areas of the South-West, especially Cornwall.

Darnley (1960) analysed uraninite from Geevor Mine by the complete lead method and concluded that the "uraninite has suffered no significant

loss or gain of uranium, thorium, or their decay products," and that "the $^{206}Pb/^{238}U$ age of 290 $\pm$ 7 m.y. can be given with a higher degree of accuracy than the others."

Post-mineralization structures have been grouped together according to their structure and age in relation to the main phases of mineralization. They are universally assigned to the Tertiary, resulting perhaps from the effects of the Alpine Orogeny.

The mode of formation of a lode or cross-course is always divisible into two separate stages, namely the development of a fissure and its subsequent mineral infilling. Each stage is composite, consisting of several intermittent and pulsational phases, and whenever possible a distinction should always be drawn between the age of the structural dislocation and the age of the infilling of the lode or post-mineralization feature.

3/4 Structural Control of Regional Mineralization

(a) Past Views

All geologists who have contributed papers on the South-West of England have noted the general agreement in distribution relationships between the lodes, cross-courses, dykes, and joints. Many theories concerning the origin of the lodes have been based upon the joint patterns, for it was early realized that mineralization was controlled not only by temperature and petrology, but also by structure. Carne (1822) provided one of the first authoritative accounts of the lodes of Cornwall, describing the minerals found within them and the localization of high values. Both he and Hawkins (1843) contributed a wealth of detail concerning the mineralization.

De la Beche (1839) provided an outstanding study of the area, reporting on both the geology and the mineralization. He considered the lodes to be faults which were subsequently filled with minerals deposited from circulating solutions. Moreover, he described the trend of the lode systems, noting the overall variations from West to East and the local variations within separate districts. The earlier E-W fractures were distinguished from the later N-S system, the local variations being attributed to 'local causes'. On this basis de la Beche assumed that age of formation of the E-W lodes of Devonshire was the same as that of the ENE-WSW lodes of parts of Cornwall. Difficulties were raised by the lode trend in the St. Just district, and by assuming contemporaneity for the

lodes of the St. Just area and the E-W lodes in the area as a whole, he concluded it was not possible to decide how far local causes had contributed to the very different WNW to NW lode strike. He emphasized the similarity in strike between the tin-copper lodes and the elvan dykes, and decided that the latter were formed before the lodes.

Very careful attention was paid by early writers to the subject of re-opening of the lodes, especially as a result of successive downward movements of the hanging-wall, and the consequent successive phases of mineralization which they had frequently undergone. Faulting as a whole was investigated by de la Beche and applied to the interpretation of age differences between intersecting lodes. The lodes were regarded as mineralized faults as distinct from mineralized joints in the granite. According to Webb (1947), "the reader is left with the impression that, although the N-S series of fractures is considered to be later than the E-W system, it is probable that the tin-copper lodes were mainly formed during one period of mineralization in a complex pre-mineralization fracture system." In Chapter XII of de la Beche's Memoir (1839) he devoted a long discussion to previous theories concerning the origin and formation of the tin-copper lodes. His review was concise and realistic, and gave a great deal of attention to the application of Hopkins' ideas (1838), which were mainly based upon the conception of an 'elevatory force'.

Hopkins believed that the first effect of such a force

"will of course be to raise the mass under which it acts, and to place it in a state of extension, and consequently of tension. The increase of intensity in the elevatory force must be so rapid as to give it the character of an impulsive force, in which case it would be impossible to calculate the dislocating effects of it."

He supposed this elevatory force to have acted "upon the lower surface of the uplifted mass through the medium of some fluid which may be conceived to be an elastic vapour, or in other cases a mass of matter in a state of fusion from heat." The tension developed in the uplifted rock was thought to have formed a series of fissures parallel with the axis of uplift. By considering that the only other fissure system which could have formed by tension must have been perpendicular to the longitudinal fissures, Hopkins thereby explained both the E-W and N-S systems,

De la Beche (1839) considered that Hopkins' theory should be borne in mind and that all the irregularities such as caunter lodes, or contra-lodes, and deviations from the normal lode trend could be regarded as modifications due to local variations. He concluded that the fissures containing elvans, and the East-West tin lodes, were of Permo-Carboniferous age and succeeded a late-Carboniferous intrusion of granite which was itself preceded by Devonian or early-Carboniferous folding of the sediments and by East-West disturbances. He considered that the late East-West "slides" and North-South cross-courses were of Tertiary age.

Henwood (1843) gave a remarkable factual description of the Cornish lodes, stating that it was not his intention to explore the theoretical possibilities which his work disclosed, and he left his records and descriptions as an excellent foundation for the work of his successors. The next theoretical writer was Moissenet (1877), whose work was summarized by Webb (1947) as follows:-

"Moissenet, a pupil of Élie de Beaumont, attempted to explain the Cornish phenomena on the principles laid down by his master. He considers the formation of the fracture system to be dependent upon a 'system of upheaval' with a complementary adjacent trough of depression. Granite

forms the core of the axis of upheaval and the stresses involved result in normal faulting under the influence of gravity trending parallel with the longitudinal axis; the major disclocations occur along planes dipping away from the granite. Other minor complementary fissures and joints form and also fractures at right angles to this axis. These latter, he says, must form whenever a long ridge is uplifted. After a system of uplift, there follows a stage of partial depression of the uplifted areas, and further sets of parallel normal faults develop, mainly dipping in the other direction. Reopening of the earlier fissures also occurs. Later systems can be superimposed on the first one and may make an angle with it. The resultant fracture pattern would be very complex. Moissenet considers that six such systems went to make the E-W fractures in Cornwall. The N-S fractures are considered by him to be the result of five later systems making considerable angles (up to 90 degrees) with the earlier E-W systems. Connected with these eleven sets he detects 132 distinct bearings of lode fissures, involving complementary perpendicular and diagonal fractures."

Moissenet's hypothesis did not include an explanation for the distribution in time and space of the variations in trend shown by the "axes of uplift" and associated fractures. He implied that the N-S fractures were the result of normal and reverse faulting, whereas many of them are known to possess horizontal displacements. His eleven distinct phases of fracturing tended to be rather imaginative and are not supported by field evidence; the same applies to his '132 distinct bearings of lode fissures'. However, Moissenet's treatise contained some very useful information under the heading of 'General Characters of the Rich Parts (of the Lodes)', and however imaginative some of his ideas may have been they served the purpose of stimulating the minds of other geologists.

Collins supported the ideas of Moissenet in his publications between 1890 and 1898 but in his major work (1912) he placed rather less emphasis on the latter's ideas. While tending to dismiss Moissenet's earlier hypothesis as being a little fanciful, he declined to add appreciably to any theories of lode formation. He confined himself to

a description of the mineralization in each of the mining districts of the South-West, supplemented by a discussion of the general characteristics of the lodes. Collins (1912) included a comprehensive appendix in which he listed all the mines and gave brief details of their life and production. Webb (1947) summarized Collin's statements concerning the fracture system, as follows -

"He considers that early lateral pressure produced folding and reverse faulting in the sediments, culminating in the rise of the granite magma. The pressure period was followed by periods of reaction and shrinkage due to cooling. Also, potential division planes formed by pressure may become actual fissures during the relaxation period, due to rupture caused by the force of gravity. In fact, he considers that in Cornwall reverse faults are pre-granite, due to pressure, and are essentially, non-metalliferous; whereas normal faults are post-granite, due to gravity, and are decidedly metalliferous. He puts the proportions of mineralized reverse faults at not more than 3 per cent."

The Geological Survey Memoirs were published around this time, the most comprehensive being that on the Camborne-Falmouth area by Hill & MacAlister (1906). Just as De la Beche (1839), Henwood (1843), and Collins (1912) had drawn on a large number of previous papers, so also did Hill & MacAlister quote freely from the literature. All the other Geological Survey Memoirs likewise provided very comprehensive bibliographies up to around the time of 1906-12 for each of the areas. Hill & MacAlister restated the important relationship between the lodes, dykes, and joints, pointing out that there is a general increase in the complexity of jointing as one approaches the mineralized areas. Concerning the formation of the lodes they stated:-

"Carne's (1822) classification of the lodes into six systems, appears to imply that movements operated successively for the production of the fissure systems, and that each movement was accompanied not only by a series of fissures, but by a distinct period of mineralization. The fissures of a single zone of fissuring, or of a whole fissure system ...

may be assumed to have had a common mode of origin. The process which produced the fissures should be regarded as a progressive or long-continued one, so that the fissures first formed should not be separated from the last. In speaking of the age of the lodes, therefore, a period is implied during which two operations may have gone on hand in hand - (1) fissuring, (2) mineralization. ..... Indeed, lines of weakness so formed do not appear to have become fissures capable of the reception of minerals until after the intrusion of the elvans. The process by which the fissures were mineralized was probably long-continued."

In discussing the work of Hill & MacAlister (1906), Webb (1947) stated that they considered that:

"The direction of the stress which acted during the period culminating in the rise of the granite is considered to have been directed from the SSE and strike deflection caused in places by the uprise of the granite column before it spread laterally as a laccolite."

The views of Hill & MacAlister (1906) on the tectonics leading to lode formation were summarized by Webb (1947). They assumed Devonian folding of the country rocks under compression from the SSE, culminating in late-Carboniferous granite intrusion. This was followed by a Permo-Carboniferous 'volcanic phase' which was accompanied by a system of ENE fractures to form the lodes parallel to the belt of the granite intrusions. The NNW cross-courses were classified as Tertiary.

A complete although academic account of the tectonic history of the area was given by Evans (1925 & 1926), who described the changing stress conditions leading to mineralization. He considered that the first folding of the Devonian sediments took place as gentle undulatory movements, These were followed by pressure from the South or SSE which produced numerous East-West and ENE-WSW overfolds and thrusts and culminated in the intrusion of the late-Carboniferous granite. Subsequently, in permo-Carboniferous times reaction after the compression led to the development of normal faults along East-West and ENE-WSW

lines. Evans postulated a later East-West compression, the reaction from which gave North-South normal faults under tension. In common with previous writers he concluded that the NNW-SSE cross-courses were of Tertiary age.

(b) Recent Views.

Ghosh (1934) provided one of the most complete structural accounts of one particular granite namely the Carnmenellis Granite. The tectonic history leading to intrusion and mineralization, as evaluated by Ghosh (1934) and summarized by Hosking (1949) was as follows:-

(1) The region was thrown into a series of anticlines and synclines by Hercynian stresses acting in a NNW direction. These folds were superimposed upon existing structures, and at the same time ENE-WSW cleavage was developed in the country rock.

(2) The magnitude of the pressure increased and was instrumental in bringing about the emplacement of the granite in the earlier-formed anticlines.

(3) The magma, entering the anticlines, exerted a centrifugal hydraulic pressure, which, especially in the east, brought about the development of local cleavage within the metamorphic aureole. At the same time it altered the strikes of the aureole beds and dolerite sills so that they, like the local cleavage, roughly follow the contact of the granite and the country rock.

(4) While the granite was still in a semi-plastic state a crustal pressure operated along an ENE-WSW direction and was followed or accompanied by tension at right angles to it. These two factors caused the development of ENE-WSW and NNW-SSE joints. At about the same time tension produced by gravity produced the 'horizontal' joints which were approximately parallel to the contact. The ENE-WSW joints are regional joints and parallel to the dykes and tin-copper veins of the district, and are found in both the granite and the country rock .....

(5) The granite became solid; Q joints (ENE-WSW) were filled with dykes and mineral deposits and some diagonal (or Mohr's) joints were initiated as a result of pressure and tension acting along the same lines as those which caused the development of the Q and S (NNW-SSE) joints in the semi-plastic granite.

(6) A little later, a pressure acting along a NNW-SSE direction, and accompanied by a tension at right angles to it, produced the remainder of the diagonal joints, and the late and often barren NNW-SSE fissures known as cross-courses (the mesothermal Pb/Zn lodes with the same trend can be included here).

Hosking (1949) also discussed the application of Emmons' conception (1940) that the strike patterns of lodes developed in association with acid intrusives are a function of the shape of the intrusives themselves, though the pattern is liable to be influenced by pre-existing planes of weakness. Hosking (1949) summed up Emmons' views as follows:-

"Following the emplacement of a given body of granite, and by reason of cooling, a solid 'hood' formed. At a certain temperature in the crystallisation of the magma beneath the hood a great deal of gas consisting largely of steam was liberated and collected beneath the hood where it finally exerted sufficient pressure to fracture, not only the overlying granite, but also the country rocks above. By slumping along the fractures thus created, fissures were formed which became infilled with minerals. This process of rupture he believes to be capable of repetition, provided the earlier formed fissures are sealed by deposited minerals and fault detritus."

Completely opposed to Emmons' theory was that of Hulin (1929), who considered that the grouping of ore deposits in close proximity to intrusive igneous bodies is dependent on structural control resulting from forces set in operation by the intrusive bodies. He attributed these forces largely to contraction of the rocks concerned. His views were summarized in detail by Hosking (1949), who also discussed Daubrée's (1879) theory of torsional stress, with general application to the South-West. Daubrée's ideas differed from those of Becker (1895) who showed experimentally that fissures developed by torsion may be expected to be curved and warped, and generally unlike the vein fissures of the South-West (according to Becker).

Hosking (1949) cited evidence for believing that the strike of

the East-West tin-copper lodes was controlled by the existence of unexposed granite ridges which were localized by pre-existing folding in the country rocks. He elaborated on the possible localities of such ridges, especially in a later paper (1959), and concluded that areas of mineralization occur at the intersections of approximately NE-SW and E-W antiforms.

The most recent publication on the structural history of lode formation is that by Hosking (1949), which may be regarded as a reflection of prevalent ideas on the subject. Hosking (1949) considered that:-

"the fissure pattern is largely controlled by regional stresses acting as postulated by Ghosh (1934), combined with the contraction of the granite and attendant slumping under gravity."

and he outlined the history of fissure development as follows:-

"(1) Emplacement of the granite which gave rise to the Castle-an-Dinas lode (not the granite which now appears in the Castle-an-Dinas Mine.)

(2) Directed S-N regional pressure causing the development of N-S Q or tensional joints, and S or compression joints at right angles. Both these systems were developed on a regional scale. The S joints may have constituted planes of weakness which were opened up after the major period of granite intrusion and infilled by the roughly E-W dykes of the Withiel district and some lodes, notably the roughly E-W cassiterite lode just to the west of Lanivet."

(3) Formation of contraction fissures and slumping and emplacement of the Watergate Bay and the Mount Joy dykes.

(4) Continued faulting and the development of the N-S striking cassiterite and wolfram lodes, and in the case of the Mulberry ore, slumping over a chonolith.

(5) Emplacement of the major Cornish granites along lines produced by Armorican folds superimposed upon earlier Variscan folds. Where anticlines of these two systems intersected, knots of granite, now represented by the large outcrops were emplaced, whilst ridges of granite were emplaced largely along Variscan lines in the west and Amorican in the east.

(6) Due to the emplacement of the granite, planes of weakness were formed in the country rock parallel to the sides of the intrusives.

(7) Regional pressure acting along WSW to ENE lines produced the regional Q (open) joints and S (closed) joints. The direction of the Q joints may have been varied in order to accommodate planes of weakness existing parallel to the long axes of the ridges when their strike was not widely different from that of the directed pressure producing the Q joints.

(8) Consolidation of the granite was accompanied by contraction along the Q joints and planes of weakness parallel to the long axes of the ridges and this, attended by gravitational slumping, initiated fractures which were filled by magma forced into them as a result of pressure of the slumping, contracting, semi-solid granite mass on the fluid residual magma. This injected magma consolidated as porphyry dykes. Also, during consolidation, pockets of magma, rich in fluxing materials, were entrapped in the mass, and these on consolidation became patches of pegmatite, whilst other femic-rich pockets of magma which were entrapped became 'basic segregations'

(9) By continued slumping, further fissures were formed and probably old ones re-opened and these were infilled by magma fractions which were becoming progressively more differentiated and are now represented by aplites, minettes, quartz veins, quartz-tourmaline veins and granite pegmatites.

(10) Still further progressive slumping, combined with increased differentiation of the magma residuum caused the development of metalliferous pegmatites and hypothermal loads of the cassiterite-wolfram-chalcopyrite type striking along lines roughly parallel to the already emplaced dykes. Possibly also some of the galen-sphalerite desposits striking parallel to or occupying the higher horizons of cassiterite type lodes were formed soon after. By this time also the temperature had dropped sufficiently for contraction to be sufficiently strong to bring about fissure initiation roughly parallel to the granite-country rock contact.

(11) When the hypothermal lodes were being formed, those Mohr (or diagonal) joints which were due to pressure acting along the direction of the Q joints were initiated and some of them were probably opened by contraction and slumping and then filled with high temperature minerals. Thus, the conjugate vein systems mentioned earlier are believed to have originated.

(12) Later pressure, acting along the S joint direction caused the remainder of the Mohr joints to develop. Probably it was this pressure which caused tension across the S. joints, thus permitting them to be converted into those fault fissures which are now termed cross-courses. Some of these fissures penetrated sufficiently deeply to tap the magma residuum and thus originated the zinc-lead-silver-iron lodes which were followed by later barren quartz veins. Still later, fissures containing only fault detritus were developed, either because the fissure did not penetrate sufficiently deeply or because the magma residuum had been previously exhausted."

(c) Further Considerations

Many theories concerning the structural control of lode formation have tended to lean too heavily upon a probable connection between the average lode trends and the possible effect of certain orogenies. A typical view was that of Llewellyn (1959) who -

"held the view that the earliest orogeny, that of West Cornwall was connected with the Caledonian movement (late Silurian - early Devonian) and that much of the fissuring and jointing took place at that time, while other structural strains were imposed. It seems doubtful whether this movement extended as far Eastwards as East Cornwall and West Devon. The later Amorican movement, with East-West folding, extended throughout the whole area and was responsible for both the mineralization and the formation of the North-South cross-courses."

The coincidence in strike of dykes, lodes and joints has always been evident, the main dyke and lode direction roughly coinciding, with some exceptions, with the trend of the cross-joints, as described particularly by Brammall (1926) and Ghosh (1934). Past theories have postulated that pre-existing joint patterns controlled the lode pattern, and there has been a general tendency to assume that an explanation of the joint patterns is also applicable to that of the lodes. Webb (1947) remarked that "it may be urged, on the grounds of similar strike, that the lode fissures are largely joint planes and that an explanation for the formation of the joints automatically explains the lode fissures." However, the present writer considers that an explanation of the joint patterns contributes only partly towards an elucidation of the lode patterns. Some reasons for this contention are given below:-

(1) The recognition of cross, longitudinal, diagonal and flat-lying joints is a simplification which takes no cognisance of the large number of additional 'secondary' joint patterns which may be attributed to later stresses.

(2) Jointing is more intense in mineralized areas than elsewhere.

(3) Lodes extend into the country rocks both above the granites and between adjacent granite outcrops.

(4) Joints in the country rocks are frequently of different origin, age, trend, style and perfection, from those developed in the granites. An explanation of joints within the granite is not necessarily applicable to those within the country rock, nor is their presence in the granite any guarantee of their presence in the adjacent country rocks.

(5) Any analysis of joints in the folded country rocks is complicated by the fact that the area contained well-developed pre-granite structures. Research into joint patterns attributable to the same stresses as those which produced folding has not yet advanced to the same degree as the study of minor structures in folded rocks.

(6) Cross-courses extend into the country rocks.

(7) Where dykes and lodes possess a similar strike direction, the dykes invariably possess a lower dip than the lodes.

(8) The lodes frequently form systems of conjugate fissures, whereas dykes which strike parallel to the lodes follow the direction of dip of only one set of the lodes.

(9) When conjugate vein systems exist the acute angle of intersection is usually in the vertical quadrant.

Webb (1947) applied the theories of Anderson (1905 & 1942) to the interpretation of the fissure pattern, and concluded that the conditions for the formation of the pattern, assuming normal faulting in the lodes, were as follows:-

"(a) the greatest stress must have been the vertical;
(b) the least stress must have been at right angles to the lode trend (horizontally);
(c) the intermediate stress must have been parallel to the lode trend (horizontally)."

He considered that these conditions could have been fulfilled by

"(1) a relief of stress in horizontal directions,
(2) an increase in the vertical force,
(3) a combination of both."

Relief of the horizontal stress might have been due to relaxation of the 'hercynian' compression, while the vertical force may have been created by either a downward one of gravity or an upward one resulting from the vapour pressure of residual ore solutions. Both forces would produce normal faulting in the planes of the lode fissures, but the effect of gravity slumping would probably be felt over a much wider area than that due to vapour pressure. The effect of the latter would tend to be concentrated over the main South-West granite ridge, the granite cupolas being solid at the time of formation of the lode fissures. Webb (1947) stressed the fact that the highest points in the ore-fluid 'chamber' occurred beneath large 'cupolas' and "at these points the overlying rock column was least and rupture would take place most easily at such points. The fracturing would be most extensive in the shallower zones, but would be restricted in depth near the ore-fluid 'chamber'." He considered that these localized points of rupture, formed when the vapour pressure of the ore residuum exceeded the retaining pressure of the overlying rock, coincided with the 'emanative centres' of Dines (1933).

Webb (1947) believed that pre-existing joint patterns in the granite, and extending into the country rocks, facilitated the movement caused by an increase in upward vertical pressure coupled with the relief of

horizontal compression. Briefly, "the joints appear to be due to 'regional forces', the lodes to the action of localized stresses influenced by actual and potential planes of weakness formed largely as a result of these earlier, more widespread phenomena."

Webb also discussed the structural history of the porphyry dykes, with special reference to Anderson's (1942) conception of 'wedge intrusion'. He accepted that the localization of dyke fissures was influenced by the presence of pre-existing joints which acted as planes of weakness, and added that "the dyke fracture is propagated along a direction determinated by the orientation of the three stress axes and the local freedom of movement." The porphyry magma was considered as having been injected along planes of weakness during a period when the major N-S compression was beginning to relax, and Webb disagreed with McLaren's (1917) suggestion that the 'elvans' and North-dipping lodes in the Camborne-Redruth area were formed in contemporaneous fractures. However, the whole question of the emplacement of the dykes and a comparison between their pattern in plan and section and that of the lodes, was largely left unanswered by Webb (1947).

3/5 Local Control of the Mineralization

Three major variants, structure, temperature and petrology, appear to have exerted a control upon the extent of tin-copper mineralization, and the localization of the richer portions, within individual lode fissures. When each control is analysed it is found to be initially dependant upon the local structural conditions. It is therefore more convenient to consider each resulting feature and to attempt to interpret it as the result of the above three controls.

Many of the Cornish terms applied to the richer portions of the lodes have been abandoned, whilst others have become international in use. Collins (1912) defined many of them on the basis of the two major dimensions. When the horizontal extent of the richer portion is greater than the vertical extent the terms 'course of ore' or 'lane of ore' are usually applied. In the reverse case the terms 'shoot of ore', 'chimney', and 'pipe' have been employed. Frequently the richer portions are quite indeterminate in form and when the ore occurs in comparatively small richer parts they are known as 'bunches', 'pockets', and 'squats'.

(a) Granite Contact

As a result of strong temperature control the vicinity of the contact between the granite and the aureole rocks has always been considered favourable for tin-copper mineralization. Although the economic ore of tin or copper may be located in either the granite or the country rocks, as in the case of Geevor and Levant Mines shown in Fig. (23), it is usually bounded on one side within the individual lodes by the contact. On a minor scale pockets of ore are frequently localized beneath the granite contact.

Structural impounding of the mineralizing solutions was an effective control and the depositions of the tin resulted essentially by replacement of the granite. Carbonas and associated replacement bodies are familiar examples. The inclination of these small pockets parallels the local slope of the nearby granite surface whereas that of the larger courses of ore is in the same direction but at a lesser angle. This effect was noted by Fox (1836) and Henwood (1843), who admitted that exceptions occur.

When the granite abuts against killas the tin ore may be equally distributed in either rock type. Assuming the lode fissure to be developed to the same extent on both sides of the contact (which is not always the case), the major controlling factor appears to be the temperature during mineralization. At a contact between granite and greenstone the tin, if developed at all, is usually concentrated in the granite and not in the latter. Nevertheless, according to various writers, copper deposition has appeared to benefit from the presence of greenstone. De la Beche (1839) observed the continuance and equal development of fissures in granite and adjacent greenstone. Temperature effects alone are not an adequate explanation, and Hosking (1951) concluded that the main control resulting in the impoverishment of a tin lode in greenstone was a chemical one. Further examples of such selective mineralization or petrological control were provided by Collins (1912) and MacLaren (1917).

The subject is complex and it is important to distinguish between the diverse varieties of greenstone which may possess different structural and chemical characteristics, and also between the separate phases of tin mineralization which, according to Webb (1947), may be dependant upon very contrasting modes of deposition.

(b) Lode-dyke intersections

The effect upon the tin content of a lode when intersecting a dyke appears, from the information available in the literature, to have been anything except predictable. The lodes were either undisturbed or they formed branches, were either impoverished or enriched. With the exception of a few cases in which enrichment was definitely the result of increased alteration within the dyke adjacent to the lode fissure, the majority may be accounted for in terms of structural control.

(c) Lode Intersections

The intersections of lodes have been of the utmost economic importance and the majority of past writers provided specific samples of either the enrichment or impoverishment of one or both lodes at a junction. In general, when the two intersecting lodes have a similar strike, meeting at an acute angle, enrichment occurs at the junction. When the angle of intersection is large the result is the reverse case.

Collins (1912) assumed in the case of the former that the movement which accompanied mineralization occurred simultaneously along the two intersecting lodes. He reasoned that additional brecciation at the junction would result in increased cavity formation and deposition surface area, and hence infilling and replacement. In the second situation it was pre-supposed, on the basis of the wide difference in strike, that movement and simultaneous mineralization took place along the two individual lodes at very different times.

(d) Lode Branches

Collins (1912) supplied the following definition of a lode branch:

"When a lode becomes divided (splits) it usually loses much of its value; the term 'branch' is then applied to the separate parts as long as they continue to be worth taking." Branches pass off from both the hanging-wall and the footwall. When they enter the lode from above they are known as 'feeders' and when leaving from below the term 'droppers' is employed.

Rich shoots or courses of ore have often occurred at the point at which a branch develops even when the lode itself was of little value. At Wheal Basset rich tin and copper ore-pipes are located at the intersections of branches with the several vertical lodes, and at Wheal Vor the occurrence of feeders and droppers provided important indications of the grade of ore to be expected in development.

(e) Variations in Lode Dip

Thomas (1819) first recorded the fact that those parts of the lodes with an inclination nearer the vertical were usually the most productive. A correlation between the increased width of a normally faulted fissure or lode and an increase in dip above the average for the fissure was clearly demonstrated by Leithart (1838), De la Beche (1839), and Henwood (1843). A century later Emmons (1943) re-presented the explanation illustrated in Fig. (105), citing examples from many localities with the exception of Cornwall.

As emphasized by Collins (1912), a lode which possesses a greater average dip than another is not necessarily the richer, but portions of either lode which are steeper than the average dip of the individual lode itself are usually the richest portions.

The increase in value of a lode at any point may result from either

a greater width of the same grade of ore or from a higher grade of ore, the latter probably being due to the stagnation of the mineralializing solutions during their ascent.

(f) Variations in Lode Strike

It has generally been assumed that the majority of the tin-copper lodes were subjected to normal faulting during the mineralization period. Indications suggest that also there was frequently extensive relative lateral movement of the lode walls accompanying the mineralization.

In such cases changes in strike, rather than changes in dip, exerted a structural control upon the mineralization. The Dolcoath Lode is a notable example and it was concluded that "changes in the bearings of the lodes appear to be the chief cause of reductiveness or otherwise." Variations in lode strike, combined with mainly lateral movement of the walls were considered by Le Neve Foster (1876) to have been the chief cause of the formation of the rich ore-pipes at East Wheal Lovell.

Many lodes were subjected to oblique relative movement of the walls and changes in both the dip and the strike were of major importance.

(g) Additional Features

Many other unexplained features of the disposition of the courses and shoots of ore were lucidly outlined by Collins (1912). One of the more important was detailed as follows: "It is a well-known rule ..... that whenever a lode has been rich for a considerable time, its branches, or neighbouring lodes which are nearly parallel; are likely to be 'cut rich' but a cross-cut starting from the profitable region, and in a direction which is that of the principal cross-courses of the district."

An account was also given by Thomas (1921), and the present writer has recently (1961), provided a preliminary possible explanation for this widespread phenomena in Cornwall.

In outlining the characteristic features of the lodes, Hosking (1951) mentioned the beneficial effect exerted upon the final value of a lode by the number of occasions on which it has been subjected to mineralization by the successive cassiterite-bearing phases occurring in quick succession. If several phases were separated by considerable time periods the resulting lode simply possesses a more complex mineralogy and internal structure without any attendant increase in value.

4. LAND'S END GRANITE AREA

4/1

General Description

The position of the Land's End Granite area in relation to the remainder of the granites is shown in Figs. (2), (3) and (4). Apart from that of the Scilly Isles, it represents the most westerly exposure of the South-Western Granite batholith. Since it is almost entirely surrounded and dissected by the rugged coastline, it displays some of the best granite exposures in Cornwall, besides revealing various contact features most clearly. There are some inland exposures of the Land's End Granite, especially on the flanks of the Northern hills, and in a number of small granite quarries.

As shown in Fig. (3) the 72 sq. mile Land's End Granite is not circular in plan but takes the form of two intersecting elongations, one trending NE-SW and the other NW-SE. The granite was intruded into Devonian strata, referred to the Geological Survey as the Mylor division. Within the latter are various 'greenstone' intrusions and pillow lavas. The area has been an important centre of mining, and a general description of the mineralisation in both the granite and country rocks was given by Robson (1948).

Owing to its exposure to the full force of Atlantic gales the area is rugged and picturesque. The coastline, in the West and North, consists of steeply plunging cliffs that rise to a maximum height of about 300 feet. To the South conspicuous jointing in the granite has been responsible for the well known cliffs of Land's End. Elsewhere, access to the sea is easier, since flat-lying joints exert a greater control

the cliff are less steep and pitch gently down to the high-water mark as shown in Photo (32). Inland the ground rises, as illustrated in Fig. (5), to a maximum elevation of 805 feet. The peninsula is connected to the remainder of Cornwall by a short isthmus composed of sedimentary strata which rises to a height of only 150 feet. Most of this ground, especially to the South, is poorly drained and includes a large amount of swamp and marsh. Except to the North the granite produces an undulating land in which the exposures are few. At the highest points there are some tors or carnes on which weathered granite is exposed. The remainder of the high ground is usually covered with large boulders which indicate the nature of the underlying granite, A central fine-grained granite, which yields no natural outcrops, is exposed at the Castle-an-Dinas quarry.

There is abundant evidence in the area of the sea level having fluctuated over a long period. An account of the recent geological history was given by Robson (1948) as follows:-

"This area ... was an extensive land mass during the Permian to Jurassic periods. The Westward advance of the Upper Cretaceous sea and its deposits in East Devonshire imply an almost total submergence, since these rocks are now planed off at 600-800 O.D. it may well be that the higher platforms in Cornwall are of late Cretaceous or Eocene age and that flint was derived from them. The excavation of the St. Erth valley and the Bovey basin (and its silting up with clay and lignite, Oligocene in age), means an emergence of over 700 feet. The extensive fluctuations in sea/land relation may be attributed to the Miocene (Alpine) disturbances, whose effects left the peninsula submerged at some 400 feet above the present sea level. At this time 'Land's End' was a granite island of 31 square miles. Sands and Clays were laid down on its flanks and in estuaries adjacent to the archipelago. Post Pliocene emergence continued into the Pleistocene period with attendant lower marine platforms, raised beach and head to a level somewhat (perhaps 40 feet) above the present .... Further depression swamped these alluvial deposits (Marazion). Thus the late-Tertiary to Recent fluctuating history of the district is preserved in the deposits of the peculiar St. Erth valley the early Tertiary features are topographical, elevation-platforms."

Robson (1948) described the possible traces of marine platforms at 800 ft., 750 ft. (Ding Dong), 600 ft. (Carn Brea, Balleswidden, Trewey Common), 250-400 ft. (common at various levels throughout the Land's End area), 180 ft., 65 ft. (Penlee), and 10 ft. (Pendeen-Botallack). The subject is dealt with in more detail by other writers, notably Carne (1863. No. XXXV.), Miss E. Carne (1863. No. LXXV.), Reid & Flett (1907), Rogers (1910), Everard (1960), Savigear (1960) and, more generally, Miss Hendriks (1923), Gullick (1936), Balchin (1937), and Fryer (1957). Drainage is controlled by the trend of the granite mass, and especially by its joint directions. The drainage pattern of the Land's End area is shown in Fig. (6).

All the low ground is used for farming, the area bordering on Mount's Bay being utilized for mixed farming, and land up to 400 feet is maintained for grazing. Above this height the ground is of little use for agriculture. The main ancilliary industries of the area are based on tourism, with some men employed in mining, quarrying, fishing, and the manufacture of light consumer goods. Consequently most of the employment tends in the Land's End area to be seasonal, the unemployment figure at times being very high.

The work of the Geological Survey was described by Reid & Flett (1907), who provided a very comprehensive account of the geology with mile by mile descriptions of the accessible coastline, besides compiling a list of references. A later general summary was contributed by Robson J. (1948).

4/2 Previous Geological Work in the Area

(a) Prior to 1843.

After reading the long and detailed papers of past workers one is left with a feeling of modesty and admiration at their conscientiousness and depth of reasoning. Nevertheless, the remarks of Read (1961, p.681) concerning the volume of work not yet completed in the Highlands of Scotland apply equally well to the South-West of England.

The research possible in an area is largely dependent upon the availability of exposures and the abandonment and consequent flooding of the vast majority of the mines in the South-West at the beginning of the 20th Century has had a detrimental effect upon the advance of knowledge. Before that time, however, it had long been realised that an increase in the understanding of the mineralization necessitated both the systematic recording of underground observations and the exchange of ideas. In 1818 the Royal Geological Society of Cornwall was founded, and its Transactions, which are still being intermittently published, provide a wealth of detail concerning mines whose existence is now indicated only by fenced shafts and waste heaps.

Davy (1818) published an account of the exposures on the coastline near Cape Cornwall, describing the granite, 'slates' and several 'granite veins'. Grouping both the 'greenstones' and the 'killas' under the caption of 'slates', he appeared to be in some doubt concerning the relative ages of some of the rock types. Majendie (1818) enlarged upon the subject of later granite veins, with special reference to the granite contact exposed at Mousehole. Hawkins (1818) described the mineralization and history of the Wherry Mine at Penzance, and

listed other mines in the St. Just area the workings of which extended beyond the low water mark.

'Elvan courses' and the various effects which they exerted upon a lode intersecting them was the subject of a paper by Carne (1818), in which he defined the term 'killas' as "proper grauwacke or argillaceous schistus or slate". He discussed the "relative ages of the veins of Cornwall." and after noting the dip of the lodes in the St. Just area stated that the richest portions of the tin lodes frequently occurred at the junction between the granite and the 'slate'.

In his next paper Carne (1822 No. V) divided the St. Just lodes into two age classes, mainly on the basis of their direction of dip, but he made a false structural comparison between the St. Just and St. Agnes areas. No authentic examples of South-dipping lodes intersecting supposedly earlier North-dipping lodes were cited in support of his hypothesis, but he mentioned that "... The tin lode of Huel Owles, in St. Just, runs nearly North-West and South-East, and traverses every other tin lode which it meets ..." Carne discussed the variation in values of the tin and copper lodes and the effect upon them of the petrology of the wall-rocks. The local 'guides' or 'cross-courses' were placed in a category apart from the lodes.

The phenomena of intersecting lodes caused considerable argument. For example; Hawkins (1822, No. X.) described the movement of lodes subsequent to their infilling, mentioning Botallack Mine ... where two distinct lodes occupy the space between the two walls." Heaves, slides and flookans were discussed with reference to specific illustrated examples, and the variation in values within the lodes was attributed to relative movement of the lode walls which possessed varying dip and

strike. Emmons (1943) credited Leithart (1838) with the distinction of first observing this particular structural control of mineralization, but it appears that it had previously been recorded by Hawkins (1822) and observed by the miners themselves for many years before that time.

Hawkins (1822, No. XI) enlarged upon the subject of faulting, giving examples from several mines, including Ding Dong in Madron where "... the tin lode is both heaved and started by the cutters and clefts of the granite through which it passes." Forbes (1822) wrote a picturesque geological account of the coastline around the Land's End Granite, but he dismissed the granite exposures as offering " ... little variety to excite curiosity or research," and devoted most of his paper to a description of the 'slate and greenstone formations'.

The first list of minerals present in the St. Just area was compiled by Carne (1822. No. XV.), who systematically described the relative importance and mode of occurrence of all the economic and gangue minerals. The local guides were identified as iron lodes, with an average width of 6 feet, and the angle of intersection between the guides and the lodes was related to the cassiterite values contained within the latter at the point of junction. Regarding lode intersections he stated that "It is very difficult to ascertain whether the tin lodes of St. Just are of different ages: they often intersect each other, but so little attention has been paid to these circumstances by the miners, that it is almost impossible to get at the truth."

Carne contributed a description of the 'tin floors' in Botallack Mine and concluded with a list of mines in the area which extended beneath the sea. Carne's (1822) mineral list was brought up to date in 1846, and was

followed by a note by Penberthy (1846) who listed the localities from which specimens of pitchoblende had been obtained at the Providence Mines, St. Ives.

Carne (1828) reported several macroscopic variations in the Land's End Granite and distinguished a fine-grained variety on the hills near St. Just. Moreover, he gave a petrological and geographical account of the Granite and the associated veins of quartz, granite and schlorl. Tin streaming in a valley at Drift Moor, to the North-West of Penzance, was described by Carne (1832).

A summary of all the preceding work, together with his own observations, was recorded by Boase (1832). He disagreed with Forbes' (1822) remarks concerning the uninteresting nature of the Land's End Granite and noted the existence of a fine-grained granite around Castle-an-Dinas. The location of several "granite veins within granite" was given and the metamorphism of the 'greenstones' by adjacent granite described. Under the title "On the Veins of Cornwall" Boase (1832) raised controversial structural questions concerning the lodes and the 'veins', and recognized the similarity between the general lode pattern and the joint patterns in the granite of the St. Just area. Instead of providing the reader with an explanation of the varying characteristics of the lodes he discussed their origin and in each case raised exceptions to the general rule. Finally, he stated "... we shall, I think, strive in vain to account for the manner of their (the lodes) production... We must therefore follow the example of the cultivators of these sister sciences (Botany and Anatomy), and be content with endeavouring to obtain an accurate description of veins: this object is, in some measure, within our reach; the other far

beyond our finite comprehension."

A great advance was made by de la Beche (1839) who was the first to recognize many features in the Land's End Granite, including its schorlaceous nature, its emplacement into greywacke beds, and the separate intrusion of the fine-grained Castle-an-Dinas granite. 'Elvan dykes' were identified as 'granite and feldspar porphyritic rock' of a later age than the enclosing granite. He dealt with the aureole rocks and the metamorphism of the 'greenstones' by the granite, together with the consequent changes in mineral assemblages. The varying attitude of the aureole rocks was described by Thomas (1846), who noted that everywhere the 'schist' dips away from the granite at a lesser angle than that of the granite surface. He recorded the fact that the granite contact is exposed at the Longships Lighthouse, where the country rock consists of greenstone.

Volume V of the Transactions of the Royal Geological Society of Cornwall contained a monumental work by Henwood (1843) upon the mines and mineralization of Devon and Cornwall. Each of the major mining districts of the South-West is outlined and the characteristic features of the mineralization described on the basis of his own observations in each mine. This was the first work in which a multitude of facts was accumulated and then analysed for the purpose of developing theories and 'rules of mining'. Henwood (1843) summarized the salient features of the lodes and made some very prescient remarks upon the structural control of the mineralization. This volume of the Transactions is invaluable as a reliable source of information even at the present time.

(b) 1843 to 1900:

Following Henwood's (1843) major publication, succeeding writers turned to the non-economic aspects of the geology. Carne (1865, No. XXIX.) described the joint pattern of the Scilly Isles Granite, and a similarity is evident between his classification and the joint pattern observed by Whitley (1865) in the Land's End Granite, who described the effect of the predominant NW-SE granite joints upon the physical geology of the Penwith area. Whitley (1865) correlated this joint direction with the general trend of the valleys and noted the fair agreement in alignment between the joints, the lodes and the cross-courses.

Raised beaches at Zennor were discussed by Carne (1865,No. XXXV.), who noted the existence of one approximately 20 feet above the water mark containing rounded boulders of 'greenstone' in a sand matrix. Several other raised beaches around the coastline of the Land's End Granite were recorded by Miss E. Carne (1863, No. LXXV.) who also discussed the significance of their distribution. Further details were provided by Rogers (1910) in a description of the whole of the Cornish coast.

In a later paper Miss Carne (1878,p. i) described the metamorphic changes apparent in the 'killas' aureole of the Land's End Granite and noted the interbedded nature of the 'killas' and 'greenstone'. Although dismissing any notion of the metamorphic origin of the granite, on the basis of the absence of a rock intermediate in composition between 'killas' and granite, she did not fully support de la Beche's idea of the intrusive origin of the granite. In her next (1878) paper she completely discounted the theory of granitization as applied to the Land's

End Granite. Three variations in the nature of the granite were classified; the normal type, a muscovite-rich type in the vicinity of Ludgvan, and a central fine-grained type near Castle-an-Dinas. She mentioned the agreement in trend between the lodes and the NW-SE granite joints in the St. Just area. The joint and lode patterns were attributed to the effects of an "undulatory force" acting upon the granite while it was "settling and shrinking," and while the granite magma was uprising and being hemmed in by the pre-existing surrounding masses of greenstone and killas. During the intrusion of the granite, the magma was thought to have been "twisted round" to the south in the St. Just area so that NW-SE fractures were initiated at the point of turn.

An important contribution to economic geology was made by Moissenet (1874) in which he related the strike of the Cornish lodes to the effects of "ancient mountain building periods". He attempted to determine the reasons for the localization of the richer ore shoots within the individual lodes, and illustrated his ideas by observations on the richer parts of copper lodes in the Dolcoath Mine. His paper was later published in English (1877) and summarized by Smyth (1878), who also lamented the pronounced dearth of underground geological records kept by his contemporary miners. Le Neve Foster (1877) contributed a description of the "tin pipes and bunches" of East Wheal Lovell which closely resembled in their mode of occurrence the carbonas of the St. Ives district, but differed from them in the absence of tourmaline.

Rowe and Le Neve Foster (1887) later described the form of the

lodes at Balleswidden Mine in St. Just, an interesting feature being the 'gries' or thin veins of cassiterite running through the 'hard-work' or granite. The NW-striking lodes were reported as each consisting of several closely-spaced 'gries' which varied in productiveness, and were notably richer when the dip of the lode was greatest. NE-striking cross-courses and NW-striking slides were also described.

The first petrological description of the 'killas' and 'greenstones' based on observations under the microscope, was given by Phillips (1875). When considering the whole of Cornwall he discussed the rocks of the St. Just area and specimens of granite from the Land's End peninsula. Microscopical descriptions were correlated with chemical analyses, and he dismissed any idea of the metamorphic derivation of the granite from 'killas'. The elvans were attributed to the same source as the granite, and the greenstones were divided into two classes; 'volcanic rocks' and 'hornblendic slates'. A short and comprehensive account of the mineral lodes was included, and Phillips made some very far-sighted remarks concerning the apparent deflection of lodes by earlier elvan dykes. The brecciation of material and the successive phases of mineralization within one lode were described in connection with the origin of the lode fissures. Many of the existing problems concerning the true nature of the 'greenstones' were elucidated by Phillips (1876), who divided the 'so-called greenstones' of the Penzance area into three classes, namely, altered gabbros or dolerites, 'killas' or 'ordinary clay-slates', and "highly basic hornblendic rocks presenting under the microscope the characteristic appearance of clay-slates." Teall (1887) described the 'greenstones' as proterobases and epidiorites, and decided that they were

originally similar to the unmetamorphosed ophitic dolerites of East Cornwall and Devon.

Allport (1876) conducted a comprehensive microscopic study of the aureole rocks of the Land's End Granite with special reference to the varying metamorphic changes in each type resulting from the proximity of the granite. The change of augite into actinolite in the 'greenstones' and the production of tourmaline schists and muscovite schists in the 'killas' were noted. He concurred with previous writers, including de la Beche (1839) and Phillips (1875), in asserting that the granites were igneous intrusions. A microscopical study of rocks in the area was continued by Le Neve Foster (1887), who described the tourmalinization of granite at St. Just and at Ding Dong mine, and by Phillips (1880) who provided both microscopic descriptions and chemical analyses of inclusions and xenoliths in the Land's End Granite.

(c) 1900 - 1961:

The beginning of the 20th Century marked the commencement by the Geological Survey of the detailed mapping of South-West England. Flett (1904) published a preliminary account of his work on the petrography of the rocks of the Land's End area, which was followed by the Geological Survey Memoir by Reid & Flett (1907). Fine-grained granite at Castle-an-Dinas was shown to be younger and intrusive into the normal variety. The latter was considered to have been intruded into an ENE-WSW trending anticline in the country rocks, identified by the correlation of separate outcrops of 'greenstone'. All the rock types, including those in the Botallack and Kenidjack area, and their transformations due to metamorphism, were discussed in detail.

Although Reid & Flett (1907) appear to have avoided the major structural problems of the area, the Geological Survey mapping was later employed by many writers as a foundation for analysing its structural history. A paper by Hill (1901) was followed by that of Green (1908), in which he attempted a tectonic analysis of the folding in West Cornwall. This subject was discussed again by Green and Sherborn (1913) when they restated their view that the South-West had been affected by the Hercynian Orogeny resulting in the formation of "over-folded anticlinals." On the structure of South-West England very little more was contributed until a paper by Miss Hendriks appeared in 1937.

After 1900 the Royal Geological Society of Cornwall published an increasing number of detailed descriptions of particular mines in Cornwall, but the St. Just area was rather neglected.

A preliminary paper by Collins (1887) dealt with many facets of lode structure. He explained that the apparent horizontal displacement of lodes, one by another, could frequently be attributed to the oblique faulting of an inclined lode. The Corpus Christi and Crowns Lodes of Botallack were mentioned and the former was described as containing only tin-ore in the granite and copper-ore in the 'slate'.

This work was followed by Collins' major publication (1912) entitled "Observations on the West of England Mining Region." He dealt with each of the mining districts and all the major features of the lodes of Cornwall, including the effect of structure, temperature, and wall-rock upon their formation and mineralization. In the Appendix all the mines were listed, followed by the relevant statistics. This work was a major contribution to the subject, most of his interpretations being founded

upon meticulous underground observations. It enlarged upon all the matters which he had previously emphasized in his Presidential Address (1905) to the Royal Geological Society of Cornwall and in his earlier publications (1891, 1893, 1896 & 1899)

Following the works of Collins (1912) and Reid & Flett (1907) there was a long period during which the economic geology of the Land's End area was overlooked, although other districts, especially Camborne and Redruth, were repeatedly described. For first-hand information later than 1912 on the mines in the area one must rely upon an assortment of reports which were usually written as a prelude to the attempted re-opening of a property.

A number of these reports are still available concerning mines in the St. Just area, and are useful in providing an overall picture of the properties when operating, as well as in giving details of their history. Some, together with written communications and periodical reports concerning Levant and Botallack Mines, are held by Mr. J. H. Trounson. Among the earliest reports are extracts from the "Mining World", between August 1872 and March 1874, concerning Boscaswell Downs Mine. Some of this information, supplemented by letters, is incorporated in a report by Steuart and James (1906) which also contains details of the various lodes within the Boscaswell sett. In connection with an attempt to re-open the mine further reports, all of which are available at Geevor Mine, were compiled by James (1916, 1919, 1924, 1925, 1927), Shepherd (1918) and Williams (1919).

As a result of the man-engine disaster at Levant Mine in 1919, which was explained by Abbott (1920), the lower levels were flooded. Oats (1920) described how development was confined to the upper and older levels of

the mine. The property eventually closed in 1930, and Ellis (1932) presented a useful report containing recommendations for its eventual re-opening. Geevor Mine was by this time developing rapidly and Collins (1920) and Leggett (1920) provided the first authoritative reports upon the property containing reliable geological information.

The Second World War gave a new impetus to Cornish mining, and the potential of the Land's End district as a tin producer was outlined by Trounson (1942 & 1951) in a survey of the St. Just and St. Ives areas. Although containing no new information on the geology, the work provided an informative account of the history of mining in the area besides offering probable reasons for the closure of many of the mines, including Levant.

The Geological Survey maintained their interest in the area by visiting Geevor Mine at four-yearly intervals to map the newly-developed workings. Their results, coupled with investigations of all the old properties in the South-West, resulted in the publication of the Geological Survey Memoir, "The Metalliferous Mining Region of South-West England", by Dines (1956). Although largely dedicated to a fathom-by-fathom description of the layout of the underground workings of mines, including those in the St. Just area, the Memoir provided a brief description of Geevor Mine. It included a diagrammatic section of the North Lode and some petrological descriptions of the lode material and wall-rock from various localities throughout the mine. The main value of the Memoir is as a source of information concerning the extent of workings and the locations of shafts and stopes in any particular lode or mine that has now become inaccessible. It suffers from a deficiency of illustrations in lieu of lengthy descriptions

and the use of a rather outmoded form of geological nomenclature.

Interest was recently revived in the South-West as a possible source of uranium ores, a considerable amount of work being carried out at Geevor Mine by the Atomic Energy Division of the Geological Survey. Ostle (1951) visited the mine and made a preliminary underground survey of those levels which yield high readings of radioactivity. Specimens were examined in the laboratory and uraninite, to which the radioactivity was attributed, was found to be associated with the commonly occurring sulphide minerals. Darnley (1959 & 1960) carried out an age determination on uraninite concentrates from the James tables in the mill.

The only other recent detailed investigation at Geevor Mine was a laboratory study by Hammond (1958) of some of the sulphide minerals from the lodes then being worked. Considering the size and economic importance of the mine, it has been seriously neglected from a geological standpoint.

During the 1940's many of the arguments concerning the origin of granites were revived by Sederholm and other workers, and the whole problem was considered by Read (1943 & 1944) in his meditations on granite. Prompted by this interest, Bagchi (1947) provided a full description of the Land's End Granite and country rocks, together with the metamorphic processes involved. He distinguished several modifications of the normal porphyritic granite and gave detailed petrological descriptions of all the rock-types. He did not discuss the economic geology, apart from commenting upon the agreement in strike direction between the lodes and the major jointing in the granite. The greenstones were divided by him into three types; those of intrusive igneous origin, those with pillow structures, and those of doubtful origin. At about the same time Robson provided

short summaries of the geology of the St. Ives district (1945) and the Land's End Peninsula (1949).

In discussing the origin of the tin lodes of Devon and Cornwall, Webb (1947) synthesized all the available information concerning the economic geology and structural control. He made a comparison between the lode characteristics of Geevor Mine and those of South Crofty Mine, his doctorate thesis being based mainly on the latter property. Wall-rock alteration was described and he discussed one of the major problems of the St. Just area, namely the average lode trend, which is at variance with that of the remainder of the County. Webb (1947) noted the similarity in appearance between a transverse section of the lodes in the Carn Brea area and a plan of the lodes in the St. Just area. He attributed the formation of the former to a dominant vertical force and the latter to a dominant horizontal force. Although many previous writers had commented upon the NW-SE trend of the lodes in the St. Just area, Webb (1947) was the first to propound a reasonable explanation of their origin, based upon the ideas of Anderson (1942).

The greenstones of Kenidjack and Botallack received renewed attention in a paper by Miss Reynolds (1947) in which she explained them as having "developed from a sedimentary series including limestones and shales with intercalations of igneous rocks of the spilitic type" by Fe and Mg enrichment on a regional scale. This development was considered as "antedating the emplacement of granites, in connection with which emplacement further enrichment in Fe and Mg took place locally."

A comprehensive survey of the aureole rocks of the Land's End Granite is now being conducted by members of the University of Birmingham, under

the direction of Lacy (1958). The stretch from Carn Moyle to St. Ives has been described by Hawkes (1958) and that from Portheras Cove to Priest's Cove by Barclay (1959). The work so far completed has concentrated upon the structure and origin of the 'greenstones' and upon minor structures in the 'killas'. The greenstones have been shown to be generally of either pillow lava or igneous origin, thus refuting the views of Reynolds (1947). By studying the minor structures in the killas an attempt has been made to elucidate the overall structure of the aureole rocks in the Land's End area.

4/3 Aureole Rocks.

(a) Killas

The aureole rocks around the Land's End Granite consist of Devonian slates and greenstone masses with a complex mineralogical and structural history. The term 'greenstone' has rightly been criticized by many writers as being a convenient caption without precise geological definition. The present writer considers that the use of this term is justified if it has first been defined, and will use it for the sake of convenience. The same applies to the term, 'killas', which the writer will employ when referring to any of the Devonian strata and related metamorphic assemblages.

The metamorphic aureole surrounding the Land's End Granite was mapped by the Geological Survey and its outer limit is shown in Fig. (9). There is no clear division between the unmetamorphosed killas and the killas lying within the metamorphic aureole. The former is represented by exposures on the shore at Porthleven where the gradual transition into metamorphosed killas around the Godolphin and Land's End granites may be observed, and was described by Reid & Flett (1907). The main exposures within the aureole lie along the North-West coast of the peninsula from Cape Cornwall to Portheras Cove and from Porthmeor Cove to Carbis Bay. In this entire stretch the killas has been invaded by greenstone and is interbedded with pillow lavas. The whole has then been folded and sheared and subsequently metamorphosed by the intrusive granite. Along the Eastern margin of the Land's End Granite from St. Ives to Mount's Bay the aureole rocks consist mainly of poorly exposed metamorphosed killas.

The unmetamorphosed killas, described in detail by Reid & Flett (1907), occurs at Porthleven as a laminated and micaceous grey phyllite. It is non-fossiliferous, free from calcareous bands, and possesses a well developed cleavage. The killas has been altered by both the greenstones and the granite. At the contacts with greenstone it is altered over a width of a few inches into a greyish-green, cherty-looking hornstone, described by Reid & Flett (1907) as a typical fine-grained adinole.

Of greater importance is the thermal metamorphism of the killas by the granite, together with metasomation at the contact. Phillips (1875) and Reid & Flett (1907) supplied a very detailed mineralogical description of the killas and the metamorphic changes it has undergone. Bagchi (1947) studied the various rock-types and tabulated them accordint to increasing promixity to the granite contact, as follows:-

"I Unmetamorphosed killas.

II Spotted Slates (a) spots of sericite and chlorite;
(b) spots of biotite and quartz;
(c) spots of biotite only;
(d) spots of cordierite.

III Phyllites.

IV Hornfelses: (a) banded biotite-quartz hornfels;
(b) cordierite-biotite hornfels;
(c) andalusite hornfels.

V Schistose hornfels. Contorted schistose biotite hornfels.

VI Metasomatism (contact) of the killas:
(a) tourmaline schist;
(b) muscovite schist.

At the outer limit of the metamorphic aureole the killas displays a megascopic and microscopic spotting due to the development of

sericite, chlorite, biotite and cordierite. The latter frequently breaks down, with falling temperature after formation, into sericite and chlorite, but its original form can always be distinguished.

The spotted slates pass inwards, into fine-grained phyllites in which spotting is absent. These possess a characteristic silvery-white lustre due to their high sericite and chlorite content, the flakes being oriented parallel to the foliation. With decreasing distance from the granite hornfelses develop, the most common variety being a banded biotite hornfels, consisting of alternate quartz-rich and biotite-rich layers. The biotite, which is frequently replaced by muscovite and chlorite, is oriented parallel to the banding. Andalusite and cordierite varieties are developed locally, as described in some detail by Bagchi (1947).

Adjacent to the granite contact the killas is transformed into tourmaline and muscovite schists, which have been described by Reid & Flett (1907). The tourmaline lies parallel to the banding and possesses some degree of colour zoning in shades of brown. Schistosity is attributable to the development of parallel muscovite flakes which sometimes predominate over the tourmaline. Other features of the metamorphism of the killas were described by Phillips (1875 & 1880) and by Reid & Flett (1907)

(b) Greenstones.

During the deposition of the killas pillow lavas were extruded intermittently between them, and dolerite sills were intruded into the still unconsolidated sea-floor muds. Although essentially dolerite in composition, the sills possess a wide variation in megascopic and

microscopic characteristics, some being coarse-grained and others fine-grained and basaltic in appearance. The greenstones have been subjected to dynamic and thermal metamorphism besides being locally folded and sheared.

The subject of greenstones is a wide and complex one which has been discussed in somewhat general terms by Lacy (1958) and Robson (1945, 1948 & 1953). Greenstone outcrops are distributed around the whole of the aureole, as indicated in Fig. (9). Forbes (1822) included the greenstones under his "slaty formations", and Boase (1832) noted the wide variation in rock-types embraced by the term 'greenstone'. After further work by Forbes, Phillips (1875) commenced a study of the Cornish greenstones and later (1876) made a detailed investigation of the greenstones of the Land's End district. Together with the work of Allport (1876) this provided a sound basis for the investigations of Reid & Flett (1907), who defined the greenstones as intrusive basic igneous rocks and concluded that they "originally included a number of different types presenting some unusual features and they have been decomposed, sheared, and in many cases, contact altered by the intrusive granite till their original state and the means by which they have reached their present condition are not always easy to decipher."

After studying the complex hornfelses in the vicinity of Kenidjack, Tilley and Flett (1930) concluded that some of them owe their origin to the leaching and subsequent metamorphism of a basic igneous rock. Tilley (1935) eventually found additional varieties of hornfelses and suggested that a major factor in their formation was Fe-Mg metasomatism of a basic igneous rock. Miss Reynolds (1947) doubted the igneous

parentage of a large number of the greenstone hornfelses and considered that they were probably formed from calcareous shales or limestones by a region Fe-Mg metasomatism during Hercynian times antecedent to the emplacement of the granites.

In view of the doubt that exists concerning the origin of many of the greenstones they may be tentatively divided into three classes distinguishable in the field:-

(a) rocks of definite basic igneous origin;

(b) rocks with a pillow lava structure;

(c) greenstone hornfelses.

The pillow lavas have a wider distribution than was thought by Reid & Flett (1907), for Bagchi (1947) was able to discover additional exposures displaying recognizable pillow lava structures.

(c) Major Structures

The elucidation of the major structure of the aureole rocks is complicated by the intense thrusting and folding that have taken place, and it is impossible to determine the true thickness of the sedimentary strata flanking the granite. In localities where the folding is not so pronounced the general direction of dip of the sediments may be measured.

Forbes (1822) recorded the attitude of the killas at several localities around the coast. At Tater Du he noted that it dips at between 20° and 30° to the East, while at Whitsand Bay it most probably dips to the North at a low angle. Of the coast between Polmear and St. Ives he remarked:- "The rocks possess nearly the same direction, dip, and inclination, as those in St. Just: that is to say, they dip North, at an angle varying from 25° to 45°" At Gurnard's Head the killas dips at 30° to 45°

to the North, and beyond Zennor at about 30° to the North".

Along the whole of the Northern coast the killas dips to the North, North-East, and North-West, but from St. Ives to Lelant there is a reversal of dip to the South-East at 30°. Although exposures are few Forbes (1822) stated that the general Southerly dip of the killas is maintained across country from Lelant to the South coast.

On St. Clement's Isle opposite Mousehole the killas dips at between 30° and 40° a little to the North of East. In the vicinity of Mousehole and Newlyn it dips, as shown in Fig. (7) at 25° to 30° to the South-East and at Penzance at 30° to 45° to the ESE, this same inclination continuing to Chyandour. Between Chyandour and Chapel Rock the exposures are poor and neither the outer limit of the metamorphic aureole nor the dip of the killas can be determined with sufficient accuracy.

The killas is well exposed around Chapel Rock where it dips to the West at 20°. Thence to Cuddan Point it possesses a low angle of dip which alternates rapidly from West to East.

An attempt was made by the present writer (1960) with the help of divers to extend the mapping of the Geological Survey into the off-shore area of Mount's Bay. It was found that only the greenstone masses and acid dykes were exposed on the sea-bed, and it was possible to trace these across the Bay. The killas, being more susceptible to erosion, is concealed beneath a covering of sand, only very occasional outcrops being visible. However, with further work in this area, it should be possible to fulfil the original intention.

Many of the inland exposures were re-examined by Thomas (1846), who provided an extensive and accurate list of measurements of the inclination

of the killas. His work agreed with that of Forbes (1822) and he made the important observation that nowhere is the inclination of the granite surface coincident with the dip of the adjacent strata. Miss E.T.Carne (1878) discussed the inclination of the aureole rocks around the Land's End Granite and in conclusion stated:-

"that all around our coast there is a predominant dip towards the East, that from Carbus-water to the Logan Rock the dip is South of East, whilst all around the Zennor coast it is North of East, or rather, perhaps, East of North."

Many of the early workers measured the inclination of the greenstone masses and found them to be sills conformable with the bedding of the killas, and Whitley (1878) constructed a map of the killas and intrusive greenstone sills of the Mount's Bay area. Although the map of the Land's End area produced by the Geological Survey is colourful it shows no measurement of dip and strike. However, Reid & Flett (1907) noted the fact that the large greenstone outcrops in the Penzance area are parts of one mass separated by denudation, and that "they have a moderate South-Easterly dip, or dip away from the granite at an angle somewhat lower than that of the granite surface beneath." They concluded that the pre-granite structures in the aureole rocks were as follows:-

"Masses of greenstone at St. Ives, Zennor, St. Just and around by Tater-du may well be parts of the same thick sill. If these be really parts of the same thick sill intruded along the bedding, the strata in this part of Cornwall must have been very slightly inclined before the intrusion of the granite, and the total thickness of the Mylor slates above and below the greenstone is probably only a few hundred feet."

On the basis of the greenstone outcrops and the attitude of the killas around the granite periphery, Reid & Flett (1907) summarized the present structure of the aureole rocks as follows:-

"The area between Carbis Bay and Ludgvan, where no thick sills occur,

probably forms part of am anticline, continued Eastward through Hayle and Gwithian, the interpretation of the South-Eastern part of the area is more difficult. It will be seen that the greenstone shown on the map forms two diverging belts, much broken, sheared, and disturbed. The Northern belt, mapped by Mr. Dixon, passes Ludgvan, St. Erth and Gwinear, running North-Eastward, in the general direction of the strike. The Southern belt, mapped by Mr. Wilkinson, runs East-South-Eastward, through Marazion and Perranuthnoe to Cudden Point, where it seems to pass out to sea. Along this belt the greenstone forms a series of disconnected masses, all apparently striking nearly at right angles to the general trend of the belt. Notwithstanding the coincidence of this strike with the direction in the Northern belt, the greenstone seems truly to mark the Southern limit of an anticline. Along the North-Eastern margin the axis of the folding coincides with the general strike; the sill, therefore, is fairly continuous, though the rock itself is badly sheared and overthrust. Along the Southern margin, on the other hand, folding has taken place nearly at right angles to the strike; the outcrop of the greenstone seems to consist therefore of a number of small broken synclines and anticlines."

continuing:

"If this interpretation be correct, the thick sill was intruded before the folding, approximately parallel to the lower surface of the Porth-scatho sandstones. Both these rocks, used as geological horizons, give the same results; they suggest a gentle syncline, with axis running from Gwithian perhaps to the Land's End; and a gentle anticline, commencing near Ludgvan, its axis running North of St. Hilary, to Binner Downs, where it passes outside the area here described. This anticline is continued, however, in the adjoining map (352), in which it is traceable as far East as Truro."

Miss Hendriks (1937) utilized the mapping of the Geological Survey in her re-interpretation of the structures of Cornwall. Employing the Staddon Grit as a stratigraphical criterion she postulated a series of synclines and anticlines in the area, which have been complicated by thrusting. She suggested the existence of an anticline trending more or less in a Westerly direction with its axis following a line joining the centres of the Carnmenellis and Land's End granites. Miss Hendriks (1937) largely confined her work to the east of the Land's End Peninsula, stating that the Land's End Granite tends to be isolated and that the interpretation of the large scale structures in the aureole rocks is hampered by the presence of only a narrow rim of outcrops around the granite.

From the available evidence it is apparent that there is an antiform and a synform in the aureole rocks of the Land's End area, which trend in a NE-SW direction parallel with the trend of the northerly part of the granite. There also appears to be a synform in the Mount's Bay area which may trend NW-SE and be complementary to an antiform trending in the same direction but lying to the West of Mount's Bay, between Tater Du and Land's End.

The attitude of the greenstone sills suggests that a NE-SW trending antiform exists between Perranuthnoe and Prah Sands following the same direction as an antiform, designated the Truro Anticline by Hosking and Trounson (1959).

Dewey (1925) described four main anticlines trending NE-SW in the South-West, into which the granite had been intruded. Regarding the Land's End Granite he stated that "the remains of a fourth anticline are seen around the Land's End mass."

Evans (1925) noted that the directions of the major fold axes are variable, and summarized the views of previous writers upon the ages of the faults and thrusts. Both he and Dewey (1925) agreed that folding and thrusting culminated in the intrusion of the granites and that the major structural features of the country rocks are pre-granite in age. It seems likely, however, that many of these structures were distorted during the granite intrusion, the attitude of the folds being altered.

Dearman and Butcher (1959) described the distortion of pre-granite folded structures in the country rocks around the Dartmoor Granite, and concluded that the disturbances may be attributed to the granite intrusion which was later than the overfolding along East-West axes.

When reading the literature one gains the impression that some writers have assumed that the granite intrusions were localized by the presence of pre-granite folding in the country rocks, and that they have then proceeded to demonstrate the existence of folding from the position of the granite outcrops. Before these assumptions are carried too far a large amount of structural work must be completed in the area.

Work by the present writer (1962) in the St. Agnes area has indicated that an agreement exists between the attitude of folding and the 'topography' of the sea-bed, the trends of folding being reflected by the trend of the sea-bed contours as shown in Fig. (148). The result of contouring the depth soundings indicated on Admiralty Charts of the Land's End area are shown in Fig. (8). The predominant contour trend is from NE-SW, revealed especially by the 15 to 25 fathom lines along the Northern coast. A NNW-SSE trend is indicated by contours between the Longships and the Wolf Rock, and the ridge between 15 and 20 fathoms situated 10 miles to the NNW of the Longships. The NE-SW trend is maintained by a line joining the Longships and the Scilly Isles. Recent work by Stride (1961, personal communication) has been centred in the Western approaches of the Bristol and English Channels, but their traverses so far have not been sufficient to reveal any major trends of folding in the areas investigated.

4/4 The Granite

(a) General Description

The Land's End Granite is potassic and porphyritic, and its configuration in plan is indicated on the structural map provided in Fig. (7). There are a large number of accessible localities around the coast where the granite may be examined, most of which were described by Reid & Flett (1907), and Bagchi (1947). Within the centre of the granite mass there is a later fine-grained granite.

The surface plan of the granite tends to be somewhat kidney-shaped, with two main axes trending NE-SW and NW-SE. Bett et al (1958) showed that this pronged form continues in depth, as indicated by Fig. (10), although the NE-SW trend becomes the dominant one at deeper levels. The slope of the granite surface is greatest on the Northern flank and least on the Southern flank, although everywhere it is greater than the dip of the contact strata. The contacts are sharp and the phenomena usually associated with stoping can frequently be seen, as illustrated in Photo. (16). Within the granite the only evident flow structures are those resulting from orientation of the 'c' axes of porphyritic feldspars. Jointing is a well developed feature and may be classified according to the nomenclature of Cloos (1922) and Balk (1937).

(b) Manner of Emplacement

The South-Western Granites bear such a marked similarity to one another that their common origin may be assumed, allowing for slight modifications in different localities. They have been subjected to all the customary arguments by different schools concerned with the

origin of granites. Usher (1892) suggested their palingenetic origin while Holmes (1916) postulated initial derivation by direct fusion of the sial and sima. A lacolithic theory of emplacement was advocated by the Geological Survey in a series of Memoirs, and was supported by Brammall & Harwood (1923 & 1926) and by Osman (1928). Worth (1930) took the view that the granites were protrusions from a granite wedge which formed the axis of the peninsula, and shortly afterwards Rastall (1931) wrote in favour of the idea that the granites were the cupolas of a batholith, the various outcrops all being connected at shallow depths below the present land surface.

By this time the magmatic origin of the granites was more or less established, though disputes continued regarding the mode of emplacement of the granite. Brammall and Harwood (1932) considered that there had been up-arching and a slow pulsational rise of magma which they had previously shown (1926) to have risen vertically in the South and then flowed horizontally Northwards, incorporating country rocks during its movement. The intrusive history of the Carnmenellis Granite was analysed by Ghosh (1934) who concluded that:-

"Stresses acting along the North-North-West and South-South-East direction (Hercynian compression) built up the anticline containing the granite, and produced the prevailing structures in the country rock. Later on, the pressure became more violent and gave rise to overthrusts from the South with which the granite intrusions are probably associated. By overthrusts from the South, which rendered the Northerly flow of the granite-magma possible, the magma-reservoir, actual or potential, was raised to a level which was higher on the South than on the North. Under the propelling hydraulic pressure from the South, the magma moved Northwards and intruded itself into the pre-existing anticline. Intrusion was initially at a high angle (85 to 75 deg. in places) in the South-West and the South; the magma then moved Northwards, tending to assume horizontality in the central part of the anticline; further North it plunged Northwards, and finally disappeared and spread, in undulating manner, beneath the cover of sediments on the North."

Both de la Beche (1839) and Miss Carne (1864) recognized the intrusive character of the Land's End Granite, while Reid & Flett (1907) later suggested that it had been intruded in the form of a laccolith into a pre-existing anticline. The important features in support of the intrusive theory are:-

(a) the clear-cut nature of the granite contacts, many of which are very steep;

(b) the absence of a transitional zone between the granite and the country rocks, as shown in Photo. (13), which could be interpreted as a partially granitized zone;

(c) the lack of a close relationship between the structure of the granite and that of the surrounding country rocks;

(d) the presence of flow-lines in the granite due to the orientation of the feldspar phenocrysts, and

(e) the presence of xenoliths, as illustrated in Photos (14 & 16).

Without delving too deeply into this subject the present writer concludes, in agreement with Bagchi (1947), that the Land's End Granite is intrusive at its present level, and also to any depths to which mining has so far extended.

Bagchi (1947) made a special study of xenoliths within the Land's End Granite, and decided that they showed some evidence of having been metasomatically granitized. He therefore concluded that a zone of granitization existed at depth, and that the transference of material from a lower horizon to the present level involved the mechanism of intrusion. According to Bagchi (1947) this was achieved largely by doming and he cited as evidence the existence of flow-lines, and the fan-shaped arrangement of cross-joints. He considered that the aplite dykes occupied marginal fissures which "were probably formed in connection with the uprising of the dome", and recalled that fan-shaped tension joints

with marginal fissures had been mentioned by Balk (1937) as providing "evidence of a strong upwards motion in the plutonic mass." Bagchi suggested that there had been assimilation at depth resulting in contamination of the original porphyrytic granite, in the manner described by Brammall and Harwood (1932).

Two granites have been mapped within the Land's End district, and Reid & Flett (1907) held the view that the central fine-grained granite (G_2) was intrusive into the earlier porphyrytic granite (G_1). Bagchi (1947) also distinguished within the porphyrytic type local variations which he named the Knills Monument, Land's End, Cape Cornwall and Pendeen types. He suggested that G_2 was a slightly later differentiate of the contaminated G_1 magma, and on this basis he outlined the history of the intrusion as follows:-

"Stage 1: Intrusion of the Land's End porphyrytic Granite into a pre-existing anticline.

Stage 2: Felspathization and granitization of country-rocks around the granite at depth.

Stage 3: Fracturing of roof rocks, and the incorporation of xenoliths, some from the feldspathized zone.

Stage 4: Assimilation of country-rocks followed by differentiation and formation of varieties.

Stage 5: Intrusion of fine-grained central granite."

Of the variations in the porphyrytic granite noted by Bagchi (1947) all but one possess gradational margins, the exception having a faulted contact. The present writer has also detected local variations of G_1 within Geevor Mine as shown in Fig. (17). It is likely that a large number of these gradations would be revealed by detailed mapping if the Land's End Granite were fully exposed. Whether or not other later

intrusive granites, such as G_2, would be disclosed is a matter of conjecture.

(c) Comparison with the other South-Western granites

Comparisons may be made between the two known granites of the Land's End Peninsula and similar variations in the other main South-Western granite outcrops, most of which are composite intrusions. Bagchi (1947) summarized the work of several writers and made mineralogicial comparisons between the Land's End granites and those of the Scilly Isles, Bodmin Moor, St. Austell, Carnmenellis and Dartmoor.

The Land's End porphyrytic granite probably corresponds with Stage II.A. of the Scilly Isles Granite, as described by Osman (1928), and the later fine-grained granite G_2 with Osman's Stage III. Within the Bodmin Moor Granite, Ghosh (1927) recognized three separate intrusions of which the fine-grained variety was thought to be the latest. Bagchi (1947) considered that G_1 and G_2 of the Land's End Granite are comparable, despite considerable mineralogicial differences, with the normal and fine-grained types of the Bodmin Moor Granite, the Godaver type being absent in the Land's End Granite.

According to Richardson (1923) there are three varieties in the St. Austell Granite, of which the biotite-muscovite-granite bears the greatest similarity to G_1. Judging from Ghosh's (1934) description of the Carnmenellis Granite, Bagchi (1947) considered that G_1 closely resembles the normal granite, or Type 1, of Carnmenellis.

Osman (1928) outlined the intrusive stages of the Dartmoor Granite, while Brammall & Harwood (1923, 1925, 1926, 1928 & 1932) added considerably to the knowledge of its mineralogy and structural history. Generally

there appears to have been a change from a relatively basic to an acid granite during the progress from early to late intrusions. Ghosh (1927) supplied several chemical analyses of the different types of Dartmoor granites, which demonstrated a progressive enrichment in silica content with decreasing intrusive age. Analyses of the Carnmenellis Granite provided by Ghosh (1934) show the same tendency but this cannot be extended to the Land's End Granite, as indicated by the analyses provided in Table (4).

Brammall & Harwood considered that the original Dartmoor Granite magma was sodi-potassic, or even dominantly sodic, and that "the potassic products of rest-magma are differentiates from magma which assimilated shales at an early stage." Ghosh's (1934) work on the Carnmenellis Granite showed that it falls into a well defined potassic field and that its variations range from dominantly potassic to sodic, as the later intrusions are more potassic than the normal type. The original magma, according to Ghosh (1934), was probably sodic, but during the formation of the normal type it changed from sodic to potassic due to the assimilation of potassic shales.

The same suggestion was put forward by Bagchi (1942) with respect to the Land's End Granite. Unfortunately he based most of his arguments merely on analyses quoted by Reid & Flett (1907), although these were supported to a certain extent by mineralogical evidence. The additional analyses of the Land's End Granite presented by the present writer in Table (4) illustrates the wide variation that exists in the sodic and potassic nature of the various granite types within G_1, thus vitiating the value of chemical comparison's based on the available information between the G_1 and G_2 types of the Land's End Granite.

4/5 Granite Structures

(a) Form of the Granite

Several measurements have been given by past and current writers of the inclination of the granite contact. To the south, where exposed, its dip is generally about 30° to the SSW. On the North-Western flank figures varying between 30° and nearly vertical have been recorded; in this area the shape of the granite contact is parabolic in section, increasing rapidly in dip with increasing depth to the North-West.

Longitudinal sections through the workings of Geevor and Levant Mines, Levant Mine, Botallack Mine and Pendeen Consols Mine, reproduced as Figs. (23), (24), (25), and (26), serve to illustrate this fact. Although the rate of increase in dip of the granite contact is variable it is apparent that if the trend is continued then the contact usually becomes vertical at a depth in the order of 2,000 feet or more. Fig. (24) indicates the frequent irregularities in the contact at Levant Mine. Similar irregularities occur within Geevor Mine, and although not indicated in Fig. (23) they may be observed on the No. 3 Branch Lode stope section.

The evidence of direct but isolated observations on the dip of the granite contact on the surface and underground can often be corroborated by the width of the metamorphic aureole. As shown in Fig. (9), the aureole attains a maximum width of over 2 miles in the vicinity of Penzance, whereas along the Eastern contact it is one mile wide. Elsewhere, the outer limit of the aureole lies off-shore.

Thomas (1846) reported that the granite contact is exposed on the

Longships off Land's End. However, Whittard has demonstrated (1959 , personal communication), as a result of extensive dredging of specimens during 1957-59, that the sea-bed at Carn Base, about three miles south-west of Land's End, is composed of granite. The Bouguer anomoly map of Bott et al (1958), reproduced here as Fig. (10), seems to indicate that the granite may have a considerable extension under the sea to the South-West. Either the granite surface slopes down at a very low angle to the South-West from the region of the coastline, or the country rocks exposed on the Longships are part of a roof pendant in the granite surface. The off-shore geophysical work initiated in this area during the Summer of 1961 will probably yield important results concerning the structure of the Land's End Granite at depth.

(b) Flow Directions

The Land's End Granite is similar to the other South-Western granites in that the only flow structures of any importance are flow lines of oriented feldspar phenocrysts. The general direction and dip of these flow lines throughout the Land's End Granite is shown in Fig. (7). They are more perfectly displayed at the margins of the Granite, and Reid & Flett (1907) noted that the occurrence of well developed oriented feldspar phenocrysts was invariably an indication of the proximity of the granite contact.

Along the whole of the Northern flank from Sennen to St. Ives well-formed flow lines locally plunge at high angles down the contact. Their dip varies between 30° and 70° but at times they assume near verticality, and their general alignment is normal to the line of the granite contact. Along the coast south-west of Sennen the flow line direction changes in

such a way that it is always approximately normal to the coastline, its plunge varying between about 15° and 35°.

Along the southern coast the flow-line direction gradually changes from north-south at Porthcurno to nearly NW-SE at Lamorna, the dip being about 20° to 50° to the South. From Lamorna to Mousehole the trend is about the same as that on the northern flank of the granite, but the dip is to the south-east at between 25° to 40°, this trend continues from Mousehole to the eastern extremity of the granite at Lelant.

Flow lines are present throughout the centre of the Granite, but are less perfectly developed than around the margins. East of a line from Penzance to Morvah the flow-lines in the central portion of the Granite are aligned NW-SE and are horizontal or dip at low angles to the NW or SE. In the Sancreed area and for several miles around, the limited number of exposures is insufficient for a reliable determination to be made of the overall flow-line trend.

Flow-lines are also present in the few exposures of fine-grained central granite, G_2, where they trend NW-SE and dip at low angles in both directions.

(c) Cross-joints

Robson (1948) described the main NW-SE and NE-SW joint directions as 'cleavingway' and 'toughway' respectively. The development of 'toughway' joints or cross-joints is variable in extent compared with that of the 'cleavingway' joints, and according to Robson (1948) they "have little influence apart from in quarrying and weathering". They have the appearance of tensional joints and are curved, irregular, and

of imperfect formation. As a rule they tend to be open and are frequently infilled with a little quartz and/or tourmaline.

On the Northern flank of the Granite cross-joints are very well developed and are almost comparable in intensity with the longitudinal joints. Jointing on Carn Eanes, above Geevor Mine, is shown in Fig. (36/3); the cross-joints strike NE-SW and dip at 80° to the SE. Along the Northern coast, the cross-joints maintain a strike direction normal to the flow-lines and approximately parallel to the direction of the granite contact at this locality; their dip varies between 70° and vertical, with an average of 75° to 85° to the SE.

From Househole to Porthcurno on the Southern coast the cross-joints are not developed to the same extent as in the North. Fig. (36/6) shows jointing at Lamorna Cove where longitudinal joints are strongly developed. A widespread development of NW and SE dipping cross-joints, with a general NE-SW trend occurs throughout the centre of the Granite, where their inclination is predominantly vertical. NE-SW trending cross-joints at Newmill Quarry are illustrated in Photo.(33 & 34).

In the fine-grained granite G_1 the cross-joints are similar in trend to those in G_2. Photo.(37) illustrates their occurrence at Castle-an-Dinas Quarry where they run ENE-WSW and dip to the NNW.

Throughout the Granite as a whole the dip of the cross-joints varies between vertical and 45°, but towards the centre of the Granite most of them maintain a dip in excess of 75°. Where the flow-lines plunge steeply at the contacts there are developed, in addition to the regional cross-joints described above, a set of local cross-joints which are more closely related to the local trend of the flow-lines and dip less steeply towards

the centre of the Granite.

With the exception of the area west of a line from Sennen to Porthcurno, the direction of the regional cross-joints is constant at a little East of NE, but the angle and direction of dip varies in such a way as to create a fan-shaped arrangement with an axis coinciding with the main NE-SW axis of the Granite. As shown in Fig. (33) the radius of the arch of regional cross-joints is greater than the original presumed arch of granite as reflected by the contacts and associated flow-lines.

The regional cross-joints are regular in their formation and attitude, and are controlled by an overall dynamic stage. They may vary locally in strike and dip from the local cross-joints, which are always normal to the flow lines. For this reason care must be exercised when interpreting cross-joints in any particular locality, since the local forms may differ considerably in attitude and intensity from the regional system.

Regional cross-joints do not terminate at the contact between the granite and the aureole rocks, but extend into the latter due to the sympathetic arching of a considerable portion of the country rocks. Their extension beyond the contact is a common feature of granite intrusives, as was first recognized and thoroughly described by Cloos (1925). Balk (1937) and Cloos cited many examples of regional cross-jointing from similar granite massifs, especially that of the granodiorite of the Sierre Nevada, where a fan of cross-joints penetrates a strip of wall rocks as much as two miles wide.

The extent to which the country rocks are affected by regional

cross-joints in the Land's End area is not easy to guage, since any estimation is hampered by the narrow width of the coastal aureole on the Northern flank and by the lack of exposures on the Eastern flank.

(d) Longitudinal Joints

Within the Land's End Granite the 'cleaving-way' or longitidunal joints are usually better developed than the cross-joints, besides tending to be more regular, straighter, and of cleaner fracture. Defined as being parallel to the flow-lines and with a direction varying between NW-SE and NNE-SSW, they are usually vertical but often have a dip varying locally up to 20° from verticality. To the East of a line joining Sennen and Porthcurno they trend approximately NW-SE to N-S and are comparable with the cross-joints in the extent of their development. Although longitudinal joints are not influenced by the plunge of the flow-lines their strike may be affected by changes in the direction of the flow-line. Where the direction of the latter varies locally, the development of the longitudinal joints is impaired, and they are temporarily less regular and more varied in strike.

Fig. (36/6) illustrates the joint pattern at Lamorna where the vertical longitudinal joints strike NW-SE. Large variations in the joint pattern are due not only to changes in strike direction but also to the later development of a superimposed secondary joint pattern. NW-SE striking longitudinal joints are exposed at Castle-an-Dinas Quarry, as illustrated in Photos (35 & 36), while Figs. (36/1,2,3,4) show the joint patterns in the granite of Carn Banes. A secondary joint pattern is superimposed on the earlier primary pattern, but the two systems are clearly defined. The longitudinal joints strike

between NW-SE and NNW-SSE and dip at between 75° and 90° to the SW. They are not infrequently poorly developed in comparison with the secondary joints.

The joints have exerted a strong control upon the development of the topography and coastal scenery, and Whitley (1865) noted the coincidence in direction between the major joints and valleys in Penwith. He calculated that the 'NW-SE joints' had controlled the course of 30 valleys in the southern part and 18 valleys in the northern part of the granite, a fact which is readily appreciated from Figs. (5 & 6). The drainage pattern is rectilinear, the main streams following the longtitudinal joints. First and second order tributaries are frequently controlled in direction by the cross-joints, a fact also noted by Whitley (1865) when he stated that "where they (the valleys) take another direction it is often that of the minor cross-joints."

(e) Flat-lying Joints

Flat-lying joints are especially well-developed around the southern coast where they exert a strong control upon coastline development, as shown in Photo. (32). Ideally they reflect the slope of the granite surface before erosion, dipping to the North-East along the northern flank and to the South-East along the southern coast at angles usually of the order of 10° to 20°.

Flat-lying joints are well developed on many of the hills along the northern coast as depicted in Photos. (18 & 33).

(f) Diagonal and Secondary Joints

Among the primary joint systems may also be included the diagonal joints, but they may equally well be classified as secondary, and care

should be exercised before referring them to any system based upon age differences.

The writer considers that a system analogous to a primary diagonal joint system has been developed locally within the Land's End Granite. The time interval between the formation of the primary cross- and longitudinal joints and this diagonal system was sufficiently long to warrant calling the latter 'secondary'. This system will be discussed in detail in a later Section.

(g) Dykes

Dykes in the Land's End area may be divided into two classes; (a) quartz-porphyries, locally known as 'elvans'; and (b) fine-grained granites, aplites, and quartz-tourmaline dykes. The distribution of the dykes is shown in Fig. (7), but it should be remembered that any map shows only the dykes known to exist.

References in older papers to 'elvan' do not necessarily imply quartz-porphyry, for the writer has encountered cases in which the term 'elvan', especially when prefixed with the words 'blue', 'grey' and 'hard', simply implies modifications of the granite, greenstones, or any unusual rock type which has been encountered during mining or quarrying operations. A section of the Crowns Lode of Botallack Mine, reproduced by Dines (1956), shows an 'elvan course' from the 190 to the 225 fathom levels, but it should not be assumed without conclusive proof that this denotes the presence of a quartz-porphyry dyke.

One of the major dykes in the Land's End Peninsula is that which can be traced through both granite and killas from Sancreed to Ludgvan. With an average thickness of 30 feet it is composed of quartz-feldspar-

-porphyry. Numerous ourcrops of quartz-porphyry dykes occur along the shores of Mount's Bay. The Wherry Elvan, with a width of 18 feet, dips at 60° to 70° to the North-West and is noted as being the site of the Wherry Mine, described by Hawkins (1818) and Russell (1949). Further exposures occur around Penzance Harbour and at Long Rock, where a fine-grained porphyrytic elvan attains a maximum width of 100 feet. The 'elvan' dykes in this area possess a strike direction common with those of the remainder of the South-West, varying between E-W and NE-SW. An unusual fine-grained, NW-SE striking, quartz-porphyry dyke was said by Reid & Flett (1907) to extend from Sennen to Porthcurno, its width being variable but at times attaining a value of 150 feet.

Important features of the South-Western quartz-porphyry dykes are their high width compared with the other dykes and veins, their general agreement in strike with the lodes, and the fact that they are more usually found in the country rocks rather than in the granite. All writers agree upon their early age compared with the other dykes and lodes. Their spatial distribution has been attributed to structural conditions, including pre-granite structures in the country rocks, fracture patterns formed in the country rocks arising from intrusion of the granite, the attitude of subterranean granite ridges, granite joints, and many other features. Hill & MacAlister (1906) provided the most detailed descriptions of such dykes in the South-West, though similar information regarding the dykes in the Land's End area is not available. Here, even the direction of dip of all the dykes is not known, and although Henwood (1843) mentioned that three dykes,

most probably the continuations of the Mount's Bay outcrops, were encountered in the workings of Darlington Mine at Marazion, no further details were given. A more complete understanding of the structural history of the quartz-porphyry dykes is precluded by the lack of observations.

Of the dykes classified under (b) - namely, fine-grained granites, aplites, and quartz-tourmaline veins, only some of those encountered in the workings of Geevor Mine are indicated in Fig. (7). Since these small dykes do not seem to have exerted any influence upon the mineralization their existence in the mines has hitherto not been recorded. Granitic dykes within the granite exist around the coast, and Bagchi (1947) depicted their distribution.

(h) Intrusive History

Having assumed the intrusive nature of the Land's End Granite in its upper levels, its structural characteristics must be considered in connection with its intrusive history. Flow lines indicate an arching or doming of the granite, with a main axis trending NE-SW along a line through Carbis Bay. Flow-lines in the western part of the Granite indicate a Westerly and South-Westerly direction of magma flow. The suggested intrusive history of the Land's End Granite is as follows:-

(i) The magma was intruded from the South-East along a line trending NW-SE through Mousehole.

(ii) East of a line from Mousehole to Cape Cornwall the magma rose at an angle of about 30° and flowed to the North-West, doming up under the main pre-existing NE-SW anticline in the

country rocks. After flowing horizontally it then plunged down at an angle of about 70° to the North-West.

(iii) West of the above line the magma flowed round from the vicinity of Mousehole and Lamorna so that between Sancreed and Whitesand Bay its flow was to the West. This direction was maintained from between Cape Cornwall and Whitesand Bay to between Land's End and Gwennap Head. The magma altered its course in the area bounded by Sancreed, Penzance, and St. Buryan, thereafter flowing to the West and plunging down at about 30° below the country rocks in the vicinity of the Longships.

Such changes of flow direction are not uncommon. Indeed, Osman (1928) provided excellent examples from the Scilly Isles where the direction varied through as much as 90° in plan over a distance of one or two miles.

The accompanying structural map of the Land's End Granite was compiled by the writer prior to forming any conclusions concerning the intrusive history of the Granite. In the limited time available the map was based upon only a very general examination of the exposures, and the suggested intrusive history is therefore simplified and open to many alternative explanations. It has been evaluated after taking into account the work completed upon the other granites of the South-West, especially that of Ghosh (1934) upon the Carnmenellis Granite.

Ghosh (1934) showed that the magma rose steeply in the South and flowed out horizontally to the North. The Southern flank of the Carnmenellis Granite, in common with that of the St. Austell Granite, is the steepest, whereas the northern flank the Land's End Granite is the

steeper. However, estimates of the dip of the granite contact to the south are based upon only a few readings at the surface, the doubtful value of which has been indicated by mining operations in the St. Just area. An estimate of the dip of the contact should be regarded as reliable only when it has been based upon observations of the contact in mine workings to a depth of the order of 2,000 feet.

If the inclination of the northern flank, which has been determined from surface to a depth of about 2,000 feet, is continued in depth then the hypothesis of the magma plunging down almost vertically along the whole of the northern flank may be valid. Alternatively, it is possible that the granite surface is stepped, resulting in an overall downward plunge at a much smaller angle than is at present indicated by the observed slope of the granite contact.

4/6 Mineralization

(a) General Description

The Land's End mining district comprises those mines lying within the Granite and in the aureole rocks around its flanks. It is connected via the mines of Marazion and St. Erth with the districts of Godolphin, Leedstown and Gwinear, and is situated entirely within Dewey's (1925) mineral belt.

On a geographical basis the Land's End district may be subdivided into several mineralized areas, the distribution of mineralization being illustrated in Fig. (9). The major producing area was that of St. Just containing the Pendeen-Botallack stretch of coastline in which Geevor Mine is situated. The Balleswidden area lies to the South-East of St. Just and to the North-East of the latter lie the areas of Morvah and Zennor. In the centre of the granite and to the South-West of the Morvah area is the Ding Dong area. Together with that of Sancreed to the west of Penzance it is situated well within the Granite.

At the North-Eastern extremity of the Granite is the St. Ives area which may be further divided into Towednack and Trencrom Hill in the north and south respectively, the latter extending into St. Erth. From the sporadic, mixed mineralization of Wheal Garth and the Wherry Mine around Penzance there extends the Marazion area where some lodes were worked beneath the marshes, themselves a source of alluvial tin.

Robson (1948), in a general appraisal of the Land's End district, quoted a figure of 148 for the number of mines known to have worked on the peninsula.

Reid & Flett (1907) listed the mines according to the parish within

which they were situated, and provided a total of 74 separate properties in the St. Just district alone, although only 49 were listed by Dines (1956). Any estimate of the number is open to question since there was a progressive trend of amalgamation whereby two or more mines were frequently combined under one registered company, the identity of the original mines being lost completely. For the same reason the difficulties of assessing the total output of the individual mines is increased, especially when at times no records of production were maintained.

The vast majority of the workings were closed down around the year 1875 and Trounson (1942) outlined the history of some of the more important properties such as Botallack, Levant, and Providence which continued working into the 1900's. A few properties were re-examined during the 2nd World War and are partly accessible for a distance along the adits, but for the purpose of a reliable examination the mines are completely inaccessible.

Although any estimate of the total ore production of the South-Western mines is hypothetical Dines (1956) calculated that the total yield of Devon and Cornwall in metallic tin alone is over 2,000,000 tons. In what Dines (1956) termed 'recent years' the relative importance of the major South-Western mining districts is shown by the proportion of the total output.

Land's End 21%	St. Austell Moor 7%	Dartmoor 2%
Carnmenellis 67%	Bodmin Moor 3%	

Further figures were supplied by Davies (1919). The output of various minerals from each of the major districts were expressed by Dines (1956) in the same manner as follows:-

District	Tin	Copper	Arsenic	Sulphur	Lead	Iron
St. Just	12.7%	2.2%	1.0%		less than 0.1%	less than 0.1%
St. Ives	4.9%	less than 0.1%	-	less than 0.1%	-	-
Camborne) Redruth) St. Day)	53.2%	52.6%	39.8%	42.2%	1.8%	1.3%

The Land's End district (with the exception of the Marazion area) ranks as the second most important tin producer. Among the districts West of Dartmoor it was, with the exception of the Wendron and Falmouth area, the lowest producer of copper, arsenic, sulphur, lead and iron.

Reid & Flett (1907) described the characteristics of the Land's End mineralization, one of the most important being the variation in strike of the tin-copper lodes in some areas from that of the remainder of the South-West. As illustrated in Fig. (9), whereas the lodes in Towednack, Trencrom Hill, Marazion and Sancreed conform to the general NW-SW direction those of St. Just and Balleswidden strike roughly NW-SE. In the Morvah and Zennor areas they tend to follow both directions but show an affinity for a NW-SE strike, whereas in the Ding-Dong Mine area the lodes follow both directions to an equal extent. The mean lode directions were tabulated by Henwood (1843) and Collins (1912).

Most of the mines are situated on the granite contact and the lodes have been worked in both the granite and the aureole rocks. Economic tin mineralization more frequently existed in the granite, although Levant Mine, where the lodes were most productive for tin in the killas, is a well-known exception.

A relationship has always been sited between the trend of the lodes and that of the granite joints. Reid & Flett (1907) among others,

concluded that the lode fissures were granite joints along which successive movements had taken place. This hypothesis was based upon the frequent indications of repeated opening and movement along the fissures that were recorded by Henwood (1843) and later by Collins (1912) from the St. Just area.

The impression that normal faulting was the most common mode of movement was created especially by references to the maximum tin values being concentrated at the regions of highest dip within the lodes, as described by Rowe and Le Neve Foster (1887). Carne (1822) provided many descriptions of the St. Just lodes, especially cases in which a lode containing brecciated wall-rock possessed one wall of granite, the other wall being composed of country rock. Mineralization was considered to have either accompanied or followed the relative movement of the fissure walls.

Despite the relatively low production of anything other than tin ore from the district, the number of mineral species recorded is enormous. The majority of the minerals were listed by Dines (1956) and Reid & Flett (1907). Tin occurred only in the form of cassiterite, there being no record of the occurrence of stannite. Wolfram was found only at Balleswidden Mine.

The chief ore of copper was chalcocite as opposed to chalcopyrite, and arsenopyrite was common in some of the lodes. There was a distinct absence of mesothermal mineralization in the Land's End district. Although galena and sphalerite have been reported in minor amounts from some of the mines they occurred, with the exception of the Pendeen lead-silver lode, as accessories in the tin lodes.

Gangue minerals included chlorite, tourmaline, hematite, quartz and pyrite, with variable amounts offlouorspar, calcite, jasper and chalcedony.

Wall-rock alteration was an important feature of the mineralization, the most characteristic form of alteration of the granite being tourmalinization, chloritization, and an intense reddening of the feldspars for several inches on both walls.

Henwood (1843) provided estimations of the mean lode widths of 2.23 and 1.61 feet for the St. Just and St. Ives areas respectively which showed they were narrower than those of other districts in the South-West. Quoting an average lode width of 3.61 feet for the South-West, he indicated that the lode widths decreased with depth. Both copper and tin lodes were considered to be wider in the "slate" than in the granite whilst the tin lodes appeared to be wider than the copper lodes.

The principles of zoning may be applied only very loosely throughout the district, and any attempt to distinguish between copper zones and tin zones must be applied with caution. Nevertheless, distinct zones of tin mineralization exist and a longitudinal section through Geevor and Levant Mines, reproduced by the present writer as Fig. (23), was employed by Dines (1956) as an excellent example of this feature. Within the tin zone, which may include a number of lodes in the vertical sense, the tin values tended to be sporadic, the richer portions being known as 'bunches'. In a description of the distribution of mineralization Robson (1948) stated:-

"If the metal production and mine situation is tabulated against the country rock and its granite contact, it becomes apparent that the 16 workings well inside the granite were largely confined to tin in limited quantity; those just within the granite (e.g., St. Ives C., Rosewall, Geevor, Providence) were important tin and subsidiary copper mines; those in the slate-granite zone (the Botallack, Levant, Carbis Bay groups) prolific in copper and tin, some arsenic and uranium; or mainly copper (Trenwith, Edward, Speed, Pendeen). There is no case of a good mine in dolerite. Primary zoning is thus well shown in plan: in depth the ore

shoots tend to pitch seaward at a far lower angle than the granite contact with the Sn/Cu ratio decreasing sea-wards but increasing in depth (hence submarine workings at Botallack and Carbis Bay) as the veins entered the granite landward, the metal content diminished and in some cases ceased (except in the large carbona replacements)."

An unusual feature of the mineralization was the occurrence of carbonas and tin floors which were peculiarities of the St. Ives and St. Just areas respectively, and were described by Reid & Flett (1907). Although they were locally rich deposits they were extremely irregular in disposition.

Cross-courses, also known as 'guides' or 'trawns', occurred throughout the district. They were usually infilled with barren quartz and crossed the lodes at varying angles. They carried a little cassiterite but were usually utilizedonly in cross-cutting. Reid & Flett (1907) described the cross-courses as "a series of fissures, joints, or faults which traverse the district in a general north and south direction." They were described in more detail by Henwood (1843)

(b) St. Ives area

In the St. Ives area the lodes were productive in both the coarse-grained and fine-grained granites, and in the country rocks which comprise greenstone and killas. The lodes strike ENE, and approximately normal to the granite contact whilst the 'trawns' trend nearly North-South. Tin ore was raised largely from lodes within the granite, whilst copper predominated in the country rocks. Robson (1945) and Dines (1956) provided general descriptions of the area and the latter mentioned the fact that while only small quantities of arsenic and zinc were recorded one feature was the occurrence of pitchblende and

other uranium ores, especially at Wheal Trenwith and South Providence. Records of the district are severely lacking but Henwood (1843) provided a description of the mines and included some details, stressing the fact that the lodes and cross-courses possessed "within certain limits an approximation to the strike of the jointed structure of the rock (granite)".

The mines were largely active during the 19th century and their history was outlined by Trounson (1942). Some of the coastal mines extended beneath the sea since, as Henwood (1843) stated, "the ores, in well ascertained cases, dip eastward, towards the slate." Dines (1956), in stating "the influx of sea-water appears to have been responsible for the lodes not having been exploited as far seawards as in the St. Just district," provided one important reason for their abandonment; pumping difficulties.

An unusual feature was the occurrence of carbonas within the granite. They were originally described by Henwood (1843) and Dines (1956) stated:

"though, in some cases, they (carbonas) may be due to mineralization of a wide belt of country rock alongside a lode, in others they are large, irregularly shaped bodies, not obviously connected with fissure veins, in which alteration accompanied by mineralization of the granite, has taken place."

Further descriptions of the area were provided by Hawkins (1822), Penberthy (1846), Henwood (1865 & 1874), Gilbert (1878), Reid & Flett (1907), Collins (1912), Cann (1917), and Dines (1930). The St. Ives district is naturally divisible into two areas; those of Towednack and Trencrom Hill. The former consists of a two by one mile belt along the valley South-Westward from St. Ives town to near Towednack Church and extending into the vicinity of Zennor.

According to Dines (1956), "apart from insignificant amounts of zinc, arsenic and uranium ores, pyrite and ochre, the main products of the area were tin and copper." He provided an account of the workings of the individual mines and decided that "the distribution of the tin and copper ores, relative to the contact, seems to support the generally held view that tin occurs in the granite country and copper in the overlying rocks." From the mine production records and the accounts of Henwood (1843), Dines (1956) concluded that "the junction between the tin and copper zones pitches eastwards but at a less steep inclination than the granite surface," and that the area "contains an important emanative centre between Rosewall Hill and St. Ives."

Carbonas were most prevalent in the granite of St. Ives Consols, Wheal Providence and Rosewall Hill and Ransom United. They were described by Henwood (1843) and Dines (1956) as "generally irregular in form and with no apparent relationship to the lodes, these (carbonas) consist of country rock, (granite), partly tourmalinized and with feldspars partly chloritized, in which cassiterite is disseminated in fairly coarse crystals; the more or less decomposed nature of the rock rendered exploitation easy." The principal producers in the Towednack area were St. Ives Consols, Wheal Trenwith, and Providence Mines.

The Trencrom Hill area, comprises that between Trink and Trencrom Hill, extending Eastward to Carbis Bay and Porthkidney Sands, and Westward to Amalebrea and Georgia, so including an area of about two miles by four. It is mainly situated in the granite, the fine-grained granite G_2 forming the Western part. The lodes were continuous throughout the two granites and the killas country rock, their main trend being ENE.

They were heaved a fathom or two by several cross-courses which trended a little West of North and were described by Henwood (1843) as being fissures containing fault gouge and bordered by a little altered granite.

A few of the mines were worked in the early part of the 20th century and the area is noted only for tin and copper. Lodes within the granite yielded the majority of the tin, the values being very patchy in the killas. Some writers have quoted the area as a possible example of one in which the copper zone may be underlain by a tin zone and a few of the mines have been re-opened since 1900 on this surmise. However, Henwood (1843) recorded cassiterite from the upper levels of the copper mines, and Dines (1956) stressed that "it is possible that the tin and copper zones are here 'telescoped', the copper occurring in parts of tin lodes that were reopened at a later period."

(c) Morvah and Zennor area

All the known lodes in the area were situated in granite and the maximum depth attained was 100 fathoms at the Morvah and Zennor United group of Mines. Four major lodes on which the amount of working is unknown trended NNW and were crossed, according to Dines (1956), by ten other NNE-trending and West-dipping lodes, of which Carn Galver Lode was the most profitable. At Morvah Consols the lodes possessed a strike of E.30^{O} S, and dipped to the South-West.

Dines (1956), considering the area in conjunction with those of Balleswidden, Sancreed and Ding Dong, stated that "the lodes are characterised, on the whole, by small widths, sporadic distribution of values and a high content of tourmaline." Reddening of the feldspars

in the granite wall-rock was common and the lodes contained hematite, pyrite, tourmaline, quartz and chlorite. Production appears to have ceased in 1875, the only product having been tin.

Extending along the coast from Morvah and through Zennor as far as St. Ives were several small workings, many of which did not extend below adit level. The lodes were situated along the granite contact and were followed in both the granite and the country rock of killas and greenstone. At Zennor Consols, previously known as Carnellow Consols and described by Dines (1956), the lodes trended NW-SE and NE-SW, the latter set dipping to the South-East. Around Zennor there have been several examinations of old properties and in 1930 Rosemorran Mine was re-investigated.

(d) St. Just area

The St. Just mining area lies between Whitesand Bay and Portheras Cove on the North-Western flank of the Granite. The extent of mineralization is shown in Fig. (11) which indicates the known lodes according to the Geological Survey (6" series), at the beginning of the 20th century. Together with Fig. (E), it illustrates the general NW-SE lode strike and the variation in direction occurring throughout the area.

Most of the mines were situated along the contact between the granite and the metamorphosed country rocks which comprise killas and greenstone. The granite is of the normal porphyrytic type, and several varieties of G_1 exist. The distribution of some is indicated in Fig. (17) and others have been revealed by examination of the mine dumps.

Collins (1912) quoted a number of 'over 50' known lodes in the area and since that time more have been discovered, especially in Geevor

Mine. The granite contact, which was indicated in the majority of old mine sections, lies about one-quarter of a mile inland on the surface and is nowhere well exposed. Although the lodes have been exploited to a greater extent in the granite they were developed for over a mile in places on both sides of the contact. In general the economic tin mineralization was confined within the granite, the majority of the copper lying, as mentioned by Carne (1822), in the overlying country rocks. However, the reverse frequently occurred, and although the tin lodes of Geevor Mine are situated within the granite, those of the adjacent Levant Mine were in killas and greenstone. It has always been considered that the tin lodes were diminished in value in greenstone which was said to favour copper mineralization.

A division between tin and copper zones is complicated by several phases of mineralization but there is a fairly sharp separation between economic and non-economic ground. An ore zone pitches towards the North-West in the same direction as the granite contact but at an angle of the order of 20° below the horizontal, and the zone of mineralization delineated by the upper and lower limits of the workings in Geevor and Levant Mines was employed by Dines (1956) as an example. The pitching of the tin zone beneath the sea bed resulted in the lodes being followed far beyond the coastline, often with disastrous results, as described by Hawkins (1818), Henwood (1843), Collins (1912), and Garnett (1961).

The cessation of mineralization at a distance of approximately one mile inland from the coastline has always been accounted for by the theory that in this vicinity the lower limit of the tin zone pitches

up above the erosional surface of the granite. The 'outcrop' of the tin zone appears to form a belt about one mile in width, the upper limit of the tin zone coinciding, between Cape Cornwall and Pendeen Watch, approximately with the coastline.

To the South of Cape Cornwall the line of the upper limit, if it continues its SSW trend more or less coincident with the outcrop of the granite contact, lies over half a mile off-shore. Since few of the mines in this vicinity have extended beyond the coastline, the potentialities of the off-shore area in the region of, and to the South of, Cape Cornwall are immediately evident, as was recognized by Dines (1956). After an examination of the lodes exposed in the adits of mines in the Porth Nanven area South of Cape Cornwall he commented:-

"In parts, coast erosion has removed the metamorphic deposits and the cliffs are formed of the granite, as around Porth Nanven. In these places the tin lodes represent the lower part of the zone as is evidenced by the shallow depth to which payable values extend and the patchy and sporadic distribution of the cassiterite in the lodes. On the analogy of the conditions occurring further North, it seems that in the lodes worked around Porth Nanven, e.g. at Wheal Hermon, Ballen Mine, etc., riches should be sought by following the North-West-pitching ore shoots of the tin zone seawards and in depth."

The largest producers in the St. Just area were Levant which attained a depth of 350 fathoms, and Botallack Mines, their situations being indicated in Fig. (13). Records of production and outlines of the history of the individual mines, together with details of the extent of their workings, were supplied by Collins (1912) and Dines (1956).

Geevor Mine now ranks equal with Levant Mine in total tin production. A general description of the mineralization in the St. Just area was provided by both the above writers and Henwood (1843).

Although very variable, the NW-SE trend of the lodes approximates

closely to the granite joint direction. The close connection between the lodes and the joints was recognized by Whitley (1865) who considered that the lodes were formed as a result of movements along joints. Repetitive mineral infilling of the lodes was observed by Carne (1822) and Henwood (1843), and they frequently recorded the intersecting of one lode by another. However, as described by Carne (1822), when displacements of one lode by another took place the amount of movement was so small as to not impede the miner in his work and the maintaining of a detailed record was not justified. When intersections were studied they caused confusion since any assessment of the relative ages of two lodes would be invalidated on another level as a result of localized repeated openings and mineral infilling.

With an average dip varying between 70° and 80°, the lodes dipped both to the NE and SW, and frequently changed their direction of inclination. Many of them tended to occur in swarms with a similar direction of dip. Henwood (1843) remarked upon this feature and stated that: "the Vale of Nancherrow in St. Just is nearly coincident with the direction of the principal joints, being about NW-SE. Most of the lodes on the SW side dip NE; those on the NE side dip SW." Collins (1912) concluded that this evidence "seems to indicate a synclinal structure in the granite in this region." This change of dip was interpreted in many ways by different authors, and Carne (1822) divided the lodes of the St. Just area into two different age groups on the basis of dip, although he did not provide a reliable instance of a SW-dipping lode intersecting a NE-dipping one.

In a later paper however, he gave less weight to this argument

saying "it is very difficult to ascertain whether the tin lodes of St. Just are of different ages."

Apart from those of the St. Ives area, the lodes are the narrowest of any occurring in the South-West. The value of the tin-ore contained in them, although quoted in old records as pounds sterling per fathom, must have been considerable to recompense for the low price of tin and the number of times the ore was handled before reaching the stamps.

Many special features of the lodes were recognized by Henwood (1843), Collins (1912) and Moissenet (1874). The latter noted that in the lodes of the St. Just area, in common with those of the remainder of the South-West, the highest values were located at the steepest parts of the lodes. Intersections of lodes were not generally regarded as being the centres of rich courses of ore, as is frequently the case in other districts. Cassiterite, the only form in which tin occurred, was, with the exception of that in Balleswidden Mine, of a fine-grained nature. Chalcocite was more common than chalcopyrite, although the latter was present to a large extent in the lodes, together with arsenopyrite, pyrite, bornite, and a large number of complex minerals. Sphalerite was a frequent late mineral but not in sufficient quantity to warrant its extraction. A first description, and the most complete account, of the minerals occurring in the St. Just area was given by Carne (1822 & 1846). Dines (1956) noted the occurrence of the different mineral species in each of the individual mines and details may also be obtained from the Cornish Mineral Indexes published within the Volumes of the Transactions of the Royal Cornish Geological Society. Bismuth, cobalt and antimony minerals were recorded and pitchblende

was common in the Wheal Owles group of lodes as described by Pearce (1878). Cassiterite was frequently accompanied by tourmaline and chlorite and a common mode of wall-rock alteration was the reddening of the porphyritic feldspars. The most common gangue minerals were quartz, calcite, flourspar and jaspercidal hematite.

Tin-floors, which were worked especially in Bottallack Mine, were comparable with the carbonas of the St. Ives area. They were thoroughly described by Carne (1822. No. XV) and Henwood (1843). North-South cross-courses, known locally as guides were common, and were frequently followed by the old miners since they provided easy ground in which to cross-cut. They were generally believed to lead into tin lodes and Collins (1912) cited the case of the Carnyorth Moor guide which "is believed to be the Old Bal Lode of Levant." Many examples may be seen in old plans of a North-South cross-course gradually changing its strike direction along its length so as to conform at one extremity, usually the Northerly, with the average direction of the lodes.

Reports have been given of guides faulting the lodes for two or three fathoms, and on other occasions of running with the lodes for considerable distances. They differed from the cross-courses of the remainder of the South-West not only in the small deflections which they inflicted upon the lodes, but also in the fact that they did not carry the low-temperature ores of lead and zinc. Instead, they tended in some cases to contain sub-economic quantities of tin and copper over a width of several feet of banded quartz. Throughout any one guide the dip was steep but varied on either side of the vertical. The most complete descriptions were provided by Carne (1822, No. V) who stated:-

"To the class of cross-courses probably belong the large North and South veins which traverse the whole of the extensive parish of St. Just. They are called by the miners 'guides' because they suppose that by following these veins, they will be conducted to the tin lodes; but they may with more propriety be termed iron lodes, as they contain, besides quartz and clay, brown iron-stone, specular iron ore, brown hematite, etc. Two of them have been traced three, and another five miles. When they intersect the lodes, they generally carry them several fathoms in their own direction, before a separation takes place. In such cases the lodes are frequently much improved. In two instances, which occurred in Botallack and Parkknoweth, very rich courses of tin have been the result of such intersection."

Further details were given by Henwood (1843) and Rowe & Le Neve Foster (1887).

Faulting appears, from the lack of literature concerning it, to have had little effect upon mining throughout the area, and if it was of the same extent and form as that occurring in Geevor Mine, the average throws must have been of the order of only a few feet.

(e) Ding Dong Mine area

In the Ding Dong Mine area, like that of Morvah and Zennor, two main lode directions are evident; NW-SE and NE-SW. Brief accounts of the history of Ding Dong Mine were given by Collins (1912) and Dines (1956) and it is probable that the workings are among some of the oldest in Cornwall, having first been started beneath ancient alluvial deposits. Dines (1956) divided the lodes, which number over 20 in an area of approximately half a square mile, into four main groups. The most important lodes, which were worked to a depth of 150 fathoms, trended approximately ENE and were more or less vertical. Additional lodes trended NNW with a South-West dip of about 60°, East-West with a high dip to the South, and North-East.

In discussing the mineralogy of the lodes which he considered to be due to a small emanative centre "within the heart of a granite mass,"

Dines (1956) concluded that

"the lodes of Ding Dong Mine, seldom over a foot wide and impersistent, are stated by Collins (1912) to be associated with carbona-like bodies, but none of these are indicated on the plans. The lodes throw out branches or strings that run irregularly through the country rock. The wall-rock is hard and red-stained and, in places, tourmalinized resulting in a fine-grained, fairly compact rock. Beyond the reddened or hematized walls the country rock is greenish due to chloritization of the feldspars. The veinstone of quartz with comby structures showing zoning, and of fine, hard, compact peach, is frequently brecciated and re-cemented with quartz; chlorite is also present."

On the basis of the narrow width of the lodes and the sporadic distribution of values, he concluded that "probably only the lower part of the tin zone is present here."

The first account of the mineralogy was given by Henwood (1843) and followed later by Reid & Flett (1907). Tourmalinization of the wall-rock, resulting in a rock resembling luxullianite, was described by Le Neve Foster (1887).

There was a coincidence between not only the average lode directions and the granite joints, but also between the latter and the NW-trending trawns and slides which dip to both the North-East and South-West. Henwood (1843) described the trawns and mentioned that they usually heaved the lodes for a short distance. Apparently, the lodes were also deflected by major joints, for according to Hawkins (1822, No. XI) "it is very remarkable that ..... the tin lode is both heaved and started by the cutters and clefts of granite through which it passes." Henwood (1843) recorded that the Malkin Lode changed in structure and mineralogy upon approaching a trawn.

(f) Balleswidden Mine area

The Balleswidden Mine area embraces several properties about

one mile East of St. Just, the most important being Davy Shaft Mine Hobboy's Mine, Balleswidden Mine, and New Balleswidden Mine. Dines (1956) detailed the location and history of each, the sources of most of his information being the works of Collins (1912), Reid & Flett (1907), Henwood (1843), and Rowe & Le Neve Foster (1887). The latter publication is the chief source of information on the area and is an excellent descriptive account of the lode structures and mineralization.

Apart from Balleswidden Mine, most of the mines were nothing more than extensive trials. A large number of lodes were discovered but too often they proved to be unpayable. Production ceased in the area before the end of the 19th century and the only work since has consisted of re-working some dumps during the 1st World War. The mines lay in an area of kaolinized granite, and china clay has been commercially recovered in the vicinity.

Few details are available of the lodes outside Balleswidden Mine, but within the latter the general lode strike was NW-SE with the dip to the SW, varying from vertical to 60°. A major lode was Arboy's which consisted of four or five parallel veins known as 'gries' only 2 or 3 inches wide. These carried, according to Rowe & Le Neve Foster (1887), cassiterite with wolfram bismuth, bismuthine, native copper and flourspar in a gangue of quartz, tourmaline, gilbertite and kaolin. They were bordered by walls of greisen up to 6 inches wide known as 'hard-work', which contained cassiterite, tourmaline, gilbertite and a little flourspar. The 'gries' and 'hard-work' together resulted in a 'lode' with an overall width varying from 10 to 30 feet. Tin values appeared to be intermittent but it was noticed that "the greater the dip of

Arboy's Lode the more likely it was to be productive."

Branches of the lodes, like carbonas in form, were known locally as 'pie lodes'. With a width of 3 to 6 feet they consisted of irregular veinlets of quartz, tourmaline, gilbertite, and cassiterite, bordered by greisen. Several cross-courses were encountered in the area and comprised "veins of quartz about 1 foot wide with red clay." Dipping to the NNW at about 70 degrees, they trended NE-SW. A similar attitude was possessed by "slides of red clay."

The lodes at Balleswidden Mine were of an altogether different character from those of the remainder of the Land's End district. Accounts of their mineralogy are indicative of a different phase of mineralization from that in the St. Just area. On the information available from Rowe & Le Neve Foster (1887) immediate similarities are evident between the 'lodes' of Balleswidden Mine and early greisen-bordered veins, which were described by Hosking and Trounson (1959) as typical of cusps in the granite surfaces.

Wolfram is acknowledged to be present in the 'tin zone' of normal hydrothermal lodes, but if the mineralization at Balleswidden Mine were of the same type as that in the adjacent St. Just area then the complete absence of wolfram, as is the case, would not be expected in the latter district. Balleswidden Mine is situated at an elevation of 600 feet above sea level and the lodes were explored down to the 180 fathom level where they became non-productive. It is also situated at the intersection of the two main axes of the Land's End Granite. These facts support the hypothesis that the 'lodes' are of the greisen-bordered variety since Hosking & Trounson (1959) considered

that greisen bordered veins often developed first in such places (the cusps on ridges) from the local residuum which accumulated in traps during the consolidation of the ridges."

(g) Sancreed area

The Sancreed area, comprising less than one square mile in area, is the least important of any of the Land's End district. A number of NE-SW striking lodes which were indicated by Dines (1956) as dipping to the SE were explored to shallow depths in about five properties. No details of the workings are available and the mines are credited with having produced only a little tin before 1875 when all operations ceased. Bartinney Mine was prospected in 1943 and Dines (1956) described a lode encountered in one of the adits.

In common with the Morvah region, the Sancreed area has been extensively investigated for alluvial deposits, but without any real success. Nearly all the alluvial tin in the Land's End Granite was found, according to Henwood (1874), in the valleys which drain the Southern part of the peninsula, an area devoid of known mineral lodes.

(h) Marazion area

The Marazion area forms part of the Mount's Bay district which extends around the Bay and Eastwards into the Carnmenellis and Godolphin granites. An ENE-trending lode was worked in the West at Wheal Garth which was briefly described by Reid & Flett (1907). The Mine was noted, as described by Henwood (1843), Carne (1832) and Collins (1912), for the occurrence of wood-tin.

Proceeding to the East, the ENE trend is maintained by the

greenstone and elvan dykes of the Penzance area where the Wherry Mine, described by Hawkins (1818) and Russell (1949), was worked on the foreshore. West of Long Rock, which has been vaguely reported as a scene of past mining activity, the general lode strike swings round to the ESE, the mines continuing through Perranuthnoe and Goldsithney. Copper was the chief product and the properties which were described by Henwood (1943) were mainly active during the first half of the 19th century. A little lead was produced at Prosper United and some mispickel and iron ore were raised at other mines. Perran Mine, a silver producer, was active for a short while in the early part of the 20th century.

A few isolated mines were situated to the East of Ludgvan, the largest being Prosper United and Marazion Mines which ceased production around 1850. Darlington Mine, an important property described by Henwood (1843), lay slightly to the North-West of Marazion and was a producer of tin and copper from lodes that outcropped beneath the marshes. Dines (1956) listed the minerals in the Darlington lodes which were reported to vary from 2 to 8 feet in width.

Collins (1912) provided some details of the Marazion mines noting that the lodes were not rich and that the elvans trending in the same direction were intermittently mineralized. All the lodes were in Killas and appear to have dipped to the South at 60° to 70°. The lodes, which were on the average wider than those of the St. Just and St. Ives areas, were described by Stephens (1893). Some flucans and cross-courses were recorded by Henwood (1843).

Whether or not the copper mined in this region is indicative of an

underlying tin zone is not certain. Although Collins (1912) stated "there can be little doubt that both lodes and elvans exist beneath the marshes near Marazion station and in the Bay between the Mount (St. Michael's Mount) and Newlyn" it should be remembered that not all lodes contain tin and of those that do, not all are sufficiently rich to warrant their extraction. One of the major mining problems in this area appears to have been the large quantity of water that it was necessary to handle in all the mines.

5. THE PENDEEN - BOTALLACK AREA

5/1 General Geology

A major division of the Land's End Granite district is the Pendeen-Kenidjack area to the North and West of St. Just. It encloses, as shown in Fig. (11), the stretch of coastline described by Barclay (1959) lying between Portheras Cove and Priest's Cove, at which localities the granite outcrops upon the cliff. With the exception of those workings driven beneath the sea, the coastline forms the North-Western limit of the St. Just mining district. From the economic viewpoint only the Northern half of the Pendeen-Kenidjack area, extending from Pendeen Consols Mine (near Pendeen Watch) to Zawn a Bal is known reliably from old mining plans and records, and will therefore be considered in detail. Together with the inland portion, for a distance of about 1½ miles, it will be referred to as the Pendeen-Botallack area. The situation of Geevor Mine within this district is indicated in Figs. (A) and (B).

The Pendeen-Botallack area encompasses the workings of Pendeen Consols, Boscaswell Downs, East Boscaswell, Geevor, Levant, North Levant, Spearn Consols, Wheal Cock, Carnyorth, Crowns and Botallack Mines. The above mines, the workings of which are shown in Fig. (H), were the major producers of the St. Just district, the original mining setts being indicated in Fig. (13).

Within this area the granite does not outcrop upon the cliffs and the only exposures occur in the mine workings and in occasional quarries and streams. Consequently, the exact position of the granite surface at depth must be deducted from the plans of the now abandoned

mines. Fig. (11) depicts the probable location of the granite contact at surface as inferred from surface land profiles, float material in the fields, very occasional outcrops, and the known location of the granite surface at depth as shown in Fig. (H). The latter plan incorporates the results of the present writer's mapping along the coastline.

The aureole rocks are exposed along a narrow coastal cliff section, part of which is shown in Photo. (4). These structurally and petrologically complex rocks were originally mapped by the Geological Survey. Further work on them has been carried out by Barclay (1959) and by the present writer, who, for mapping purposes divided the rocks into 'killas', 'greenstone', and 'greenstone hornfels', The term 'greenstone' includes both the pillow lava series and basic igneous sills which, although easily distinguished in the field, have been grouped together since they form an alternating series. The latter may be conveniently considered as a unit, described by Barclay (1959) as "an extensive dominating series of pillow lavas with minor bodies of massive greenstone."

With a total thickness of the order of hundreds of feet, the series is both overlain and underlain by killas to the NE and SW. Barclay (1959) examined the pillow lavas in detail and concluded that, as in the case of the killas, there is no evidence that they have overturned, except on a very minor scale. The pillow lavas are frequently interbedded with killas, the whole being intruded by basic igneous sills of basaltic and doleritic character.

The folded structure of the country rocks and their petrological features were complicated by the effects of the granite intrusion and subsequent mineralization processes. The greenstone series is more or less

conformable with the killas bedding which strikes between NNE-SSW and ENE-WSW and dips at about 30° to the NW throughout the area. Low-angled shears are fairly common and most of the junctions between the greenstone and the killas have been subjected to some indeterminate movement. Individual pillow lavas also show signs of shearing, as illustrated in Photo. (23).

The killas lies entirely within the thermal metamorphic aureole of the granite, the largest continuous exposure being at the Avarack, whence it extends to the NE along the coast to Pendeen Watch. Additional outcrops occur near Levant Zawn and Zawn Brinny, and between Botallack Head and the Crowns. Isolated patches of killas, interbedded with the greenstone and greenstone hornfels series, are exposed along the whole coastline, as shown in Fig. (H). Moreover, killas underlying the greenstone series and concealed by overburden, undoubtedly occurs between the coastal outcrops and the projected line of outcrop of the granite contact on the surface.

Included in the Pendeen-Botallack area are some of the greenstone-hornfelses which extend from the Crowns southwards beyond Zawn a Bal. They are frequently interbedded with killas, especially between Zawn a Bal and De Narrow Zawn. These greenstone-hornfelses include many of the varieties described by Tilly (1935), and Photo. (22) shows some of the typical cordierite-anthrophyllite rocks in which Barclay (1959) recognized traces of original pillow lava structure. In attempting a broad correlation he placed the greenstone-hornfelses "below a killas belt at the Crowns and above a pillow lava series and greenstone mass to the South side of Kenidjack Castle which, in turn, overlie the Southern killas." He estimated that the altered pillow lavas, within the mass of "peculiar

hornfelses", must be at least 100 feet thick.

Among the various metamorphic assemblages of the killas, hornfelses are predominant, although several other local varieties are present. Lacy (1958), Hawkes (1958), and Barclay (1959) considered that the typical banding of the killas represents original bedding. The killas is traversed by abundant quartz veins which occur as ptygmatic forms shown in Photo. (25), as injections parallel to the banding, and as late veins cross-cutting all the earlier forms.

The amount of minor folding in the killas is very variable. On occasions it is impossible to determine the correct attitude of the strata whilst in other places the killas has suffered only a slight buckling. Belts of highly contorted rock trend NE-SW parallel to the coastline, and the folding appears to intensify with increasing proximity to the granite.

In relative undeformed areas the attitude of the aureole rocks may be determined from the orientation of remnants of interbedded killas, but it is best observed from the sea whence an overall appreciation is more easily obtained, as shown in Photos. (19) and (20). The dip of the greenstone series conforms to the overall attitude of the killas, being about 30° in approximately the same direction as that of the granite contact, with greater variations in strike than in dip. In general the strike of the aureole rocks swings round from ENE-WSW in the vicinity of Pendeen Watch to N-S in the region of the Crowns Engine House, thus approximately paralleling the line of outcrop of the granite contact at surface.

Many old mine plans and sections imply that the tin-copper lodes

were followed through the greenstone series but no indication can be gained of its exact distribution. Many early writers suggested that the greenstone series is continuous along this coastline, and Abbott (1920) summarized the majority view when he stated:-

"Almost parallel with the cliff in the killas is a greenstone dyke which can be traced from Gurnard's Head to the North, to the Longships Lighthouse off the Land's End to the South, and at different depths in the mine (Levant). The greenstone dyke, which is of considerable width, is very hard and not congenial, the lodes in every instance being squeezed up and not very productive in passing through it."

From the economic viewpoint the correct delineation of the attitude of the greenstone series is of great importance. Numerous writers have stated that the presence of greenstone caused impoverishment of the tin values in a lode, and this is a factor which must be considered in any future underground development in the aureole rocks. In a previous section of this thesis it was suggested that the granites in the South-West were selectively intruded into pre-existing anticlines in the country rocks. Such pre-granite features would tend to be exaggerated and distorted during intrusion of the granite due to sympathetic up-arching and thrusting. Both the pre-granite structures and those caused by intrusion would be accompanied by contemporary minor folding and associated features.

The known sub-surface contours of the granite contact, shown in Fig. (H), indicate the existence of subsidiary NW-SE crests on the flank of the major NE-SW granite crest. These subsidiary crests, which tend to occur between adjacent mines exerted a structural control, upon the regional (Pendeen-Botallack) extent of the mineralization and the depth of the zone of economic tin mineralization. They lie parallel

to what appears in Fig. (7) to be a major NW-SE crest whose axis trends through the centre of the area, as shown in Fig. (H).

It is most probable that the attitude of the aureole rocks overlying the NW flank of the Land's End Granite reflects to a varying extent the configuration of the granite surface at depth. The narrow width of the aureole rock outcrops along the coastline, and the absence of any mappable stratigraphic horizons in the killas, renders the determination of the attitude of the conformable greenstone series a prior necessity. If the series is fairly constant in width it may be employed in the interpretation of the major structures within the aureole rocks, and thus serve to elucidate the form of the sub-surface granite contours and lead to a more accurate prediction of the localization of economic mineralization.

The local configuration of the greenstone series between Trewellard Zawn and Levant Zawn may be determined by mapping of the coastal outcrops and from a study of the relevant underground workings. In Geevor Mine the following drives have been extended into the country rocks for short distances beyond the contact:

(a) Prospect No. 2, Level 11;
(b) No. 3 Branch Lode, Levels 11 and 12;
(c) The x-cut North-West from the No. 3 Branch Lode, Level 11 (West).

During the course of his investigations at the Mine, Dines examined the Coronation and No. 3 Branch Lodes on Level 6/7, where he found only killas to be exposed beyond the contact.

Webb (1947) observed "on the 10th Level" a contact rock "which has the appearance of an altered greenstone", but this is no longer

accessible. Level 3 adit in Geevor Mine, shown in Figs. (G), (H), and (23), is open to inspection from Carn Shaft to Trewellard Zawn, and Fig. (115) incorporates the evidence which it reveals. A small band of greenstone is separated from the granite surface for a short distance by killas. Although the main greenstone series is depicted in depth any representation of its attitude is at present purely tentative.

Methods by which the form of the greenstone series may in future be determined are as follows:-

(a) The employment of divers to obtain oriented specimens from the sea-bed along pre-determined traverse lines normal to the coastline between Boscregan Zawn and Trewellard Zawn. It is uncertain whether the upper surface of the series outcrops on the sea-bed immediately off-shore in the vicinity of Levant Zawn and Zawn Brimny. Recent diving operations over the '40 Backs' (Garnett 1961) indicate the presence of greenstone on the sea-bed at a distance of 600 feet from the coast.

(b) The use of a continuous series of colour photographs of the cliffs, taken from a boat under suitable weather conditions.

(c) Detailed mapping of the Levant adit and Skip Shaft, shown in Figs. (24) and (H), which have recently (1962) become accessible.

(d) More detailed mapping of the coastal outcrops, with close attention to minor structures.

Fig. (12) indicates intersections obtained in horizontal diamond drill holes Nos. 9 and 10 from Level 11. D.D.H. No. 10 is reported to have penetrated a small patch of greenstone, as illustrated, but the present writer has been unable to examine the drill cores and it is impossible to provide further information concerning the nature of this intersection. However, it may represent the downward continuation of the small band of greenstone present in the Level 3 adit, in which case, assuming a NE-SW strike, this smaller greenstone series dips at 25° to 30° to the NW.

If Level 15 of the Coronation Lode is extended in future to connect with the 170 fm. level x-cut in Levant Mine it will be possible to determine whether or not there was up-arching of the aureole rocks during granite intrusion. This will have an important application in underground exploration, as demonstrated in Fig. (115).

5/2 Minor Folding in the Country Rocks

Interpretation of the minor folding in the killas depends upon the prior assumption that the characteristic banding in the rocks is representative of the original bedding. Stone and Lambert (1956) described banding in the killas exposed in cliff sections at Porthleven, due to alternations of dark argillaceous material and light silty bands which they interpreted as bedding. Lacy (1958), in discussing the Land's End Granite Aureole, mentioned the laminated appearance of the killas, and considered that the quartzose laminations represent the original bedding and therefore lead to the "correlation of these rocks with the Mylor series outside the aureole". He was supported by Hawkes (1958) who stated:-

"Within the Land's End aureole, there are killas sections in which the quartzose laminations give way to quartzose augen remarkably similar to the Porthleven silty structures. It appears likely therefore that the quartz laminations represent the site of original silty bands, a process of metamorphic segregation having produced their present aspect"

Hawkes (1958) also described the uncontorted laminations in the Carn Moyles - St. Ives area as approximating in dip and direction to that recorded in the pillow lavas.

Both Barclay (1959) and the present writer infer that in the Pendeen-Botallack area the laminations observable in the killas, as shown in Photo. (28), represent original bedding. Minor folding is sporadically distributed, areas of intense contortion being separated by stretches of undisturbed strata. Large-scale folding in the Land's End area has affected both the killas and the various greenstone series, and these rocks were subsequently subjected to minor folding. Although the latter is readily recognized throughout the killas, it

is easily observed in the greenstone only when thin basic sills are interbedded with killas and the whole has been folded.

Barclay (1959) detected less-well developed folding in the greenstone-hornfelses and utilized measurements of the minor folds within both killas and greenstone. The present writer has confined his studies for structural interpretation to the minor folds in the killas. The extent of folding varies considerably and within a few feet it may change from a gentle buckling or undulation to close severe folding. The main types of folds are ptygmatic, concentric and similar.

Ptygmatic folding is occasionally seen throughout the area, the ptygmas taking the form of an irregular quartz vein, as defined by Wilson (1952), an example from the Avarack being illustrated in Photo. (25). Here the quartz shows thickened hinges with attenuated limbs and it is noticeable that the axial planes of the individual tight folds are parallel to the prevailing laminations of the killas, but there is very little evidence of distortion of the killas such as might account for the formation of the ptygmatic quartz vein. It is possible, however, that it was produced by shearing along the bedding planes, as described by Kuenen (1938).

Concentric folding, as defined by De Sitter (1956), was recognized in the area by Barclay (1959) who mentioned that true concentric folding may be observed on the Avarack. This variety of folding, shown in Photo. (30), is present, but less well developed, elsewhere. Slip along the planes of lamination or bedding results in folds with an amplitude of under 10 feet, with axial planes dipping to the North-West. These often grade into similar folds which combine to varying extents the bedding plane shear of concentric folds and the axial plane cleavage of shear

folds, as shown in Photo. (26).

Similar folding is common throughout the Tendeen-Botallack area. Such folds vary in amplitude from a few inches up to about 5 feet and are distinguished by quartzose laminations and frequent injections of quartz parallel to the bedding. Fracture and slaty cleavage, described by Knill (1960), are developed and there is frequently a slight apical thickening of the folds coupled with limb attenuation. Some folds approximate to accordion folding with the development of a series of identical similar folds having parallel axial planes. Photo. (27) shows a typical similar fold from above the Crowns Engine House. Most of the gentle plunging folds are asymmetrical.

Two sets of readings of the minor folds were taken, the first extending along the base of the cliffs from the Avarack to Zawn a Bal and the second along the top of the cliffs from the Avarack to the Crowns Engine House. The purpose was to test the validity of utilizing the measurements of 50 minor folds. The fold axes measured during the separate traverses are plotted in Figs. (34/1) & (34/2), which clearly demonstrate that the predominant set of minor fold axes trends 17/18 NNE in each case.

(N.B. A fold axis or stress direction trending 17° and plunging at 18° to the NNE is written 17/18 NNE. In a similar manner, an axial plane or joint plane striking 17° and dipping at 18° to the WNW is written 17/18 WNW).

Reference to the stereograms reveals that there is a spread on either side of the maximum with two minor maxima trending 174/12 N and 64/33 ENE. A second and less important set of folds trends approximately NW-SE and plunges at low angles in both directions. The poles to the axial planes of the folds between the Avarack and the Crowns Engine House are plotted

in Fig. (34/3), which indicates that the major set of 17°-trending folds possesses axial planes dipping NW. A maximum, obtained by plotting the poles to the planes, strikes 30/48 NW. The spread in fold axes to the North and NE is shown by two minor groups of poles to the axial planes, with maxima striking 177/42 E and 61/67 SW, corresponding respectively to the 174° - and 64°- trending fold axes shown in Fig.(34/2). The NW-SE trending folds are indicated by the axial planes dipping to the SSW at 70°. By plotting the axial planes according to geographical distribution (not shown) a change of strike from around 70° to 170° through NE-SW is apparent in traversing from Pendeen Watch to the Crowns Engine House.

If it is assumed that the axial planes of these folds are aligned with their poles in the direction of the principal compressive stress which resulted in the fold formation, then it is possible to determine the direction of that stress.

Accordingly the 17° -trending minor folds may be attributed to a stress, P, shown in Fig. (34/5), which trended 120/42 SE.

Barclay (1959) did not take into account the attitude of the axial planes and assumed that the stress operated normally to the fold axes. Having defined a main set of minor folds trending 20/25 NNE, he postulated a stress (say P_a) acting with a direction of 110°. For the less important or subsidiary set of minor folds which he defined as trending 145/17 NW he invoked a stress (say P_b) with a direction of 55°.

Simply for purposes of comparison the present writer has also determined P_a and P_b on the basis of the fold axes shown in Fig. (34/5), which indicates directions of 107° and 24° for P_a and P_b respectively.

A more correct estimate of the stress direction is obtained from a consideration of the trends of the axial planes, and P_a corresponds to P, already determined as 120/42 SE for the main folds. P_b, the stress which produced the subsidiary NW-SE trending folds, corresponds to a stress aligned 24/20 NNE.

Barclay (1959) observed cross-folding of the two trends below the northern side of Pendeen Lighthouse and from field evidence he deduced that the subsidiary NW-SE folds were possibly later than the main NNE-SSW folds. He attempted to relate the two trends, on the basis of their direction and relative age, to the Caledonian and Armorican orogenies, stating:-

"..... it may be true to say then, that the NNE-SSW folding could be represented by the Caledonian compression, while the folds trending NW-SE may be a younger folding, due to American earth movements. In the latter case it can be seen that the folding is not strictly along E-W lines, as mentioned by Robson (1945). The difference in trend may be due to the local attitude of the country rocks at the time of the Armorican pressure, from the south, giving a consequent deflection from a true E-W folding. However, Hendriks (1937) indicates in her diagram of Armorican structure, that the axes of the folding may vary in direction locally between NW-SE and E-W."

The present writer has been unable to discover any conclusive evidence in favour of a significant age difference between the two fold trends. Whilst admitting that the evidence presented is far from decisive, the writer prefers not to relate the two fold trends to any particular orogenic periods. Until further evidence to the contrary is available the writer considers that the two fold trends may be assigned to local variations in a regional stress system acting throughout a period of earth stress, and/or to overall changes of short duration in a delicately balanced stress system operating during one period.

Fig. (41) indicates the theoretical attitude of shear fractures produced by the orientation of three mutually perpendicular principal stresses, as propounded by Anderson (1942). Most of the similar folds are aligned in such a way that the a-b plane is normal to the direction of the maximum principal stress, P_1, with the fold axes probably in the b-direction. Conjugate shear folds which are a form of shear phenomena may also develop in the killas with axial planes coinciding with the planes of maximum shear stress. The latter are theoretically oriented at 45° to the direction of P_1 but in practice they vary on either side, depending upon the internal friction of the rock under stress.

The small 174°- and 64°-trending folds with axial plane maxima striking 177/42 E and 61/67 NW, shown in Fig. (34/3), may thus be accounted for and the three principal stresses may be determined graphically as shown in Fig. (34/4); the maximum principal stress P_1 trending 125/14 WNW, the intermediate principal stress P_2 trending 45/34 NE, and the minimum principal stress P_3 trending 15/47 SSW. P_1 has been assumed on the basis of field evidence to bisect the obtuse angle rather than the acute angle, which is bisected by P_3. Immediately noticeable is the agreement between the value obtained for P_1 of 125/14 WNW and the value already obtained for P of 120/42 SE, and between P_2 and the direction of plunge of the main folds. An analysis (not illustrated) of a single pair of conjugate minor folds, of which the fold with a NW-dipping axial plane possessed a NE-SW, rather than a ENE-WSW, strike, resulted in a better agreement between the determination of P_2 and the direction of the 17°-trending folds.

It is therefore reasonable to suppose that the minor 174°- and

64°-trending folds shown in Fig. (34/2) may also be attributed to the stress system to which the main and contemporaneous 17°-trending folds owe their origin. The intermediate principal stress during the formation of the 17°-trending folds may be taken to be coincident with the fold axis, the minimum principal stress being perpendicular and mainly in a vertical direction.

Badgley, (1959) illustrated the mode of formation under certain conditions of 2nd order stress directions which result in the development of 2nd order folds. The 2nd order stresses and 2nd order fold axes are theoretically aligned at 45° to the 1st order stresses and fold axes, variations on either side being likely in actual fact.

The 174°- and 64°-trending folds in Fig. (34/2) are separated by an angle of 110°. The bisector of this angle is approximately normal to the 17°-trending folds and possesses a direction of 119°, compared with one of 107° for P_a, 120/42 SE for P, and 125/14 WNW for P_1. A similar result is obtained from measurements of the fold axes presented in Fig. (34/1). The equivalent subsidiary folds are represented by maxima at 65° and 152°, separated by an angle of 87°. The 17°-trending folds are again represented by a maxima oriented in the same direction, the normal to which, at 107° (P_a), intersects the acute angle of 87° between the subsidiary fold trends into arcs of 42° and 45°.

Judging by this close agreement in the calculated direction of the maximum principal stress it is reasonable to suppose that some of the subsidiary folds described above may have been formed as a result of shear folding in which the axial planes are aligned normal to a 2nd order principal stress arising from, and at approximately 45° to, the 1st order

maximum principal stress, known variously as P_a, P, and P_1.

In recent years the term 'cross-fold' has frequently been utilized, and although the writer is not altogether in favour of the term it will be employed here because of its wide use in current literature. Loosely, the term refers to subsidiary folds trending obliquely to a better developed set, without any definition of relative ages. The formation of minor or cross-folds resulting from the development of 2nd order stresses as described above is now recognized to be more common than was formerly realized.

De Sitter (1960) cites many examples of the formation of Hercynian cross-folds in the Pyrenees where NW and NE trends, crossing the E-W trend, may be attributed to a constant N-S directed stress. Sutton (1960) described the formation of contemporaneous cross-folds in Northern Scotland which possess axial planes differing from those of the main folds, due to a secondary stress field derived from the first one.

Whereas Barclay (1959) found the two stresses P_a and P_b to be separated by an angle of 55°, the writer has found them to be 83° apart on the basis of fold axes alone. By taking into account the attitude of the axial planes of the 17°- and NW-SE trending folds the directions of the two maximum stresses responsible for their separate formation are, as seen already, 120/42 SE (P) and 24/20 NNE respectively. An immediate comparison may be made with the values obtained in Fig. (34/4) of 125/14 WNW, 45/34 NE, and 15/47 SSW for P_1, P_2 and P_3 respectively. With an interchange between P_1 and P_2, or between P_1 and P_3, and an alteration of the plunge of the stresses it is obvious that with the maximum principal stress P_1 aligned in a NE-SW direction then NW-SE trending folds would be formed approximately

normal to the 17° trending folds.

On the limited amount of evidence available it seems more likely that an interchange took place between the directions of P_1 and P_2 to produce the NW-SE trending folds. Such an interchange between principal stresses must be expected in an area subjected to high stress conditions. Localized interchanges would result in the comparable development of contemporaneous NW-SE folds amongst the 17°-trending folds. Intermittent overall changes in the direction of maximum stress would result in poor development of the NW-SE folds throughout the whole of the area in which the 17°-trending folds would predominate. Interchanges in stress would frequently occur if the balance between the three principal stresses was delicate; indeed, during any period of diastrophism the earth stress must not be regarded as being consistent in direction or force throughout wide areas.

Barclay (1959) suggested that the NW-SE folds are not contemporaneous with, and may be later than, the NNE-SSW folds. If this were so one would expect more definite field evidence of this contention, together with some statistical confirmation. Ramsay (1958) showed conclusively that deformation of a fold system by a second period of folding results in a spread in the distribution, when plotted on a stereogram, of the fold axes and poles to the axial planes of the first folds in comparison with the second set.

Such a spread would be expected in the Pendeen-Botallack area if one set of folding were later than the other, but in fact there is no such scatter. Nevertheless, further field measurements are essential in order to determine beyond doubt the origin, the relative ages, or the synchronous nature of the different fold trends. De Sitter (1960) stated that concentric folds are normally regarded as being earlier than similar folds, and

in future work it would be advantageous to treat the two forms separately both in the field and statistically.

Examples of minor folding in the killas of West Cornwall have been given by other writers. Lacy (1958), in describing the stretch of coastline between Carn Moyle and St. Ives, stated:-

"The killas often shows minor folding, the structures being marked by the quartzose laminations. The axial planes of the folds strike at about 45-deg. east of north and dip to the north-west at angles between 20 and 55 deg. Parallel to them a cleavage is frequently developed."

It appears that the predominant NNE-SSW folding in the Pendeen-Botallack area is continued to the north as far as St. Ives, where it veers to NE-SW, though the attitude of the axial planes is maintained in dip and direction.

Lambert (1959) described minor similar and concentric folds in the Gramscatho Beds at the mouth of the Helford River, with two predominant trends, namely main WSW-ENE folds with subsidiary NW-SE cross-folds. They possess sub-parallel apical planes and a cleavage dipping to the SSE. Lambert suggested, on the basis of the relationship between the two systems of folding, that they are virtually synchronous, and concluded that the style of folding "can be explained by a uni-directional regional stress acting normal to the apical planes of the folds."

In the Perranporth area Cox (1961) illustrated the existence in the killas of ENE-WSW trending folds with axial planes dipping to the SSE. These are supplemented by NNE-SSW folds with axial planes inclined to the WNW.

Sutton (1958) stressed the importance of a study of minor structures, stating that "the attitude and form of practically every

observed small structure can be related to the development of some much larger fold". Consequently a correct interpretation of minor structures is imperative in order to elucidate regional structures.

Barclay (1959) found that the attitude of the minor folds varies considerably in the Pendeen-Botallack area and concluded that the NNE-SSW trending folds possess a long shallow-dipping WNW limb. A shorter, steeper limb dipping to the ESE is often vertical and sometimes overturned. To the South of the area the same folds possess a shallow-dipping limb to the ESE and an almost vertical limb to the WNW.

Barclay (1959) concluded that if these minor folds can be considered as drag-folds upon the flanks of major regional folds then those in the Pendeen-Botallack area indicate the existence of a major anticline to the East. This is in agreement with the hypothesis of Reid & Flett (1907) who postulated the presence of a pre-granite anticline in the country rocks, trending in a NE-SW direction along the main axis of the Land's End Granite.

According to Barclay (1959) NW-SE folds occur only between Carn Vellan and Portheras Cove. With a longer shallow limb dipping NE and a short, almost vertical, limb dipping SW these folds may imply the existence of a major anticline to the SW having a NW-SE axis through Carnyorth and Spearn Consols Mines. This postulated anticline would coincide with that which may exist in the western part of the Land's End Granite area and might concur with the present NW-SE trending granite crest.

The preceding analysis of minor structures in the Pendeen-Botallack area corroborate the hypothesis that a major NW-SE trending subsidiary crest occurs in the surface of the granite, on the flank of the NE-SW crest,

with an axis through Carnyorth and Spearn Consols Mines. This configuration of the granite surface at depth is echoed by the attitude of the overlying aureole rocks.

The strike of the aureole rocks varies according to that of the granite contact. A comparison of Figs. (34/3) and (111/1) indicates close agreement between the attitude of the axial planes of the minor folds and that of the granite surface in the vicinity of Geevor Mine. The form of cordierites developed in the greenstone-hornfelses denotes that they were probably formed under stress conditions which resulted in the formation of similar minor folds.

It is probable that most of the local folding in the aureole rocks of the Pendeen-Botallack area originated during the period of granite intrusion when the stress distribution pattern was as follows:-

(a) The maximum principal stress was approximately horizontal and was aligned in a NW-SE direction, locally normal to the granite surface.

(b) The intermediate principal stress was also horizontal and aligned in a NE-SW direction. This decreased in intensity so that towards the end of the intrusion period it became the minimum principal stress.

(c) The minimum principal stress was aligned in a more or less vertical direction.

5/3 Jointing in the Granite

(a) Introduction

Compared with the aureole rocks, the granite in the Pendeen-Botallack area is very badly exposed. Along the coastline it outcrops at its contact with the killas in Portheras Cove. Inland, apart from some float rock on Portheras, Trewellard, and Carnyorth Commons, there is only a small outcrop on the summit of Carn Eanes and nearby there are two miniature granite quarries. Throughout the area there are no other outcrops large enough to warrent an examination of the joint patterns. The most continuous exposures are in the workings of Geevor Mine, but owing to the effect of blasting on the fracturing of the granite, care must be exercised in the statistical measurement of the joints.

The origin and form of the joint systems of the Land's End Granite have been described in a previous section. In the Pendeen-Botallack area the flow-lines trend approximately NW-SE, perpendicular to the granite contact. They are roughly normal to regional SE-dipping cross-joints and are parallel in trend to the steeply dipping longitudinal joints. Inclined to the SE at a lesser angle than the regional system are a series of local cross-joints which frequently contain dykes. Flat-lying, NW-dipping, joints are visible on Carn Eanes and along the coast to the north of Portheras Cove. Superimposed upon the primary joints of the area is a secondary conjugate shear system.

Variations from the usual coarse-grained, porphyritic Land's End Granite, G_1, are common, as illustrated in Fig. (17). The Carn Eanes type has been detected only on the surface where it is exposed in outcrops and

quarries on the Carn. Both the Boscaswell type and the Western type have been detected only in the underground workings of Geevor Mine.

The three variations of granite are regarded as local modifications contemporaneous with, and probably produced by contamination of the normal Geevor type of granite, G_1. They were intruded before the commencement of jointing in G_1 and are enveloped by the same system of primary joints as the latter. The differences between G_1 and its local modifications are petrological and not structural. Measurements of the joint patterns were confined to the Carn Banes type and the normal Geevor type granites on the Carn and in Geevor Mine respectively, and none were made in the Boscaswell and Western type granites. The results show that the joint patterns present in the granite on Carn Banes are typical of the granite throughout the Pendeen-Botallack area, where large scale jointing is ubiquitous.

Flow lines, in the form of oriented c-axes of porphyritic feldspars, plunge to the NW at a low to medium angle which increases towards the granite contact. The general trend direction of the flow-lines is recognizable only by obtaining an overall view of the workings of Geevor Mine and not by the examination of any one small area, for at almost adjacent localities they may plunge in widely different directions and at variable inclinations.

Within Geevor Mine the trend of the flow-lines varies between NW-SE and E-W with a maximum concentration in a WNW-ESE direction. The attitude of the granite contact in the Mine is shown in Fig. (111/1); it possesses a maximum striking 40/38 NW. The mean trend of the flow-lines in plan makes an acute angle to the North-East with the surface outcrop of the

granite contact.

(b) Cross-Joints

A consistent arrangement of regional cross-joints in the Pendeen-Botallack area is superimposed upon local, variable cross-joint systems. Since the general direction of the flow-lines in the area is not the same as that throughout the NE-SW axis of the Land's End Granite the local cross-joints possess a different strike from the regional ones.

As shown in Fig. (32), the overall radius of the granite surface in a NW-SE vertical section over the total granite outcrop is greater than that developed locally on the NW and SE flanks, where the dip of the granite surface increases rapidly from about 15° to nearly vertical. Whereas a complete fan of radiating, regional cross-joints is developed, only an incomplete system of inward-dipping, local cross-joints is formed in any one area along the flank.

The dip of the regional cross-joints is consistently variable but that of the local cross-joints is dependent upon the local attitude of the granite surface. Consequently, the regional cross-joints form a fan of a larger radius than that of the local cross-joints, which are concentrated along the granite flanks as shown in Fig. (33). In these areas the regional cross-joints possess a higher dip towards the centre of the granite mass than do the local cross-joints.

In the vicinity of Geevor Mine the regional cross-joints trend consistently NE-SW whilst the local cross-joints trend WNW-ESE and are more variable in strike. With an inclination towards the SE, the former verge towards the vertical whereas the local cross-joints possess dips of the

order of 60°. Cross-jointing is well developed but it does not compare either in intensity or strength, apart from a few exceptions, with the later longitudinal and secondary shear jointing. Regional cross-joints are more perfectly developed but less frequent in distribution than the local ones.

Carn Eanes affords the best location in the immediate vicinity of Geevor Mine for a study of the cross-joints, and the results of plotting the poles to joints may be observed in the stereogram of Fig. (36/3). The well developed regional cross-joints are grouped with a strike between 36° and 66° and possess dips varying between 60° SE and 82° NW. The maximum strikes 49/80 SE, which is very nearly NE-SW, and should be compared with the attitude of the granite surface, shown in Fig. (111/1). Equally well developed local cross-joints strike between 10° and 155°, and dip between 70° W and 80° E. A maximum which strikes 176/85 W or nearly N-S, should be compared with the attitude of dykes in Geevor Mine, illustrated in Fig. (37).

The regional cross-joints at Geevor conform to the mean attitude throughout the Pendeen-Botallack area, whereas the local cross-joints on the Carn are almost vertical, since here the granite surface, now eroded, was horizontal. Towards the coastline the angle of dip of the local cross-joints gradually decreases.

Variations in the intensity of regional cross-jointing is illustrated by comparison with jointing in the quarry to the East of Carn Eanes. As shown in Fig. (36/4), there is a wide spread of joints but no concentration of regional cross-joints, although the quarry and the summit of Carn Eanes are separated by a distance of only a few hundred

feet. The slight change in the inclination of the local cross-joints is evident; they strike between 15° and 172°, dip between 70° W and 82°E, and again possess a vertical maximum striking N-S.

Joint patterns on opposite sides of the larger quarry on Carn Banes, shown in Photo. (31), are illustrated in Figs. (36/1) and (36/2). On one side of the quarry there is a general spread of cross-joints striking between 10° and 70°, with dips varying between 66° SE and 64° NW. A general maxima strikes 17/79 NW. On the other side of the quarry there is again a general spread of cross-joints striking between 10° and 70°, with a maximum striking 18/83 NW.

As in the quarry on the north-east flank of the Carn this larger quarry reveals no regional cross-joints, although there is a tendency towards a concentration striking NE-SW. The two maxima striking 17/79 NW and 18/83 NW may be attributed to local cross-joints which dip to the NW; they may result from a local variation in the dip of the granite surface which is reflected by the present day topography. It is possible that they have been accentuated by release effects following the formation of later secondary shear joints.

Both regional and local cross-joints are well developed throughout Geevor Mine. The local forms are visible on all levels and there appears to be no variation in their intensity with depth. Between Carn Shaft and Wethered Shaft their average inclination changes from vertical to ESE, and between Wethered Shaft and the coastline the average dip decreases from about 85° to 50° to the ESE.

Local cross-joints, which are irregular in dip and strike, possess slightly curved faces. The regional cross-joints throughout the mine

are characterized by a NE-SW strike and consistently high dip of 85° to 70° to the SE. Both the regional and local cross-joints provided planes for movements to accommodate changing stresses during later structural episodes. They frequently bear traces of slickensiding, together with kaolinization of the adjacent granite; features not associated with their original formation. All the regional cross-joints, unlike the local ones, extend beyond the granite contact into the aureole rocks, where they become difficult to distinguish from joints related to the folding.

Small dykes and faults commonly occur within Geevor Mine, the locations of some of the more important being indicated in Fig. (31). The dykes rarely attain a width of more than 15 feet and have an average width of about 5 feet. Consequently, they do not possess their own system of longitudinal and cross-joints caused by flow of the dyke magma during intrusion. Instead, the dykes reflect the later joint pattern of the host granite and are thus of value in determining the age relationships of the different joint systems.

One of the more important dykes is the Complex Dyke exposed on Levels 8, 9 and 10 at the junction of the Coronation Lode, Prospect South, and Prospect East. It is illustrated in detail in Fig. (65), and in common with other major dykes it exhibites two main directions upon which there is locally superimposed a later secondary shear system.

Fig. (36/7) illustrates jointing in the Complex Dyke on Level 8 where the joints strike NE-SW and dip both to the NW and SE, with a maximum striking 42/83 NW. A similar distribution of joints occurs in the Dyke on Level 9, with a spread in strike between 30° and 60°, and on Level 10, where it varies between 30° and 76°. These joints, which coincide in

strike and in character with the regional cross-joints of the granite, display only slight local variations in their direction of dip.

The Complex Dyke strikes approximately NE-SW and occupies a fissure originally developed as a regional cross-joint. It reflects the surrounding system of regional, but not local cross-joints. Most of the other major dykes, such as the Main Central Dyke shown in Photo. (82), occupy fissures which coincide in strike direction with the local cross-joints, and reflect the attitude of both the regional and local joints in the host granite. It is evident that the local cross-joints formed before those of the regional system, and hence were more amenable to infilling by magma of the fine-grained dykes. The cross-joints (and longitudinal joints) were the first to be formed during the consolidation of the granite magma. As consolidation of the upper arch progressed the radius of the arching effect increased and the formation of regional cross-joints commenced, concomitantly there were less frequent injections of dyke magma from greater depths. Although the intensity of jointing diminished progressively with time, those formed in the later stages were longer and more regular in extent, both vertically and laterally. Fig. (37) indicates the results of plotting the poles to the dykes, This reveals a N-S local system with a relatively low dip, and a NE-SW system dipping at about 80°, with a greater concentration of dykes around the former.

Well-developed local and regional granite cross-joints are visible on the coast to the North of Portheras Cove, but examples from the Pendeen-Botallack area are lacking due to the absence of exposures. Another locality which displays a similar development of joints, illustrated in Photos. (35-39) is the Castle-an-Dinas Quarry, situated within the fine-

grained granite, G_2, and a further example is provided by Newmill Quarry where local and regional cross-joints in G_1 are developed, as illustrated in Photos. (33-34).

(c) Flat-lying Joints

Well formed, flat-lying granite joints are visible at Portheras Cove and on Carn Eanes in the immediate vicinity of Geevor Mine. Reflecting both the configuration of the now-denuded granite roof and the attitude of the erosional surface, they dip consistently at low angles to the NW. On Carn Eanes flat-lying joints, shown in Photo. (18), reflect the local granite roof by dipping NNW. Poles to the joints are plotted in Fig. (36/3), which indicates that their dip varies between 5° and 20°.

In the quarry on Carn Eanes the flat-lying joints, as shown in Photo. (31), appear to be progressively less extensively developed at increasing depth below the ground surface. As illustrated in Fig. (36/2,4), they tend to mirror the local erosional surface rather than the original granite roof, by dipping between North and East at from 5° to 25°.

With the exception of the small exposure on Carn Eanes the flat-lying joints are imperfectly developed in comparison with the other primary granite joints. In Geevor Mine infrequent, well-formed, flat-lying joints dip NE at between 15° to 30°. There is no evidence to suggest that the density of the flat-lying granite jointing increases towards the granite surface where it is accessible in the underground workings.

Recent development on the Grenfell Lode on Level 10 (West) has disclosed the presence of two closely spaced dykes, illustrated in Photo. (84), which occupy flat-lying joints. These dykes are also visible in the drive on the Prospect between the 'D' Lode and Coronation Lode on the same level.

They are exposed over a strike distance of about 500 feet and have a dip of about 25° to the NW, thus showing a closer relationship to the attitude of the overlying granite roof than do the joints developed on the surface on Carn Eanes.

Judging by the primary tourmaline content and other petrological features of the dykes, the joints they occupy were probably opened at a late stage during the formation of the primary joint system, pene-contemporaneously with the infilling of the regional cross-joints and longitudinal joints. Their opening probably resulted from a relaxation of the principal stresses which operated during the emplacement and consolidation of the granite magma.

(d) Longitudinal Joints

Longitudinal joints are the most prominent of the primary granite systems in the Pendeen-Botallack area. They are theoretically aligned parallel to the flow-lines and normal to the local cross-joints. In the granite cliffs to the North of Portheras Cove they are closely spaced at intercals of 12 to 18 inches apart and maintain a constant strike and a dip of 70° to 80° to the SW. Their general NW-SE strike is continued throughout the area, but their direction of dip, although constant in the immediate vicinity of Geevor Mine, cannot always be ascertained with certainty.

They possess throughout Geevor Mine a constant intensity of development which is continued both laterally and in depth. With a cleaner fracture the longitudinal joints tend to be straighter and more regular in dip and strike than any other comparable joints. They were frequently

subjected to movement during the immediate post-consolidation stage of the granite intrusion. Renewed stress directed horizontally in a NW-SE direction resulted in the formation of a secondary conjugate shear system throughout the area. In the manner described by Firman (1960) the stress was accommodated whenever possible by the dislocation of pre-existing longitudinal joints. The secondary system was perfectly developed only when the stress could not be relieved by movement within the already fractured ground, owing either to the absence of sufficiently developed joint planes or their unsuitable orientation. In most of the Geevor Mine area displacement occurred along the longitudinal joints in such a way that they became equivalent to one of the complementary sets of the conjugate system.

Later vertical and oblique movements along the longitudinal joints also took place during the mineralization stages. Adjacent to the lodes the joints are often surrounded by reddened or greisenized granite, as shown in Photos. (43, 56 and 84). The dislocations and the accompanying alteration of the granite wall-rock have obliterated most of the evidence, such as that described by Roberts (1960) and Hodgson (1961), which might indicate the original primary or secondary origin of the joints.

Barclay (1959) presented the results of joint measurements on Carn Clough and Carn Gloose and around Priest's and Portheras Coves. In each area there is a strike variation between E-W and NW-SE due to a multitude of longitudinal and secondary joints. Although the longitudinal joints in the Pendeen-Botallack area vary between the limits indicated by Barclay (1959), in Geevor Mine they usually possess a strike of 110° to 125°, with a high dip to the SW of between 60° and 80°.

Since most of the primary granite joints were subjected to many later movements, each of which tended to destroy the evidence of previous movements and of their original formation, the maintenance of a constant strike and dip by the longitudinal joints throughout the Geevor Mine area is a most important clue, together with their relationship to the flow-lines and primary cross-joints, to their identification.

Their average strike and dip may be determined in the major x-cuts, outside the mineralized areas where they may be readily distinguished from the secondary joints. Elsewhere they may be identified by their regular strike and dip. The secondary joints have a tendency on both a large and small scale to curve noticeably in strike.

In the vicinity of the mineralized areas there appears to be a greater intensity of secondary jointing, as indicated by the measurements on Carn Banes which are illustrated in Figs. (36/1-4).

On the Carn the longitudinal joints, which often form the quarry walls as shown in Photo. (31), strike approximately East-West. At the four localities studied the maxima occur at 101/75 SW, 105/74 SW, 98/68 SW, and 98/70 SW, normal to the local cross-joints. In each case the longitudinal joints provide one of the complementary set of fissures in the later secondary shear system. Further west in the workings of Geevor Mine the longitudinal joints tend to adopt a more WNW-ESE strike, varying between 110° and 125°.

Narrow, steeply-inclined dykes occasionally infill the longitudinal joints. One was recently disclosed, as shown in Photo. (83), on the Grenfell Lode. A further example, illustrated in Fig. (53), is a small dyke, very variable in strike and dip, exposed in the Prospect South for

several hundred feet.

Such dykes normally possess an individual joint pattern which echoes that of the surrounding granite. The Complex Dyke, however, possesses on Levels 8, 9 and 10 longitudinal joint maxima of 121/73 SW, 100/73 SW, and 120/80 SW as shown in Figs. (36/7, 8, 9) respectively.

The relative paucity of dykes associated with longitudinal joints may be indicative of their late development compared with the other primary joints. Such dykes are typically tourmaline-rich, as illustrated in Photos. (82) and (83); owing to their relative scarcity they have not been included in the measurements presented in Fig. (37). Alternatively, the longitudinal joints may have been formed at the same time as the local and regional cross-joints, but the prevailing stress distribution prevented their dilation and consequent infilling by dyke magma.

(c) Secondary Joints

Upon consolidation of the granite in the Pendeen-Botallack area it possessed local and regional cross-joints and longitudinal joints. These were infilled to varying degrees with dyke magma, the composition of which may indicate the relative age of the joints and/or their infilling.

The discontinuous ascent in time of the dyke magma denotes an intermittent and variably directed relaxation in the stresses which operated during the intrusion and consolidation stages. No regional stress such as that responsible for the intrusion of the South-Western granite could be expected either to diminish gradually over a considerable time or to decrease suddenly over an extensive region. The regional stresses accompanying the granite intrusion gradually ceased, but doubtless there were frequent local resurgences and the intermittent relaxation was not

equal in all directions.

Rejuvenation of the maximum principal stress, aligned horizontally in a NW-SE direction, resulted in the creation of a secondary joint pattern within both the granite and the country rocks. Williams (1959) demonstrated the reactivation of existing fractures by changes in a stress system, the stress resurgence being accommodated in part by movement along pre-existing joints. A multitude of assorted joints and fissures were already present in the aureole rocks as a result of folding and granite intrusion, so that the secondary system was only partially developed outside the granite.

During the granite intrusion and consolidation stages the maximum and intermediate principal stresses, P_1 and P_2 respectively, were aligned, with local variations, horizontally with P_1 in a NW-SE direction. As consolidation progressed and the vapour pressure of the underlying, concentrating volatiles increased, the resulting vertical upward pressure became more effective. The direction of P_1 was maintained but the relative intensity of the previous intermediate and mimimum stresses was reversed, resulting in the intermediate principal stress, P_2, being aligned in a vertical direction and the minimum principal stress, P_3 in a horizontal NE-SW direction.

Being the more brittle rock type the granite was easily fractured by the secondary system. Only the ESE-WNW trending longitudinal granite joints were suitably aligned to accommodate by selective movement some of the stress, and they therefore formed one of the complementary sets of the conjugate shear system. The stress, P_2, resulting from the increased vapour pressure, was directed away from the granite centre

and approximately normal to the major arch of the granite surface. Both the strike and the dip of the pre-existing longitudinal joints influenced the disposition of the other complementary set of shear fractures. Since P_1 was aligned in a NW-SE direction the sets of conjugate joints adopted a strike of approximately ESE-WNW (equivalent to the longitudinal joints) and NNW-SSE. Their direction of dip is generally south-westwards at inclinations of between 50° and vertical, though variations are common, especially in the dip of the NNW-SSE set which is often to the NE and which characteristically possesses very few dykes.

The secondary system of joints cannot be classified as primary diagonal joints since, according to Balk's (1937) definition, they should be aligned in such a manner that the direction of the flow-lines bisects the acute angle between them. However this is not the case here, where the bisector and the flow-lines are aligned in a NW-SE and ESE-WNW direction respectively.

Barclay (1959) recognized the effect of a later post-consolidation stress in the Pendeen-Botallack area, but confused the primary granite cross-joints and the later secondary joints. He considered that the maximum principal stress was directed in a NE-SW direction and proceeded to analyse all the joints in the granite and aureole rocks on this assumption.

The results of the later resurgence of stress upon the pre-existing primary joint system are illustrated diagrammatically in Figs. (36/1-4). There is a general spread of joints between N-S and E-W, through NE-SW. By applying the principles of Anderson (1942), illustrated in Fig. (41), the determination of the three principal stresses operating during the

formation of the secondary joints may be effected graphically in the manner described by Phillips (1954).

The joint measurements on Carn Lancs illustrated in Figs. (36/1,2) were combined and analysed graphically as shown in Fig. (42/2). One set of the complementary conjugate shears is represented by the longitudinal joints, and the other more steeply inclined set was created with an average strike of NNW-SSE. Denoting the maximum, intermediate, and minimum principal stress by P_1, P_2 and P_3 respectively, the following results were obtained from the analyses presented as Fig. (42/2) and from an additional analysis (not shown) on a further set of joint measurements:-

P_1 - 128/15 NW P_2 - 176/68 S, P_3 - 43/17 NE, and

P_1 - 126/13 NW P_2 - 177/70 S, P_3 - 40/15 NE.

(N.B. A stress directed in the direction of 145° and plunging to the NW at an inclination of 25° is represented as 145/25 NW.)

This stress distribution resulted in the formation of some tension joints, as shown in Fig. (54), and the dilation of pre-existing joints trending NW-SE in the direction of P_1. The corresponding maxima are apparent in Figs. (36/1,2).

The granite joint pattern at the Castle-an-Dinas Quarry was graphically analysed, as shown in Fig. (42/1), and yielded the following determinations of the principal stresses:

P_1 - 116/18 NW, P_2 - 126/73 SE, P_3 - 27/3 NE

Theoretically, the planes of maximum shear are aligned so that the maximum principal stress, P_1, bisects the angle of 90° between them. Hubbert (1951) demonstrated that in practice this angle is reduced to between 60° and 70° by a factor depending upon the internal friction of

the rock, in which case it becomes equivalent to $(90^{\circ} - \phi)$, with ϕ approximating to the angle of internal friction averaging about 30° to 35°. A correct measurement of ϕ may only be obtained under laboratory conditions since it varies according to the composition, texture, and degree of compaction of the rock.

When the rock undergoing stress is already fractured as a result of previous differently oriented stresses, any estimation of ϕ is rendered very inaccurate. However, two separate estimates of ϕ for the granite were obtained graphically; they were 31° and 35°, which are within the limits that would be expected for such a rock type under ideal conditions.

5/4 Jointing in the Country Rocks

There are two main fold directions in the country rocks of the Pendeen-Botallack area. One trends between NNE-WSW and NNE-SSW with a mean direction of NE-SW, and the other trends approximately NW-SE. Both possess associated longitudinal (crest) and cross-joints, formed in the manner outlined by Badgley (1959) and De Sitter (1956). The economic importance of such fractures was described by Balk (1936) and Wisser (1960). Minor vertical and inclined, diagonal shear joints and other features were most probably formed during the folding stage, and if 2nd order folds were developed they had subordinate related joints.

Better understanding of the major folding would probably allow closer correlation between the joint patterns and the major structures, but at present their relationship is obscure and an account of the jointing must be confined to a description of the distribution and orientation of the major joint patterns.

The longitudinal and cross joints associated with folding before and during granite intrusion were supplemented and complicated by small conjugate shear faults, thrusts, and extensions of the regional granite cross-joints. Examination of the granite contact underground suggests that the longitudinal and local cross-joints probably did not extend into the aureole rocks, but their wide variation in attitude and coincidence in strike with previously developed joints in the country rocks renders their identification impossible out of sight of the contact.

All the aureole rocks in the area have well developed joint systems on every scale. Around Pendeen Watch the denudation of the cliffs is controlled by the fracture pattern which is emphasized both

by the exposed lodes and the joints, the character of the latter being illustrated in Photos. (29) and (30). To the south and throughout the area the effect of major NW-SE joints and lode fissures is apparent in the coast erosion. Zawns are frequently the result of selective undercutting along a pronounced fracture, as exemplified in Photos. (19) and (20). Above Levant Mine a strong jointing is developed in the cliffs as shown in Photo. (5). Within the greenstone series the fractures are often infilled with a variety of minerals, including axinite, actinolite and tourmaline.

The coastline, from the Avarack to De Narrow Zawn, may be divided into five zones in each of which the distribution of joints in the country rocks was measured, the results being shown in Figs. (40/1-5). Two major joint directions are present; one trends between NNE-SSW and ENE-WSW with a mean strike of NE-SW, and the other trends between NNW-SSE and WNW-ESE with a mean of NW-SE.

Reference to Figs. (H) and (40/1) indicates that from the Avarack to Trewellard Zawn there is a greater tendency towards the formation of the ENE-WSW joints, whereas this proclivity is slowly reversed in passing south. The effect is illustrated by Fig. (40/5), which shows the joint patterns developed between Wheal Cock Zawn and De Narrow Zawn where the NNW-SSE joints agree in strike direction with the tin-copper lodes shown in Fig. (H), and with a partly overturned fold along the pathway above the Crowns Engine House.

Joint distributions in the two most northerly and southerly zones were measured separately in the killas and greenstone, as shown in Figs. (35/1) and (35/2). Between the Avarack and Trewellard Zawn the killas

and sheared pillow lavas of the greenstone series possess two major joint patterns which are common to each rock type. Steep NW-SE joints dipping on either side of the vertical possess maxima of 110/78 SW and 135/87 SW in the greenstone and killas respectively. A major set of SE-dipping joints trends approximately NE-SW with maxima of 64/62 SE and 57/60 SE.

In addition to the wide spread of joints which is common to both rocks, the greenstone possesses a major set of ENE-WSW joints, with a maximum of 77/85 NW, which is sntirely unrepresented in the killas. There is, therefore, a marked localized variation in the joint and fracture formation between the killas and the greenstone series. The extra set of joints in the greenstone is unrelated in orientation to any of the tin-copper lodes, as shown in Fig. (H).

The joint distribution between De Narrow Zawn and Zawn a Bal for the greenstone hornfelses and killas is shown by Figs. (35/3) and (35/4) respectively. Both rock types, in common with those in the Avarack-Trewellard Zawn area, possess a major SE-dipping joint system with maxima of 61/66 SE and 75/62 SE for the greenstone and killas respectively. Although the NW-SE joints are not represented to the same extent as in the northern area there is again a marked difference between the joint patterns developed in the killas and the greenstone.

No dykes associated with the granite are visible in the northern half of the Pendeen-Botallack area. To the south there is a tendency for narrow, fine-grained granite and aplite dykes with a variable dip and a width of only a few inches to be developed along WNW-ESE and W-E directions - approximately normal to the granite contact.

Barclay (1959) measured the joint distribution in the country rocks from Pendeen to Kenidjack and recognized the development of the SE-dipping, NE-SW joints in the killas and greenstone. By measuring the parting and flat-lying joints he demonstrated the prevailing NE-SW strike and the dip of 20° to 30° to the NW of the aureole rocks.

Fig. (35/5) indicates the distribution throughout the Pendeen-Botallack area of selected joints which have been subjected to a slight amount of movement and infilling. Whereas the NW-SE joints were dislocated and enlarged, the SE-dipping, NE-SW joint set was relatively unaffected. Displacements along pre-existing joints, and the creation of new fractures, during the granite consolidation stage are evident. The resurgence of stress after the completion of consolidation resulted in the partial formation of a system of conjugate shear joints, which are more perfectly developed as secondary joints in the granite. This conjugate system, and its localized variable and partial development, yielded a wide spread of joints in the NW-SE direction.

Graphical determinations of the resurgent principal stress orientation, resulting in the formation of conjugate shear joints in the country rocks, may be made either from a large number of joint mesurements taken throughout the whole area or from the selective measurement of a small number made in a restricted area. All the joints measured and presented in the form of Figs. (35/1-5) and (40/1-5) were combined by the present writer and analysed as shown in Fig. (42/3). This resulted in the determination of the three principal stresses as follows -

P_1 - 118/28 NW, P_2 - 155/56 SE, P_3 - 38/18 NE.

The above results, together with those obtained by the analyses of

selected joint measurements over small areas, are summarized in Fig. (45/2). Comparison may be made with the results of stress distribution determinations on the secondary granite joints, shown in Fig. (45/3). Similar determinations of the stress orientation in the country rocks during the folding and granite intrusion stage are illustrated in Fig. (45/1).

Certain general comparisons may be made between the joint patterns in the granite and aureole rocks, each possessing a major system which trends approximately NE-SW and dips to the SE. Those in the country rocks may represent extensions of the regional cross-joints of the granite, which decrease in dip in passing to the NW. The local cross-joints or longitudinal joints in the granite do not extend into the aureole rocks. Secondary joints, resulting from the same stress distribution, and contemporaneous with those in the granite are developed to a lesser extent in the country rocks. In the latter there is a wider spread of NW-SE joints and fractures which are unclassified on the basis of their origin but provide a broad continuation to the longidudinal and secondary joints in the granite. The general SW dip of the jointsis maintained with greater local variations.

5/5 Summary of the Pre-Mineralization Structures

The structures in the Pendeen-Botallack area before the tectonic stages leading to mineralization did not greatly differ, from those of the present day. Lying on the NW flank of the main NE-SW trending Land's End Granite crest, the area is divided by the axis of a major NW-SE trending crest, the limits of which lie approximately at Morvah and at a point to the South of Cape Cornwall.

Each of these two main features is supplemented respectively by additional NE- and NW-trending crests on the surface. Where the granite surface plunges steeply to the NW under the aureole rocks the subsidiary NW-trending crests are visible as oriented undulations, as shown in Figs. (H), (21) and (116). Further inland, where the now-eroded granite surface flattened they were probably more pronounced and are now partially reflected by the present day topography. Similarly, the subsidiary NE-trending crests on the steeply plunging granite surface, appear as slight steps, as shown in Figs. (11), (23) and (113). Inland they probably resulted in alternate steep and gradual slopes on the NW flank of the Granite.

With a strike of between ENE-WSW and NNE-SSW, the country rocks dip off the granite flank at about 30° to the NW. Their attitude is moulded to a certain extent upon the granite surface and they were probably arched considerably, as shown in Fig. (115), during intrusion of the granite. Minor folds in the aureole rocks trend approximately NE-SW and NW-SE.

In examining the Geevor Mine area it is convenient to consider separately the joints in the granite and those in the country rocks.

In the granite the major joint systems, and their characteristics, are as follows:-

(a) Local cross-joints trend NNE-SSW and dip at 50° to 85° SE. They are quite common, moderately well developed, have a variable strike and dip, and often contain dykes.

(b) Regional cross-joints trend NE-SW and dip at about 80° SE. They are few in number, but are very well developed and constant in dip and strike.

(c) Longitudinal joints trend approximately ESE-WNW and dip at 60° to 80° SW. They are very numerous, well formed, and characteristically better developed near the granite contact.

(d) There are two complementary sets of secondary joints; one trends ESE WNW and dips at 50° to 90° SW, while the other trends NNE-SSW and has a high dip to the SW or NE. Both sets are numerous and well developed.

Within the country rocks the main joint systems are as follows:-

(a) A major set trends between NE-SW and ENE-WSW with a fairly constant dip of 60° to 65° SE; these joints are well developed but are not the most abundant ones.

(b) A dominant NW-SE set of joints dips on either side of the vertical, but mainly to the SW. This set is supplemented by a plexus of joints of different origins, trending between NNW-SSE and WNW-SSE with variable dip directions and marked local variations in their intensity of development.

5/6 Mineralization

"Many of the mining districts of Cornwall afford more employment, and yield greater mineral riches than that of Saint Just; but in its well-displayed junctions of granite and slate, its veins of granite, of rare and curious earthy minerals, and of metallic ores, its widely and singularly situated mines, and its bold and romantic cliffs, it is surpassed by none of them in interest and importance."

.....Henwood (1843)

(a) Introduction

The general mineralization characteristics of the St. Just district, of which the Pendeen-Botallack area is a part, have been described in a previous section. Since the only accessible workings in the latter area are those of Geevor Tin Mine it is impossible to supplement the descriptive information regarding the mineralization, beyond that already supplied by Henwood (1843), Reid & Flett (1907), Collins (1912) and Dines (1956), and by the additional papers and reports listed in the References and previously summarized in Section 4/2.

The locations of the St. Just mining setts in 1863 are shown in Fig. (13) which diagrammatically indicates the position of the major known lodes. They are shown in greater detail in Fig. (E) which is a reproduction of a map by Symons (1857), and Fig. (11) shows the position of the lodes of the St. Just district as they were known and mapped by the Geological Survey at the beginning of the 20th century.

Fig. (D), a copy of an undated prospectus illustration, indicates the lodes and setts of the northern half of the Pendeen-Botallack area, parts of which are also shown in Figs. (16A) and (C). The inferred position and lateral extension of many of the lodes was slightly imaginative and some were no

more than isolated outcrops graphically extended along the line of strike. However, the history of Geevor Tin Mines Ltd., has demonstrated that even if the reputed location and extent of the lodes were somewhat fictitious, their representation on these ancient plans does indicate the existence of major lodes, not necessarily identical to those shown, in the immediate vicinity.

Underground workings, of which reasonably detailed plans are available, are indicated in Fig. (H). A discrepancy is immediately evident between the lodes accurately located, especially in extent, by the surveyed workings and those illustrated diagrammatically in the older plans. This applies not only to the Geevor and North Levant Mines setts but especially to the area N.E. of Geevor Mine. Many of these unconfirmed lodes, which are more prevalent in the inland areas, were developed along, and possibly above, the adit levels only, the workings being classified as old and discussed long before 1900.

(b) Individual Mines

The Northern limit of the Pendeen-Botallack area is defined by the Pendeen Great Lode, depicted in Fig. (D), which was encountered in the workings of the Pendeen Consols Mine, shown in Fig. (26). Only the Southern workings, which were on a North-South tin-copper lode, are shown in Fig. (H). They extend southwards through the area of Hodgsonia (or Main) Shaft and Stewart's (or Steuart) Shaft into the Boscaswell sett where most of the development was concentrated, as shown in Fig. (H), upon the Main Lode, which actually consists of at least two or three structurally individual lodes. A certain lack of agreement, probably resulting from different dates of construction, is evident between the longitudinal section of the Main Lode shown in Fig. (87) and the detailed mine plan shown in Fig. (I), especially

over the deeper workings in the vicinity of Treweek's Shaft.

An additional undated plan, presented as Fig. (15), indicates numerous lodes, some of which are shown in Fig. (D). A large number undoubtedly exist in this extensive sett, although they are localized in Fig. (H) merely from the position of several ventilation shafts and isolated workings. Development on the line of the Boscaswell Main Lode extended S.W. as Wheal Powell into the area shown in Fig. (E). To the north of the latter the reputed S.E. extensions of the Bridgework and Bill Lodes, previously developed from the Boscaswell Guide north of the Boscaswell Main Lode, were exploited in Wheal Hearle, which attained a depth of 120 fms.

The area to the south of the Boscaswell Main Lode is occupied by Geevor Mine, the workings (1961) of which are shown in greater detail in Fig. (G). Development commenced from Carn Shaft and extended to the West via Wethered Shaft, as shown in Figs. (16) and (J). Workings in the adjacent North Levant Mine, which is now included in the Geevor sett, are shown in detail in Fig. (F), and longitudinal sections through some of the lodes are provided in Figs. (86A) and (86B).

To the West of Geevor Mine and extending beneath the sea for one mile, as shown in Fig. (H), are the workings of Levant Mine, the history and main lodes of which were described by Reid & Flett (1907), Oats (1920) and Dines (1956). Its Eastern section is in two parts. That to the north consists of substantial driving on the Levant North Lode which now extends, as shown in Figs. (H) and (23), below the workings of the Geevor No. 2 Branch Lode, with which it is almost certainly equivalent.

The Southern section comprises workings on the South, Old Bal and Boscregan Lodes, and continues via the Guide Lode on the adit and 15 fm. levels,

as indicated in Fig. (24), into the workings of Spearn Consols Mine. Like the Boscaswell Main Lode, and the lodes of Geevor and North Levant Mines, the principal lode of this property is situated entirely in the granite. It differs from the Pendeen Consols Main Lode, which was developed equally within the granite and the killas, and from the lodes of Levant Mine, the economic portions of which were confined almost entirely to the country rocks.

Carnyorth Mine to the South of Spearn Consols Mine, is also wholly in the granite but the mineralized zone in which it was situated was worked in the country rocks to the N.W. at Wheal Cock. This property, together with Crowns and Parknoweth Mines, was eventually incorporated into Botallack Mine, which lies to the south and embraces lodes worked in both the granite and the country rocks. Levant and Botallack Mines, which extend for considerable distances beneath the sea, comprise two of the most famous properties in West Cornwall. A longitudinal section through Botallack Mine and along the Crowns, Wheal Hazard, and Chycornish Lodes, shown in Fig. (25), indicates the Boscawen Diagonal Shaft, the location of which is illustrated in Photo. (6).

With few exceptions most of the mines in the area were abandoned before the opening of the 20th century, the approximate dates of closure, or last major production, of the principal properties being as follows:

Pendeen Consols	- about 1870	) with later unsuccessful attempts
Boscaswell Downs	- about 1875	) to re-open the properties jointly.
East Boscaswell	- about 1875	
Geevor	- still working	
North Levant	- about 1890	
Levant	- 1930, after the man-engine disaster of 1919 rendered the lower levels inaccessible.	
Spearn Consols	- 1878	

Wheal Cock - amalgamated with Botallack Mine 1841) Closed around
Carnyorth Mine - " " " " 1866) the 1890's.
Parknoweth Mine - " " " " 1875)
Crowns Mine -)

An attempt at re-working Botallack Mine, by sinking Allen's shaft, ended unsuccessfully in 1914.

It is significant that during the period around 1875 the price of black tin sank to its lowest figure of £35 per ton.

(c) Regional Mineral Zoning

"The best portions of the veins have, with increasing depth, to be sought for an increasing distance from the shore....."

Warrington Smyth (1864).

Many ancient mining maps of the Pendeen-Botallack area distinguished between tin, tin-copper and copper lodes. This differentiation, although made by Symons (1857), is not evident in Fig. (E) owing to its method of reproduction, but Fig. (C) shows part of Symons' map and the distinction is there apparent. Unfortunately, the lodes are not on comparable horizons and consequently no reliable interpretation of mineral zoning may be made.

When Symons' map was published the relative economic importance of tin and copper was rapidly changing. At the beginning of the 19th century copper was more in demand than tin, whereas in the latter half of the century the position was reversed. What may now be regarded as an economic tin lode with a high copper content, may have been assessed around 1857 as a tin-copper lode or as a copper lode from which tin was obtained as a useful by-product.

The only section through any old mine workings in the area which distinguishes between stopes for tin and copper is that of Pendeen Consols Mine, shown in Fig. (26). The granite contact, the position of which is

not known accurately and hence not indicated, divides the copper stopes in the killas from the tin stopes in the granite.

Old reports and plans indicate a general tendency for the tin and tin-copper lodes to be distributed throughout both the granite and the country rocks, and for the copper lodes to occur only in the latter. Any division between copper and tin ground was normally less well defined than in the case of Pendeen Consols Mine. Certainly the widespread existence of lodes so productive in tin justifies the application of the term 'tin zone' to the whole area in which the lodes were exploited. In many lodes sufficient copper existed to warrant their exploitation for that metal alone without the assistance of tin as a by-product, so that the copper zone appears to be partially superimposed upon the tin zone.

A little lead is reported to have been mined in the vicinity of Pendeen Watch, and Fig. (D) indicates the position of the reputed lead-silver lode on which a small shaft was sunk near the coastline. Other prospectus plans (not reproduced) indicate the existence of additional NW-SE lodes outcropping along the coast between Pendeen Lighthouse and the Averack, but they appear to be devoid of all sulphide mineralization and their exact spatial relationship to the surrounding tin-copper lodes is unknown. Many plans and reports refer to iron lodes which, by comparison with the North Levant Lode in Geevor Mine, featured in Photos. (66) and (68), are equivalent to the guides normally occurring in the granite.

The tin zone may be graphically delineated in section by connecting the respective upper and lower limits of stoping in adjacent lodes. In so doing, however, the following sources of error are ignored:

(a) The lodes may not have been exploited to their full vertical economic extent.

(b) There were variations in cut-off grade for tin stopes in individual mines.

(c) Fluctuations in the market price of tin resulted in changes over the years of the cut-off grade of tin stopes.

(d) Some of the stopes, especially at the top of the zone, may have been for copper alone.

(e) Substantial amounts of copper in the tin stopes may have rendered the lode workable, whereas without copper as a by-product the lode may have been below economic grade.

Dines' (1956) longitudinal section through Levant and Geevor Mines, here brought up to date (1960) and included as Fig. (23), denotes the zone of economic tin mineralization. Its upper and lower limits and its gradual downward inclination to the NW at an angle of about 15° are indicated in Fig. (114). Within this zone both tin and copper were mined, separately or together, from the lodes of Levant Mine, and an example has been recently provided by off-shore work over the '40 Backs' shown in Fig. (142). Here, a rich bunch of copper ore was reputed to have been followed too near the sea-bed, but specimens from the outcrop of the lode at this locality possessed a very high cassiterite content.

This NW zoning is evident throughout the whole of the St. Just district, as demonstrated by the increasing depth of mine workings towards the sea. Another form of widespread zoning results in variations in depth of the zone of economic tin mineralization along a NE-SW line, approximately normal to

the average lode direction. Fig. (19) shows diagrammatically the lodes of the Pendeen-Botallack area, and transverse sections along the lines e-f, c-d and a-b are shown in Figs. (20), (21) and (22) respectively.

Fig. (20) provides a vertical section entirely in the granite through the Stennack Shaft of North Levant Mine. By making the assumptions outlined above and noting that the Wethered and Borehole Lode have now (1962) been developed down to Level 13, with mineralization of the latter most probably being economic on Level 14, a very pronounced arch in the tin zone is defined by the generally SW-dipping lodes. It is significant that the axis of this arch extends through Spearn Consols Mine coincident with the axis of the major NW-SE granite crest.

The same arch effect is depicted in the NE-SW transverse section, shown in Fig. (21), through the Man-Engine Shaft of Levant Mine. Although the line of section distorts the true outline of the granite surface to the NE of Levant Mine, the coincidence between the axis of the arch and that of the NW-SE granite crest to the South of Levant Mine is repeated. Fig. (22) provides a NE-SW section entirely in the country rocks through the Old Submarine Shaft of Levant Mine, and the change in the attitude of the lodes, dipping to both the NE and SW, is apparent. Although the zoning arch is preserved in the country rocks the radius of curvature of its upper and lower limits is decreased. This may partially result from the presence of significant additional copper ore, especially over the centre of the granite arch which, although not visible in this section still appears to exert an influence upon the mineralization, as testified by the cohtinued arched effect.

The zone of economic tin mineralization with its upper and lower limits is further illustrated in Fig. (118). It possesses an average vertical extent

of the order of 1,000 ft. Below the zone the lodes are completely uneconomic, but above they may possess relatively high copper contents despite the paucity of tin.

Sufficient space, hitherto not penetrated by exploratory mine development, as shown in Fig. (23), exists in the country rocks for a copper zone to occur, perhaps separated from the tin zone by one of impoverishment. A tin zone normally underlies a copper zone only when the granite is directly underneath, so that if the tin zone is already proved, as in this case, then a copper zone most probably lies above it. The high copper content of some of the lodes, corroberated by the copper production records of Levant Mine, suggests that a copper zone was telescoped into the tin zone. Inland the entire copper zone, if one existed, is assumed to have been removed by erosion. Future work to the NE of Geevor Mine, where the zone of economic tin mineralization plunges in depth (the permanence of this tendency is uncertain), may yield the answer, since the ground that might be occupied by a copper zone will not have been removed by erosion to the same extent as that which may have overlain Geevor Mine.

(d) Lode Distribution

> "All the more important lodes have a north-westerly course, but there is a good deal of variation both in course and underlie".
>
> ..... Collins (1912).

Although no additional descriptive information regarding the mineralization is provided by the present writer, plotting details of the mine workings enables a more accurate account to be given of the major structural distribution characteristics of the lodes and the guides. Fig. (H) shows in detail the attitude of the lodes, but Fig. (18) is more useful for

deducing their overall features. Like any mine plan, it shows only the lodes which have been discovered in the course of mining operations, but there may be many more undiscovered, especially in the country rocks, which if considered would slightly alter the general characteristics of the area.

The following are the main structural distribution characteristics of the lodes:

(i) Regional Distribution.

(1) The granite surface at sea-level, plunges NW at 10° to 15°, with the country rocks dipping at 30° in the same direction, until it is almost vertical at a depth of about 2,000 feet.

(2) The lodes are distributed equally in plan around the granite contact.

(3) The zone of economic tin mineralization is in the form of a fold with an axis striking NW-SE through Carnyorth and Spearn Consols Mines and plunging at 10° to 20° as shown in Fig. (118), so that the zone presents a subdued replica of the attitude of the granite surface, which is itself dictated by the existence of two main NE-SW and NW-SE trending granite crests.

(4) Lode development is generally terminated in the SE against a line trending NE-SW, and approximately parallel to, and at a distance of 4,000 feet from, the line of outcrop of the granite contact.

(5) Economic mineralization extends for an approximately equal distance on either side of the granite contact.

(ii) Lode Strike

(1) The mean lode strike, NW-SE, is normal to the average for the remainder of West Cornwall.

(2) Although the mean lode strike is NW-SE there is a wide variation between WNW-ESE (and approaching N-S) and NNW-SSE (and approaching E-W).

(3) The WNW-ESE and N-S trending lodes are generally confined to the granite, the lodes in the country rocks being more nearly NW-SE and NNW-SSE in strike.

(iii) Direction of Dip

(1) The average direction of dip of the lodes is shown in Fig. (18). It is apparent that of the lodes in the granite, those striking NW or N of W generally dip NE, whereas those striking S of NW dip SW.

(2) In the country rocks the lodes dip either NE or SW.

(iv) Lode Dip

(1) Variations in the lode dip are shown diagrammatically in Fig. (119). It is clear that of the lodes in the granite, those dipping NE are steep (80°), often vertical, and locally overturn, whereas those dipping SW are never very steep, but may be either relatively flat (65°), or relatively steep (75°).

(2) In the country rocks the lodes are steep, often vertical, and locally overturn.

(vi) Strike Variations

(1) Distinctive curved WNW-ESE lodes are developed in the granite, with a low dip (60°) to the SW. An equal number are convex to the NE or SW, and are situated entirely in the granite, rarely approaching within 500 feet of the contact. Their radius of curvature and other structural features are remarkably constant. Towards the south they possess a slightly steeper dip, but still remain flat in comparison with the other lodes.

(2) There is a tendency for all the lodes to curve to some extent along their strike, convex either to the NE or SW.

(vii) Lode Terminations

(1) Only the steep, NW-striking, NE-dipping lodes tend to be continuous through, and productive on both sides of, the granite contact.

(2) The other lodes in the granite usually cease to be productive before reaching its contact, or immediately upon intersecting it. If they are productive on both sides of it, the economic portions are separated by a zone of impoverishment about 1,000 feet wide which is bisected by the contact.

(3) Neighbouring, WNW-striking, SW-dipping, straight lodes tend to occur more usually within 2,000 feet of the contact and in closely spaced belts bounded between the same limits, which trend NE-SW, e.g., Geevor Mine (West).

(4) Neighbouring, WNW-striking, SW-dipping, curved lodes also tend to be confined between the same limits which trend N-S, e.g., Spearn Consols, Carnyorth, and Botallack (East) Mines.

(5) Neighbouring, NW-SE lodes tend to be confined between the same limits which trend NE-SW, e.g., Geevor Mine (East).

N.B. It is probable that if all the lodes in the area were plotted they would be bounded between sets of limits trending both NE-SW and N-S.

(viii) Lode Pattern

(1) The pattern of lode distribution in the area is complex, but in general it shows a zig-zag form, one limb being formed by the steep, overturning, NW or NNW-striking lodes, and the other by the relatively flat, SW-dipping, WNW-striking lodes.

(2) The WNW-striking, curved lodes appear to beequally well-developed throughout the granite from south to north, and are present on both limbs of the zig-zag pattern.

(3) When variations in strike occur, all the lodes appear to branch one from another.

(e) Guides and Faults

"Besides the lodes proper there are many cross-veins, coursing much more nearly north to south than the lodes. In general these are non-metalliferous when they are known as guides...."

..... Collins (1912).

Of the several guides known to occur in the area, the majority are indicated in Fig. (E). Less attention has been paid to them during the last fifty years than in the previous fifty. Those encountered in 'recent' workings are accurately located in Fig. (H) and are shown diagrammatically in Fig. (120). Two forms of guides are present, occurring separately in the granite and the country rocks. The main structural features of those situated in the granite are as follows:-

(1) The guides usually strike between N-S and NW-SE and dip either W or E with variable inclinations.

(2) Although not apparent in Fig. (120), some guides are reported to be more than 5,000 feet long, although one which is said to have extended more than three miles, may have been composed of several individual guides, each fairly continuous along its strike.

(3) When viewed in plan, the guides gradually change in strike with a sigmoidal form. At the northern and southern ends they usually strike N-S, but for about half a mile in their centre they strike NW-SE.

(4) Continuations along the northern and southern ends of the guides become asymptotic respectively to the granite contact (in plan) and to the NE-SW line which marks the terminations of lode development to the SE.

(5) The guides frequently junction with lodes, especially at the northern limits of the former.

(6) The pattern displayed by the guides in plan becomes confused when one of them meets a lode because it then often assumes the

attitude of the latter and follows it indefinitely.

(7) Examples of the uniting of guides and lodes are provided by the following:-

(i) As the North Levant Lode develops a N-S strike to the north it joins the Footwall Branch Lode of Geevor Mine. To the south in North Levant Mine it was not followed beyond the section possessing a NW-SE strike.

(ii) The Carnyorth Guide joins the Guide Lode to the north of Spearn Consols Mine and continues with it into the Old Bal Lode. To the south of the Nogger Lode in Carnyorth Mine it starts to reassume its N-S strike.

(iii) The Crowns Guide joins the Crowns Lode in Botallack Mine, as shown in Figs. (E) and (11).

(8) If a guide is only partially exposed in underground development and unites permanently with a WNW-ESE lode it gives the impression of being approximately NNW-SSE in strike with the two apparent ends asymptotic to the average lode direction, especially to the lode which the guide follows.

(9) The guides are normally infilled with an average of 3 to 5 feet of quartz, the surrounding wall-rock alteration being usually no more than widespread discolouration and slight kaolinization of the granite.

(10) Because the guides were believed to lead into a lode they were frequently employed as sites for cross-cuts.

Dines (1956) compiled most of the information from the publications of earlier writers concerning the strike and orientation of guides in the country rocks. They are usually about two or three feet wide, with a regular NE-SW strike and steep SE dip, and consist of a strong fissure infilled with quartz and fragments of the surrounding country rock. Little information is available regarding faults in the area, but in general the major faults trend approximately NE-SW and have a high dip.

Fig. (121) diagrammatically illustrates the locations of some of the known guides and major faults, the latter in Geevor Mine. Both features were often employed as sites for exploratory and development cross-cuts, owing to the more easily broken nature of the ground. In Fig. (121) the more important cross-cuts have been indicated, the coincidence in their strike and that of the major faults and some of the guides in the granite and country rocks being quite evident.

LODES OF GEEVOR MINE

"The principal lodes of Geevor consist of a group of narrow interlaced and branching veins, in granite country, with a general NW-SE trend".

..... Dines (1956).

6/1 Introduction

The lodes of Geevor Mine are shown relative to those of the remainder of the Pendeen-Botallack area, in Fig. (H). Lying entirely in the granite they form one limb of the incomplete zig-zag pattern already described. The ground which they occupy forms a zone trending NW-SE, within which the individual lodes display all the variations in strike and attitude that are apparent throughout the whole area.

Confusion may arise in the following discussions if the term 'lode' is not clarified. When used in the mining sense the term normally refers to the total extent over which a lode fissure is finally developed within and outside the limits of economic grade. The present writer employs the term 'lode fissure' when speaking of a lode in the geological sense. For example, although in practice the Wethered Lode may be regarded as expiring around the present Eastern development ends, the Wethered Lode fissure continues for an unknown distance beyond.

Similarly, the term 'lode' is usually employed to denote both the fissure, which may or may not be infilled with economic minerals, and the altered wall-rock. As Dines (1956) demonstrated, the latter

sometimes contains considerable quantities of cassiterite. It may be mined together with the lode, because of its cassiterite content, or because the combined width of the lode fissure and wall-rock is less than the stoping width. When it is necessary to differentiate between the two lode components the term 'lode fissure' will be restricted to the central infilled fracture.

Complications arise from the fact that what is normally regarded as a single continuous lode often comprises two or three individual lode fissures, each possessing its characteristic features of structure and mineralization. For practical purposes this at first sight simplifies planning and day-to-day operations, but it is geologically misleading. The North Pig Lode, shown in plan in Fig. (81), constitutes three or four structurally individual lode fissures, and the continued use of the name results from the uninterrupted lode development from one fissure to the other. Very frequently there was little change in strike, beyond the average usually encountered within an individual lode, when passing from one lode fissure to another; the fissure continuations expected beyond an intersection of lodes were commonly absent or not recognized.

The mean direction of lode dip in Geevor Mine is SW, in common with the dip of other lodes in the area. Some lodes locally reverse their direction of dip, and the two prominent N-S lodes, the Hanging-Wall Branch and Wethered No.2 Branch Lodes (the latter vertical and overturning in parts) dip East.

Fig. (30) shows diagrammatically the distribution of the lodes, which may be classified as follows:-

(1) Major Lodes: 'A', Borehole, 'C', Coronation 'D', Footwall Branch, New, North, North Pig, No. 3 Branch, South Pig, Wethered and Grenfell (not shown due to very recent development, but situated between the 'C' and Wethered No. 2 Branch Lodes) Lodes.

(2) Minor Lodes: Caunter, Hanging-Wall Vein, North-West Branch, No. 1 Branch and No. 1 Lodes.

(3) Older Lodes: Black, Blue, Jumbo and Mundic Lodes, together with the older (developed early in the history of the Mine) lodes in the vicinity of the Victory Shaft.

(4) Major Prospects: Prospect No. 1, No. 2, No. 3, East and South

(5) North-South Lodes: Hanging-Wall Branch and Wethered No. 2 Branch Lodes.

(6) Guides: North Levant Lode.

There are additional ancient lodes in the original Geevor Sett, two drives in the main Level 9 X-cut, and a few other small Prospects such as that between the No. 3 Branch Lode and the Coronation Lode, and between the latter and the 'D' Lode.

As shown in Fig. (48), the lodes may be divided according to their direction of dip. Only those which strike NW-SE, such as the North Pig, Borehole and Grenfell Lodes, dip steeply NE and reverse their direction of dip.

With the exception of the above three lodes, they may be classified, as shown in Fig. (49), according to their average inclination. Together with those of relatively high (70 to 85°) and relatively low dip

(65 to 75°), there are the predominantly curved lodes, common throughout the area, with a dip of 55 to 65° SW. The large variation in the strike of the lodes, demonstrated by Fig. (28), results in frequent intersections, junctions and branches.

6/2

Major Structural Distribution

"Ore is where it is, not purely by chance, but by the result of definite processes which operated under certain conditions within the crust of the earth".

..... Bateman A.M. (1919).

The Geevor Mine area may be divided on geological and structural grounds into three units bounded by the following limits:-

(1) The granite contact in the West.

(2) The Hanging-Wall Branch Lode.

(3) A broad zone N-S through the Western end of the Caunter Lode and the Northern end of the Wethered No. 2 Branch Lode.

(4) A line N-S through Carn Shaft.

Each unit, considered separately, possesses individual structural distribution characteristics.

(a) Western Unit

The Western unit is bounded by the granite contact and the Hanging-Wall Branch Lode in the west and east respectively, and its main features are as follows:-

(1) The predominant lode strike is WNW-ESE.

(2) The only exceptions to the WNW-ESE strike are:

- the North Pig Lode strikes NW-SE over most of its length, but at its junction with the No. 3 Branch Lode it trends N-S, and dips W in contrast to the Wethered No. 2 Branch Lode (North).

- the Western end of the North Lode is very curved in plan and develops an E-W strike before meeting the Footwall Branch Lode, which is also slightly curved.

(3) In comparison with the lodes of the other units, those in the Western unit are, with the exception of the Coronation Lode and the North Lode (West), fairly straight along their whole extent.

(4) All the lodes dip SW and only localized portions of the No. 3 Branch, No. 2 Branch and 'D' Lodes overturn locally.

(5) When the lodes are curved in plan they are convex to either the NE or SW.

(6) The lodes are easily divisible, as shown in Fig. (49), into those possessing a relatively high or low dip.

(7) When viewed in section, as in Fig. (29), there is an alternation from north to south of Lodes of different inclination, in the following manner:-

Prospect No. 2: low dip

No. 3 Branch Lode: high dip

Coronation Lode: low dip

No. 2 Branch Lode: high dip

Footwall Branch Lode: low dip

(8) With the exception of the Coronation, North Pig and North Lodes, the more important ones in the Western unit, such as the No. 3 Branch, No. 2 Branch, Coronation (West), and the Footwall Branch Lodes, are longer than the average for the Mine and vary between 1,500 and 2,000 feet.

(9) The minor lodes vary between 400 and 1,000 feet in length.

(10) Most of them, with the exception of the North, Coronation and North Pig Lodes, are not continuous to the east of the Hanging-Wall Branch Lode. In general:

- the major, flatter lodes, such as the Coronation (West) and North (West) Lodes, are productive both to the east and west of the Hanging-Wall Branch Lode,
- the steeply-dipping, NW-striking North Pig Lode is productive both to the east and west,
- the steep, WNW-ESE lodes are productive only to the west.

(11) Complications arise through:

- the 'A' and 'D' Lodes each occupying different fissures to the east and west of the Hanging-Wall Branch Lode.

(12) The major lodes have been followed for only short distances beyond the granite contact into the country rocks, the mutual structural relationships being shown in Fig. (27).

(b) Eastern Unit

The Eastern unit is bounded to the west by a zone extending N-S through the Wethered No. 2 Branch Lode and the western end of the Caunter Lode, and to the east by a N-S line trending approximately through Carn Shaft. The main features of this unit are as follows:-

(1) The Borehole and North Pig Lodes, and the Prospect South, possess very variable strikes and dip directions over short distances.

(2) The NW-SE striking lodes are represented by the New Lode which dips SW.

(3) Fairly uniform WNW-ESE lodes, common in the Western unit, are represented only by parts of the lodes over short distances.

(4) Very flat-dipping, curved lodes, represented by the Wethered, North (East) and South Pig Lodes, and on a minor scale by the Prospect East, typically possess the lowest lode dips, of 55° to 65°, in the Mine.

(5) The curved lodes are convex in both directions, those in the NE and SW parts of the Mine being convex to the NE and SW respectively. They vary in strike over their full length from nearly E-W to NW-SE, with an average of WNW-ESE, and dip to the SW.

(6) There is the same tendency as in the Western unit for some of the lodes to assume a nearly N-S strike at their lateral extremities. The North Pig Lode swings around at its western end to strike N-S before joining the No. 3 Branch Lode and in the east the Southern Branch develops the same strike to the south of the South Pig Lode.

(7) The average lode length is less than in the Western unit. Separating the North Pig Lode into its integral lode fissures, the mean length is approximately 1,000 to 1,200 feet, with minor lodes and prospects 400 to 500 feet long.

(8) The eastern ends of the Borehole and North Pig Lodes terminate against a N-S line through Carn Shaft.

(9) The predominantly curved lodes terminate in the east against a NE-SW line 300 to 400 feet east of the Wethered Shaft.

(10) The Western limit of the Eastern unit comprises a belt of ground nearly 500 feet wide to the west of a N-S line through Wethered Shaft. Throughout its course there is very evident dislocation of the lodes, producing frequent changes in strike and dip, and the development of several branches. Those most affected are the Coronation, North, and and South Pig Lodes, there being little visible effect upon the North Pig Lode.

(11) Figs. (16), (28) and (J) show the older mine workings in the vicinity of the Wethered Shaft, and the manner in which the Jumbo Lode assumes a N-S strike around the Western limit.

(12) Transverse sections through the Eastern unit, shown in Fig. (29), reveal no immediately apparent uniformity to the pattern of distribution.

(c) Central Unit

The Central unit is bounded between those to the west and east and whereas the latter two units are approximately equal in their NW-SE dimensions the Central unit is only about 800 feet long. Its main features are as follows:-

(1) In common with the Eastern unit the Central one displays a diversity of lode strikes, but in general it is sparsely populated by lodes.

(2) Only three major lodes, the Coronation, North and North Pig Lodes occur in the unit, and each continues into the adjoining units.

(3) Only the Grenfell and North-West Branch Lodes are confined entirely within the Central unit.

(4) Those lodes which are productive in an adjoining unit, either the Western or the Eastern but not in both, and are continuous into the Central unit, such as the Prospect between the 'D' and Coronation Lodes, the 'A' (East), 'C', 'D' (East) and South Pig Lodes, are essentially unproductive in the Central unit.

(5) Transverse sections, provided in Fig. (29), display a tendency towards a pattern of development from north to south as follows:-

'C' Lode - flat, minor producer;
Grenfell Lode - steep, intermediate producer;
Prospect No. 1 - steep, minor producer.
Coronation Lode - flat, major producer;
'D' Lode - steep, minor producer;
'A' Lode - steep, minor producer;
North Lode - flat, major producer;
North Pig Lode - steep, major producer;
South Pig Lode - steep, minor producer.

On a reduced scale, the Geevor Lodes possess the same structural pattern of mineralization as those of the entire Pendeen-Botallack area. The Geevor Mine area is naturally divisible into three units,

within which the lodes are terminated by boundaries which possess two major trends, N-S and NE-SW. Belts of ground with a N-S trend disturb the lode structure. The complexity of the major lode structures and their diversity of strike and dip intensify with increasing distance from the granite contact.

6/3 Major Zoning

The form of major zoning in the Pendeen-Botallack area is maintained in Geevor Mine. Zoning from the SE to the NW is apparent in longitudinal section, as shown in Fig. (23), and is present on a less well defined scale in the individual lodes, as exemplified by the North Pig Lode in Fig. (81) and the South Pig Lode in Fig. (86C). The inclination of the upper and lower limits of economic tin mineralization varies a little with the individual lodes, but is maintained at 10° to 20° to the NW.

Geevor Mine is situated on the NE flank of the arched zone illustrated in Fig. (118), and the increasing depth of the workings to the NE persists as shown in Fig. (117), which provides a transverse section through Wethered Shaft and includes the lodes of North Levant and Boscaswell Mines. Additional transverse sections, presented in Fig. (29), demonstrate the diminishing (at the present stage of development) effect of this zoning towards the NW. In the Eastern and Central units, the upper and lower limits of the zone are inclined, as demonstrated by the sections I-J and E-F in Fig. (29), at an angle of around 20° to the NE.

In the Western unit this effect is absent, as shown by sections A-B and C-D. A section, the line of which is indicated in Fig. (19), through the Man-Engine Shaft of Levant Mine and including the granite contact, is provided by Fig. (116). The Footwall Branch Lode and/or the Hanging-Wall Vein may (1962) be expected to extend from Level 9 to Level 15, and the lowest horizon on which stoping took place on the Old Bal Lode in this section was the 160 fathom level, as shown in

Fig. (24). The lower limit of the zone extends horizontally between levels 14 and 15, and the upper limit, with the exception of the stoping on Boscregan Lode, reflects the attitude of the immediately adjacent granite surface.

Within the tin zone all the Geevor Lodes contain sulphides, and from the 65,000 tons of run-of-mine ore put through the mill annually there is an average yearly production of about 300 tons of sulphide concentrate as flotation residues. These figures provide some indication of the sulphide content of the lodes, if it is borne in mind that the stoping width exceeds the average lode width. Chemical analyses of the residues are provided in Fig. (129).

The common sulphides are pyrite, arsenopyrite, chalcopyrite, chalcocite and bornite, and there are many accessory varieties. They were deposited during several mineralization phases which were separated both in time and space. Although in some lodes there is a tendency towards a pattern of sulphide distribution, especially of arsenopyrite, in the mine as a whole the sulphides are confined to the tin zone. At the upper limit of a fully developed lode both the tin and sulphide content decreases below that of the underlying economic horizons. Zoning of the economic and gangue minerals is discussed in a later section.

6/4 Lode Structure

> "Whatever the 'modus operandi' which has resulted in the concentration of the mineral ores, there can be little doubt that the mineral lodes of Cornwall occupy, in the main, planes of fissure analogous to ordinary faults".
>
> ..... Hill (1902).

(a) Lode Components

MacAlister (1908) provided a broad classification of the predominant Cornish lode structures, distinguishing between:

(1) A fissure or a series of closely spaced fissures, all, or some, of which are infilled.

(2) Alteration of the adjacent wall-rock by impregnation or replacement.

(3) Inclusion of breccia and fragments of wall-rock within the infilled fissure.

A similar division of the major components of the lodes in Geevor and South Crofty Mines was made by Webb (1947) as follows:-

(1) Altered wall-rock, locally known as 'capel'.

(2) The lode material, usually on both sides of the leader, which consists of tourmaline, chlorite and cassiterite and is locally known as 'peach'.

(3) The 'leader' of quartz which may also contain chlorite and tourmaline.

The Geevor lodes comprise the above three components illustrated by Dines (1956) in a generalized section of the North Lode. A fissure is infilled with lode material, often veined by later quartz (leader), and bordered by altered granite wall-rock which sometimes contains

substantial amounts of cassiterite, as shown in Photo. (89). Usually the lodes are far more complex and their character is dictated not only by their structure, but also by the relative extent to which the above components are represented.

Most of the wall-rock alteration preceded the infilling of the lode fissure, and age relationships are indicated by the extent of alteration of wall-rock fragments included in the fissure infilling. The latter may usually be traced to a branch fracture which was simultaneously infilled but is bordered by no alteration of the type shown by the fragments.

The alteration may be divided into well-defined zones and the most intense forms frequently grade imperceptibly into the lode infilling, especially when the latter consists of tourmaline or chlorite. The gradational and often sinuous outline of the boundary between the two forms is shown in Photos. (48) and (80), as opposed to the sharp division, bearing evidence of fracture and movement, which is displayed by the infilling phase. The contrast is illustrated in Photo. (89).

The main varieties of infilling display the following features:

(1) Vein structures, due to a simple infilling of the original lode fissure during the initial stages of mineralization. It is usually displayed by the hydrothermal feldspar and early quartz phases, shown in Photos. (50), (76) and (104/D).

(2) Banded structure, shown in Photos. (59), (60) and (73), which indicates that infilling accompanied, or immediately followed upon, relative movement of the lode fissure walls.

(3) Repeated veining; instead of forming a banded structure

the successive phases of infilling repeatedly produced cross-cutting veins, as shown in Figs. (132 upper) and (137 lower).

(4) Brecciated fragments of the wall-rock and previous infilling material are frozen in the lode infilling. They exist on either a large scale, as shown in Photos. (56), (63), (64), (81) and (82), or on a relatively small scale, as shown in Photos. (45), (79), (88/B), (98), (99) and (105). Often, and more usually in the latter case, the fragments take the form of splinters elongated in the direction of the lode fissure, as shown in Photos. (62), (63), (76), (89), (91/B) and (93/D). Very occasionally their original orientation is evident, but usually they are rotated and far removed from their oroginal source.

(5) Crustified ore, shown in Photos. (66) and (69), indicates pulsational opening of the lode fissure and slow, out-of-phase infilling.

(6) Comb structure, shown in Photos. (58), (109) and (110), indicates opening of the lode fissure and slow, intermittent infilling.

(7) Massive infilling, usually by quartz, as shown in Photos. (69), (80) & (54).

The final structure of the infilling arises from a combination of various processes, and incorporates many of the above forms, as shown in Photos. (54?, (58), (69), (79), & (81) and Figs. (131 lower), (134 upper), (136 upper), (137 lower) & (138 upper).

The leader, which is a common feature of the Geevor lodes, invariably consists of a more or less central vein of quartz, as shown in Photos. (41-47) & (80). It contains accessory amounts of sulphides and other gangue minerals, and varies considerably in width in the different lodes.

Closely situated parallel and branching fractures were selectively opened and infilled at various times during the formation of the lodes, especially during the earlier stages, owing to successive relative movements of the fissure walls and changes in stress distribution. All the lodes provide evidence of several mineralization stages, which are selectively represented in the surrounding fissures. As mineralization progressed the infilling and movement tended to be concentrated increasingly along a central fissure, and to cease abruptly in the parallel fractures, in and near which the earlier wall-rock alteration and economic mineralization was equally concentrated. Examples of such fractures are provided by Photos. (43), (45), (53), (55), (57), (76) & (82).

(b) Lode Displacement

"Many of the lodes and cross-veins are distinct faults".

..... Collins (1912).

In several respects the Geevor lodes (and those of the Pendeen-Botallack area, as far as may be ascertained from the literature) are very different from the lodes of other mining districts, such as the Camborne-Redruth area, in West Cornwall. They are narrower,

generally steeper, and less inclined to be sheeted. The Geevor lodes bear every similarity to the surrounding major joints and differ from them only in the fact that they have been subjected to infilling, wall-rock alteration, and displacement. The majority are normally surrounded by similarly oriented major joints which are identifiable as the primary or secondary granite joints.

Most of the economic phases of mineralization and infilling were accompanied and preceeded by relative movements of the lode fissure walls. Evidence of each stage of activity is testified by the displacement of pre-existing features in the wall-rock, and the brecciation of earlier lode material. Slickensides with a wavelength of $\frac{1}{4}$ to $\frac{1}{2}$ inch are a common feature of the lode walls, although they are not so extensively developed as in some of the Camborne and Redruth mines, where they have been reported to cover, with a uniform plunge, extensive areas of the hanging-wall and footwall.

In the latter area the slickensides indicate predominantly vertical and oblique movement in the lode fissures, but at Geevor Mine they display every possible plunge direction. During most of the movements which accompanied the economic mineralization phases the lode fissures were not open so that slickensides were formed, especially where changes in dip and strike occurred, on the existing walls and on various planes within the lodes. During the earlier stages of mineralization movement of the ground was decreasingly accommodated with time in the parallel fissures. The latter thereby provide an invaluable criterion for recognizing and determining the relative ages of the different mineralization phases.

Slickensides indicate only the latest line of movement in the plane of the lode fissure and associated fractures, some of which were formed during successive stress stages, but the relative displacement and extent of movement may be determined from the amount of dyke dislocation. The major dykes, indicated in Fig. (31), are supplemented by numerous small ones, one to two feet wide, which can be traced between a pair of levels, but rarely from one lode to another unless the drives are closely spaced. When their attitude and faulting is determined they can be used to corroborate the direction of movement indicated by some of the slickensides. They thus define the relative displacement of the lode fissure walls in the final arrested stage at the present day compared with the period of dyke formation. The majority of the total displacements, which comprise unequal component movements, are either vertical or oblique, and vary between 5 and 20 feet. In the Camborne-Redruth area the lodes, which are major sheeted zones several feet wide, are characterized by extensive displacements of the order of 100 feet.

(c) Lode Width

> "A distinction must be noticed between the width of the lode and the width of the lode fissure. In some instances this is the same, in others the fissure is wide while the workable part of the lode of 'paystreak' is much narrower. Again, in other instances the lode fissure is very narrow, while the 'country rock' is impregnated with mineral to a greater or less distance from this fissure. All such workable material would be called the 'lode' by the miner".
>
> ..... Collins (1887).

Any estimate of the average lode width in the Mine depends upon whether it is calculated over the whole finally developed extent of the lodes or only over those portions which are eventually stoped. Towards the development limits the width of a lode usually decreases and the fissure is infilled with only quartz, a little tourmaline and sulphides, and the later non-economic mineralization. The more intense wall-rock alteration diminishes and the lode eventually assumes the appearance of a major joint with a knife-edge fissure along which a little movement may have occurred. The only signs of movement and mineralization are slickensides, kaolinization of the granite and the presence of hematite, as shown in Photos. (77).

The width of the lodes varies from a fraction of an inch to about 6 feet. With the exception of the North Levant Lode, and that part of it which assumes the attitude of the Footwall Branch Lode for a considerable distance to the west of the North Lode, as shown in Fig. (63), the lodes maintain an average width of 18 inches.

A regular strike and dip, or a constant rate of change of the latter features, may normally be correlated with a consistency of lode width. Whereas in the major lodes possessing a uniform attitude, changes in width are relatively gradual and may be forecasted for short distances in advance of the development ends, variations in the width and value of the Borehole lode, for instance, are completely unpredictable.

Even in the structurally most uniform lodes, however, rapid changes are not uncommon, the lode passing from a width of about 3 feet and carrying over 300 ft.lb.SnO_2/ton into one about 2 or 3 inches

wide and carrying only traces of cassiterite. A recent example is provided by the Western Extension of the Borehole Lode.

(d) Lode Branches

> "The extremities of the curves uniting portions of the lode having different bearings frequently form branches, running off into the other lode, these branches are often as rich in tin as the parent lodes".
>
> ..... Collins (1920).

A prominent feature of the Geevor lodes is their tendency to develop branches which make an angle of 20° to 45° in plan. These are often no more than a major fracture, with the same slight wall-rock alteration and diminished infilling as many of the accompanying approximately parallel fissures. Alternatively, many of them have developed into major lodes, as indicated by their nomenclature, which is, however, sometimes misleading regarding their true branching nature. With the exception of the predominantly curved lodes in the Eastern unit, it is noticeable that many of the major lodes which were discovered as branches of a curved portion of a lode are located, regardless of the direction of dip of the latter, on its convex side, either the hanging-wall or the footwall, when viewed in plan.

Less important branches are developed from both walls of the lodes; they possess the same dip direction and approximate inclination, but have a different strike from the lode itself. Examples are provided in Photos. (45), (53), (65) & (67), and by Figs. (51) & (65). Branches with the same strike and direction of dip as the lode, but a different inclination, and known in Cornwall as 'droppers' and 'feeders' are less important.

Subsidiary fissures, with associated wall-rock alteration and some infilling, cross the lodes at an angle usually greater than 45° in plan. Faulting of a fissure by the lode, or vice versa, is common and examples are provided in Photos. (71) and Figs. (58).

The extent of displacement suffered by the branches and crossing fractures is normally less than that incurred by the dykes due partly to the lesser average inclination of the latter.

Many features of the branches and crossing fractures are repeated on a larger scale by the junctions between lodes. The N-S lodes, such as the Hanging-Wall Branch and Nethered No. 2 Branch Lodes, normally make high angle intersections in plan with others of a more normal strike, and small displacements with a horizontal component of the order of 1 to 2 feet are common, as shown in Fig. (57).

N.B. The terms cross, intersection, and junction do not imply any relative age of formation or mineralization.

When the lodes approach each other at angles of about 30° in plan, as is more usual, the strike of one often changes within 10 or 15 feet of the junction so that it finally approaches the other lode at either a larger or smaller angle. Examples of the former case are provided by the junction between the No. 3 Branch and North Pig Lodes, and between the Grenfell and Nethered No. 2 Branch Lodes. A decrease in the angle of intersection is shown by the junctions of the Nethered and Coronation Lodes, illustrated in Fig. (56 upper), and the Coronation and Nethered No. 2 Branch Lodes, shown in Fig. (67). Such strike changes cannot be attributed to drag phenomena arising from displacements.

Frequently the fissure infilling of one lode penetrates that

of the other with which it junctions. Any determination of the apparent relative ages of lodes based on such evidence, as shown in Fig. (56 lower), is unconfirmed and conflicting if the junctions between the same lodes are examined on different mine levels.

Post-mineralization movements resulted in further displacements, and a cursory examination of many of the lode junctions discloses only the total displacement that may have occurred. It is important to distinguish between the individual mineralization phases and to assess the movements, if any, associated with each, rather than to ascertain the overall relative displacement.

The more important lode constituents commonly either increase or decrease rapidly near a juntion with another lode and for a short distance on both sides. In each case, a study of the junctions alone is misleading.

Displacements of one lode by another have always been small and have proved to be of no hindrance in mining operations. If the junctions were productive in the drive they were stoped out in the older workings, and recently the majority of the evidence has been obliterated by the unfortunate siting of raises and boxholes. This is to be regretted since the correct interpretation of lode junctions, viewed against extensive lateral development on both sides, is vital to the determination of the modes of structural control of mineralization. No stope layout should be so inflexible as to prevent the leaving of lode junctions, major branches, crossing fractures and faults in the form of boxhole pillars, since by so doing the evidence which remains may lead indirectly to the finding of further stoping ground merely at the expense of a slightly staggered boxhole layout a short distance.

6/5 Individual Lodes

"When we refer to the plans of our mines as ordinarily kept, and look upon mere ranges of straight lines which record the progress of the workings, it becomes obvious that many of the important phenomena of lodes are totally omitted from them, and that the observant miner alone who has watched their gradual opening is in possession of the details".

..... Warington W. Smyth (1875).

Each Geevor Lode possesses its own immediately recognizable characteristics of structure and mineralogy. Although the individual lodes vary in character throughout their extent it is possible for an experienced official to relate an isolated exposure to a distant lode, or to recognize the source of a specimen brought to the surface as being one lode and no other.

The present writer could present innumerable detailed descriptions of the lodes at various localities, the majority of which have been accessible at some time since 1958. Development is centred unequally throughout the mine and this would result in an incorrect emphasis being placed upon some areas. Because the majority of the lodes are reasonably visible in the back of the drives the present writer visited and mapped selected portions of all the accessible workings from Level 3 to 15.

Before any detailed study may be commenced of either the structural or mineralogical aspects it is essential to obtain an overall appreciation of the individual lode characteristics. Otherwise, to adapt an old adage, one is unable to see the lodes for specimens.

Many features of the mineralization are illustrated by the accompanying figures and photographs, each of which conveys more information than a page of text, and constant references will be made to them in the following brief

description of the individual lodes.

They have already been classified according to their relative extent, production and history and will be considered commencing with the more important group. The location of each, unless stated, is indicated in Fig. (30), and the majority were geographically described by Dines (1956).

(a) Major Lodes

(1) The 'A' Lode

Shown in Fig. (72) in relation to the Hanging-Wall Branch Lode, the 'A' Lode comprises two main lode fissures which are fairly constant in strike and dip. The upper, Western one, with a length of 600 feet, strikes NW-SE and dips SW at a relatively low inclination. The deeper, 900 feet long, Eastern fissure is fairly convex to the NE in plan, and the rate of change of strike gradually increases to the east. It strikes WNW-ESE, dips SW at about 75°, and develops a N-S strike, in line with the North-West Branch Lode, at its eastern extremity before junctioning with the North Lode.

By the standard method illustrated in Fig. (88), the relative displacement of the walls of the 'A' Lode may be evaluated for the lower fissure. It comprises reverse faulting with an overall throw of 5 to 10 feet in either a vertical or oblique direction inclined to the SE, as shown in Fig. (90/G). The absence of any records concerning the upper fissure, coupled with its present inaccessibility, prohibit the determination of any movements.

The 'A' Lode maintains a mean width equal to the average for the whole mine, and consists of a clean fracture subjected to three main phases of mineralization. The first comprised a little reddening and kaolinization of the wall-rock, and was followed by some tourmaline and eventually by later quartz, as shown in Fig. (135).

Displacement was associated with each mineralization phase, and slickensides indicate that the direction of movement accompanying the introduction of quartz was vertical, whereas during the tourmaline infilling phase it was oblique and inclined at about 60° to the SE, coinciding with the plunge of the line of intersection of the 'A' and Hanging-Wall Branch Lodes. For a short distance on either side of, and at the junction with the latter, the 'A' Lode either contains only quartz or simply comprises a major plane of movement with surrounding wall-rock alteration, as shown in Photo. (72). Although, as indicated in Photo. (102/A), a little cassiterite occurs in the quartz, the majority was associated with the earlier tourmaline.

(2) Borehole Lode

With a length, excluding the Western Extension of 1,200 feet, the Borehole Lode is situated in the Eastern unit of the mine. It characterizes the very irregular North Pig and Grenfell Lodes which also possess an overall NW-SE strike, and the typical complexity of the lode is shown in Fig. (51). Sections strike between NNW and WNW, and, as indicated by Fig. (43/7) which shows the poles to planes of the lode at 50 ft. intervals along all the levels, there is no preference for either a NE or SW dip by any particular strike direction. The lode dip varies between 60° SW and 65° NE and there are four major maxima of 123/83 SW, 144/86 SW, 124/84 NE and 142/86 NE.

Four prominent dykes intersected by the Borehole Lode are shown in Fig. (89), but it is impossible to evaluate the direction of overall displacement by the method shown in Fig. (88) unless the lode's integral SW-and NE-dipping sections are considered separately. The substantial evidence of slickensides and the deflections of numerous dykes indicate that the NE-dipping sections

have been subjected to normal faulting through 10 to 15 feet, as shown in Fig. (90/H), the direction of movement being inclined at about 70° to the SE. Similarly, the SW-dipping sections underwent reverse faulting of the same magnitude in the manner indicated by Fig. (104).

Recent (1962) development on Level 13 and earlier driving on Levels 8 and 9 has proved the Western Extension of the Borehole Lode to the west of the line A-A in Fig. (73). This is a different lode fissure, and although possessing an erratic high tin content in common with the Borehole Lode, it should in future be considered separately, otherwise confusion will arise. Present indications are that this fissure, over the area now developed, underwent reverse faulting through 10 to 15 feet.

One of the most characteristic features of the Borehole Lode, which is still being developed in depth, is the highly fluctuating tin content and lode width. Numerous branches develop, especially where the lode changes appreciably in strike and dip.

The lode possesses a characteristic black colour due to a high tourmaline content, the latter arising from both wall-rock replacement, as shown in Photos. (57) & (92), and from infilling with which cassiterite was associated. The major movements preceded some of the wall-rock alteration, other forms of which are kaolinization and the development of earthy hematite, but followed the majority of the tourmalinization and often intense sulphide impregnation of the fissure walls. The infilling was succeeded by a further cassiterite phase shown in Photo. (95).

Pyrite and chalcopyrite, usually more massive than in the other lodes, as illustrated in Photos. (100/A) & (102/B), are common, although late quartz is generally absent.

(3) The 'C' Lode

The 'C' Lode, shown in Fig. (74), occupies a strongly developed regular fissure and has been developed over a total extent of about 1,000 feet. With a WNW-ESE strike and a relatively low SE dip, it possesses a maximum illustrated in Fig. (43/12), of 112/65 SW.

Only a very small amount of stoping has resulted from the extensive driving, and is centred on Levels 12 and 13 around the intersection with the N-S drive in the western end. Slickensides and the displacement of the Main Central Dyke indicate that normal faulting in the plane of the 'C' Lode was essentially vertical through a distance of 10 to 20 feet.

Wall-rock alteration, comprising slight reddening and tourmalinization of the granite, was followed as shown in Fig. (66) by the introduction of quartz which, although banded in the upper levels, tends in the lower horizons to be massive and to include fragments of the wall-rock, as indicated by Photo. (63). This quartz, which is less opaque than usual, is accompanied by a little cassiterite which accumulated as small bunches, whilst some coats quartz crystals in the vughs.

Further dilation of the fissure allowed the introduction of the late massive quartz and jasperoidal hematite characterized by the North Levant Lode and shown in Photo. (110). Recently (1962) an additional quartz-cassiterite mineralization phase, similar to that shown in Photo. (102/C) has been disclosed in Level 13 (East). The 'C' Lode structurally and mineralogically resembles the North Lode, but differs in its lower cassiterite content and the rarity of sulphides.

(4) Coronation Lode

Penetrating the three units of the mine, the Coronation Lode is the most extensive flat-dipping lode and is shown in plan in Fig. (75). It

comprises two major lode fissures, of which that to the west, with a length of 2,000 feet, is the more important. Striking WNW, the latter dips at 60° to 70° SW and junctions with the North Pig and 'D' Lodes. With a slight convexity to the NE, the Western fissure is quite uniform in attitude and is itself composed of two lode fissures which are discernible in Fig. (75). The upper one is continuous from Level 6/7 to 12, from where the lower fissure extends to Level 15. It is noticeable that a N-S line through the western end of the North Lode, near the North Levant Lode, passes through the eastern end of the lower Coronation Lode fissure.

The Eastern fissure is the more complex of the two and is very variable in strike and dip east of its junction with the Wethered Lode. South of the latter the fissure divides the North Lode into two sections and joins the Prospects South and East, shown in Fig. (65), in the vicinity of the Complex Dyke. The two main fissures with maxima of 113/66 SW and 151/69 SW are represented in Fig. (43/3).

Two main periods of movement on the Coronation Lode resulted in an overall normal faulting of about 15 feet in a direction inclined at 60° to 70° SE, as shown in Fig. (90/A), the movement having been of the same order on both the upper and lower Western fissures. That on the Eastern fissure cannot be evaluated, owing to the scarcity of dykes and the lack of records.

The minor structure and form of the Coronation Lode is fairly uniform over short distances. At the junction of the Western and Eastern fissures, the region of which on Level 12 is shown in Fig. (50), many branches are developed, one on Level 8 being the Grenfell Lode.

Wall-rock alteration usually comprises a little reddening and kaolinization of the granite. The majority of the lode, with a high average width,

originated from infilling of the fissure to form banded quartz and tourmaline, as shown in Photos. (59) & (60). Some cassiterite is associated with the tourmaline but the majority is present in the quartz in the form known locally as 'steel tin', and which is representative of a quartz-cassiterite phase illustrated in Photo. (101/C). Some, however, is later than the quartz through it which forms veinlets.

Most mineralization phases in the mine, from occasional wall-rock alteration to late massive quartz infilling, are represented in the Coronation Lode, as shown in Photos. (62) & (80). Accessory amounts of sulphides are present in the central quartz leaders and chlorite is usually associated with the tourmaline.

There are frequent signs of repeated movement in the form of slickensides and the shearing of the granite walls, as shown in a section through the Footwall Branch of the Coronation Lode illustrated in Fig. (134 upper). Although the tin content tends to be fairly sporadic on the Coronation Lode, there are well defined courses and shoots of ore.

(5) The 'D' Lode

The 'D' Lode consists of two lode fissures, the major one which may itself be multiple and the less important fissure, each being confined to the west and east respectively of the Hanging-Wall Branch Lode. The major fissure, with a maxima indicated in Fig. (43/9) of 127/77 SW, strikes WNW, and possesses a relatively high SW dip overturning locally as shown in Fig. (76).

Near the North Pig Lode (West) the 'D' Lode junctions with the Coronation Lode at a very low angle in plan and approximates closely in attitude to the lower Coronation Lode fissure. The major fissure, with a total length of

about 900 feet, has been subjected to reverse faulting through 5 to 10 feet, as indicated in Fig. (90/F).

The lode, on which development has now ceased, is known for its width below the mine average and its 'hard' nature. With well-defined walls which show only a little reddening and kaolinization, the lode suffered sparse quartz infilling. Cassiterite occurs as 'steel tin' and chalcopyrite is abundant, especially on Level 9.

(6) Footwall Branch Lode

The Footwall Branch Lode, which is still being developed, is shown in plan in Fig. (77) and more completely in Text Fig. (3). It was discovered as a branch of the North Lode (West), shown in Fig. (63) and now (1962) extends for an overall distance of over 1,100 feet. Like the other relatively flat lodes of the Western unit it is fairly curved in plan, and with a WNW strike and SW dip it is uniform in attitude over short distances.

Present determinations of the displacement along the Footwall Branch Lode are inconclusive owing to the dearth of dykes, but a preliminary estimate indicates that the lode underwent normal faulting through approximately 10 feet, and numerous slickensides demonstrate that the direction of movement was inclined at 60° to 70° SE.

The predominant form of wall-rock alteration is kaolinization, hematization and discolouration of the granite. Although tourmalinization occurs as shown in Fig. (136), reddening is generally absent, and the mineralization and wall-rock impart an overall characteristic grey colouration to the Footwall Branch Lode. Fine-grained cassiterite is associated with tourmaline, hematite, chlorite, and quartz infilling, with a simple banded appearance to the lode as shown in Photos. (54) & (74).

Evidence of repeated movement is often present in the lode walls as illustrated in Fig. (136 upper), and the Footwall Branch Lode is accompanied over a large extent by the North Levant Lode, shown in Photo. (69).

(7) Grenfell Lode

Although the lateral limits have been located on Levels 8 to 12, the Grenfell Lode, with a length of 800 to 900 feet, has not been completely developed. Workings on Levels 8 and 9 are shown in Figs. (G), and its eastern limit is provided by the Wethered No. 2 Branch Lode. Overall, the lode strikes NW-SE with an inclination in excess of 80° to both the NE and SW, but with many local variations, thereby being structurally similar to the Borehole Lode.

The Grenfell Lode shows every possibility of yielding economic mineralization down to Level 15, and in contrast to the more regular, flat-dipping, major lodes of the mine, the lateral extent of its economic portion is only slightly greater than the vertical extent.

The customary steep dykes, are supplemented by the flat-lying sills shown in Photo. (84), and slickensides indicate that the overall movement on the Grenfell Lode was a downward displacement of the NE wall through 10 feet in a direction inclined at 70° to 80° SE.

The tin content of the lode is fairly erratic but the fluctuations are attributable to structural features, and there is a well defined overall division between the stoping and non-stoping ground. The predominant mineralization phases are those of cassiterite-hematite and cassiterite-quartz, which succeeded the earlier phases common to both the 'C' Lode and parts of the Grenfell Lode, and shown in Photos. (81) & (73).

(8) New Lode

Since the New Lode was exploited early in the history of the mine very few records are available. As shown in Fig. (79), it strikes NNW-SSE and the SW dip varies between relatively steep and flat. With a maximum of 158/75 SW and a subsidiary one of 123/70 SW, as shown in Fig. (43/10), the New Lode shows a major structural similarity to the Coronation Lode (East).

With a total length of about 1,400 feet, the lode is limited in extent between the North Lode and the Southern Branch of the North Pig Lode, junctioning between them with the Northern Branch of the latter. There is an unconfirmed indication that movement on the New Lode comprised normal faulting with a displacement of 5 to 10 feet, as indicated in Fig. (90/D). The fairly narrow lode fissure is usually infilled with tourmaline and quartz as shown in Fig. (58 lower).

(9) North Lode

The North Lode and Coronation Lode are the two major relatively flat, SW-dipping lodes of the mine, and the former, as indicated in Fig. (80), comprises three component lode fissures on all of which major development has now ceased. The Western section, with a nearly E-W strike and a length of about 1,000 feet, was an important producer and extended from Level 4 to 13. It junctions with the Hanging-Wall Branch, North Pig and North Levant Lodes, the western limit being marked by the latter, as shown in Figs. (63) & (64). The overall movement on the Western section comprises normal faulting through about 20 feet, in a direction between vertical and an inclination of 60° SE, as shown in Fig. (90/B).

The line of demarcation of the Western and Central sections is the region of sudden change in lode strike, an example of which is provided in Fig. (54), around the junction with the North-West Branch Lode. If the

latter is projected to the north along a N-S line it intercepts the junction of the Western and Eastern sections of the Coronation Lode. The limit of the 500 feet long central section to the east is marked by the junction with the Coronation Lode. The central section was also subjected to normal faulting through about 10 to 15 feet, in a direction that was either vertical or inclined slightly to the SE.

With a length of about 900 feet, the Eastern section is confined to the east of the Coronation Lode and is otherwise terminated by the NE-SW line marking the end of the Wethered Lode. This section possesses the same major structural characteristics as the latter; convex to the NE, a mean WNW strike, and a relatively low SW dip. Movement on the Eastern section comprised normal faulting with a vertical displacement of 10 feet as shown in Fig. (90/C).

The entire North Lode is plotted in Fig. (43/4) and although there is a wide spread in attitude, the major maximum of 107/62 SW is supplemented by one of 171/59 W.

The Lode consists predominantly of quartz, chlorite and tourmaline, often with later phases of mineralization, as shown in Photo. (58), infilling a strongly developed fissure. Cassiterite is associated with the quartz, tourmaline and chlorite phases, and often occurs in the form of 'steel tin' and as veins in the quartz, which is normally hard and brittle. Wall-rock alteration usually consists of slight reddening, tourmalinization and kaolinization of the granite, and the infilling is characteristically either simply banded or repeatedly veined, in similarity to both the Coronation and Wethered Lodes. Fragments of wall-rock are often included in the quartz infilling as shown in Photo. (64), and are sometimes veined by later quartz,

the abundance of which is a feature of the North Lode.

(10) North Pig Lode

The North Pig Lode, upon which work has now almost ceased, has been stoped, as shown in Fig. (81), for over 3,500 feet and from the shallow adit level in the region of Carn Shaft to Level 14, with additional development on Level 15. The overall strike is NW-SE but, in common with the Borehole Lode, the North Pig Lode locally possesses large variations in attitude. It is shown in plan in Fig. (81) and is divisible into several component lode fissures, each of which bears considerable major structural resemblances to those characterized by the No. 3 Branch, Coronation and Borehole Lodes. The overall correspondence to the latter is indicated by Fig. (43/8) in which the North Pig Lode possesses a major maximum of 129/86 SW and a subsidiary one of 113/84 SW.

Between Carn Shaft and the No. 3 Branch Lode, to the north of which it was not traced, the North Pig Lode junctions from east to west with the South Pig, New, Hanging-Wall Branch, and North Lodes, and the following have developed as branches: No. 1 Branch, No. 2 Branch, No. 3 Branch and North-West Branch Lodes, and the Southern Branch of the North Pig Lode.

Most of the North Pig Lode is completely inaccessible, and with the exception of the very recent workings no records, apart from development samples, are available. Nevertheless, there are indications in the vicinity of the North Lode that the NE wall of the North Pig Lode moved downwards through a distance in excess of 10 feet. This evaluation applies only to the lode fissure in this immediate area and cannot be extended to the remainder of the North Pig Lode.

Even where the older and central workings are accessible the entire lode has been mined, leaving no pillars in the drives. It is subsequently impossible to determine the overall mineralization characteristics and any first hand data is necessarily localized. The lode was apparently quite variable over its whole extent, and was structurally described by Collins (1920) who, together with Mr. H. Grenfell (personal communication), remarked upon the abundance of earthy hematite in the upper levels. Gregory (1925) described the lodes in the Wethered section as generally possessing an infilling of quartz, cassiterite, hematite, pyrite, chalcocite, chlorite, and jasper, but makes no mention of tourmaline. Overall, the lode appears to contain chlorite, quartz and tourmaline, and to be bordered by reddened granite which on occasions becomes intensive, as shown in Photos. (41) and (42). It is characterized in depth (Levels 13-15) by the occurrence of arsenopyrite and feldspar illustrated in Fig. (132 lower) & Photo. (102/D), and the relative absence of quartz.

(11) No. 2 Branch Lode

The No. 2 Branch Lode, approximately 1,500 to 1,600 feet long, was discovered as a branch of the North Pig Lode and extends as shown in Fig. (27) as far west as the granite contact where development ceased. The lode strikes WNW with a relatively high dip to the SW, and locally overturned, as shown in Fig. (83). It is slightly curved in plan and the structural similarity in strike and dip to the 'D' Lode, and in strike to the Coronation and North Lodes, is visible in Fig. (43/2) which indicates a maximum of 116/77 SW.

Movement on the lode consisted of reverse faulting through about 5 feet in a direction that was either vertical or inclined slightly to the SE. In similarity to the Footwall Branch Lode wall-rock alteration comprises

mainly inconsistent kaolinization and heavy discolouration, and only a little reddening of the granite. Cassiterite is often confined to an association with earthy hematite which was a fairly common constituent and occurred as bands in the lode. Tourmaline and chlorite are common and a specimen illustrated in Photo. (103/A) is fairly typical of the No. 2 Branch Lode which was 'soft' and comparable in value to the No. 3 Branch Lode.

(12) No. 3 Branch Lode

Shown in plan in Fig. (84), the No. 3 Branch Lode strikes WNW and possesses a relatively steep SW dip. With a maximum, as shown in Fig. (43/1), of 117/77 SW, it is similar in its major structural characteristics to the No. 2 Branch Lode, but shows less tendency to curve. The lode is confined, with a length of about 2,000 feet, between the granite contact, shown in Fig. (27), and the projection to the north of the Hanging-Wall Branch Lode.

Evidence of the extent of displacement on the No. 3 Branch Lode is slightly conflicting at first sight, especially with respect to the granite contact shown in Fig. (59), but the overall movement comprised reverse faulting through about 5 feet in a direction steeply inclined to the SE.

The lode, on which production has now ceased, is reputed to have been the richest in the mine. This is a correct appraisal if the lode is viewed against development in more recent years, but its main value lay in its consistently high tin content. One of the lode's most characteristic features is the extensive wall-rock alteration, shown in Photos. (48), (88/D) and (90), which usually comprises reddening, tourmalinization, chloritization, and kaolinization. Some alteration is always present, merging into the fissure infilling as shown in Photo (94/B), and often containing substantial quantities of cassiterite as illustrated in Photos. (89) & (93/D). The

No. 3 Branch Lode possessed the lowest fissure-width/lode-width ratio of any of the Geevor lodes.

Where the alteration is most intense, the wall-rock is often impregnated with sulphides as illustrated in Photos. (88/A) and (100/B). Sulphides infilling the fissure, as shown in Photos. (48), (51), & (97/B), are abundant, the most prominent being pyrite, chalcopyrite and chalcocite. Arsenopyrite is common in the lower levels where, as illustrated in Photos. (76) & (105), it is associated with feldspar and tourmaline.

Post-cassiterite mineralization phases, apart from sulphides are not well represented on the No. 3 Branch Lode, and the only significant infilling, apart from calcite, is a narrow quartz leader, often containing amethyst, as shown in Photos. (49), (50), (51), & (52) and Fig. (133). In the killas the lode consists of a narrow irregular fissure shown in Fig. (130).

(13) South Pig Lode

The South Pig Lode was exploited in the early years of the Company between the shallow adit and Level 7 (Wethered), as shown in Fig. (86C), over a total lateral extent of about 3,300 feet. It comprises two main lode fissures to the west and east of the Jumbo Lode which lies on the continuation of the N-S line of dislocation through the Coronation and North Lodes.

The Western section strikes NW-SE with a relatively steep SW dip. The lode, or one of its branches, junctions with the North Pig Lode but is developed between the Hanging-Wall Branch and North Lodes. The Eastern section possesses an average WNW strike and is convex, with a relatively flat dip, to the SW, bearing a close major structural resemblance to the Wethered and North (East) Lodes. This is visible, despite the inclusion of the Western

section, in Fig. (43/6)in which the South Pig Lode possesses a maximum of 115/62 SW.

The lack of records of dyke displacements prevents an evaluation of the relative displacement of the lode walls. According to a first-hand report by Collins (1920) the South Pig Lode generally contained more quartz than the North Pig Lode, both lodes being described as 'tight'. The other main mineral constituents were tourmaline and chlorite with a little reddened granite in the walls.

(14) Wethered Lode

The Wethered Lode is situated in the Eastern unit and development has now (1962) been completed between Levels 6 and 13 and over a total lateral extent of 1,500 feet. With an average WNW strike and a relatively low SW dip, the lode is predominantly convex to the NE, as shown in plan in Fig. (85), and possesses a maximum in Fig. (43/5) of 121/57 SW.

Slickensides are common on the Wethered Lode which displaces several dykes, the most prominent of which branches as shown in Fig. (88). All the displacements indicate normal faulting in the Wethered Lode through a vertical distance of about 10 feet.

Most of the lode resulted from the infilling of a single well-defined fissure accompanied by a very slight tourmalinization, kaolinization and discolouration of the wall-rock, and hence the lode width is usually equivalent to the fissure width. Downward movement of the hanging-wall accompanied many of the mineralization phases and the mean fissure width on different levels may be employed, as outlined by Emmons (1943) and illustrated in Fig. (104), to determine the relative displacement of the walls. Numerous

calculations by this method confirm the results obtained from the analysis of the dyke deflections.

All the forms of veining, brecciation, and banding, as shown in Photo. (79) and Figs. (137 lower) & (138), are illustrated by the infilling of the Wethered lode fissure. Cassiterite is mainly associated with tourmaline and chlorite, as indicated in Photos. (101/A), (104/B) & (104/F) respectively, and quite often with earthy hematite.

Continued vertical movements caused the introduction of increasing amounts of quartz, with which pyrite, chalcopyrite and chalcocite are associated. Sphalerite is common and typically occurs in the forms shown in Photos. (61), (101/B), & (103/B). The lode is noted for the wide variety of late mineral assemblages which include calcite, siderite shown in Photo. (108/D), numerous varieties of quartz, chalcedony, amethyst, and jasper as illustrated in Photo. (109). Minor amounts of opal have been observed by the present writer.

(b) Minor Lodes

(1) Caunter Lode

Shown in Fig. (30), the Caunter Lode is situated near Wethered Shaft, and because it was worked in the early years of the Company it is almost completely inaccessible. About 500 feet long, it is slightly convex with a relatively flat SW dip. The lode strikes parallel to the South Pig Lode, and, as Gregory (1952) remarked, it is caunter only in name. The latter term could equally be applied to all the Geevor lodes with respect to both the remainder of West Cornwall and to one another.

The Caunter Lode, shown in detail in Figs. (16) & (J), is terminated to the west against the N-S striking Jumbo Lode, on the other side of which the Blue and Black Lodes were developed. No records are available but the

lode was known as a hazardous one due to the 'rotten' nature of the wall-rock. In one exposure it consists of heavily hematized granite traversed by stringers of quartz and tourmaline. On Level 6 there is a central quartz leader containing numerous vugs and bordered on both the footwall and hanging-wall by wide belts of kaolinized granite.

(2) Hanging-Wall Vein

The Hanging-Wall Vein was recently discovered as a branch of the Footwall Branch Lode and has now (1962) been developed for a distance of about 400 feet. The relatively flat SW dip of the Footwall Branch Lode is maintained but the strike is more inclined to the west, as shown in Text Fig. (3).

Insufficient dykes, branches and other features have so far been disclosed to permit an accurate determination of the relative overall movement of the lode walls, but there is every indication that normal faulting has occurred.

The Vein is fairly narrow and includes either hematization of the wall-rock shown in Photo. (55) or tourmalinization and greisenization, as shown in Photo. (56). The value is due to a cassiterite-quartz phase shown in Photo. (101/C).

(3) North-West Branch Lode

The North-West Branch Lode was, as the name implies, discovered as a branch of the North Pig Lode, and with a length of about 300 feet is confined between the latter and North Lode. It strikes NW-SE with a relatively high NE dip, and is illustrated in plan in Fig. (82). The Lode is now inaccessible and no records are available. It appears to be a direct continuation of the North Pig Lode fissure to the east, and at its northern end it tends to develop a N-S strike, especially on Level 8. As shown in Fig. (G), it forms a strike continuation in the north to parts of the

Coronation (East) Lode to the west of the Wethered Lode.

(4) No. 1 Lode.

Illustrated in Fig. (70), the No. 1 Lode, is situated between the No. 2 Branch and Footwall Branch Lodes, extending a little to the NE of the former. With a relatively low SW dip it strikes WNW and has been developed over a total distance of about 700 feet. Level development has now ceased and there is insufficient evidence for an evaluation of any possible relative movement of the lode walls.

Mineralogically the lode is very similar to the adjacent lower levels of the No. 2 Branch Lode and contains, as illustrated in Photo. (98), tourmaline, feldspar, arsenopyrite, and later chlorite and cassiterite.

(5) No. 1 Branch Lode

The No. 1 Branch Lode, now inaccessible, was discovered as a branch of the North Pig Lode and is about 400 feet long. Shown in Fig. (82), it strikes WNW with a relatively high SW dip, and although it bears a marked structural similarity to the North Pig and No. 2 Branch Lodes it contains quartz in contrast to the latter. With a high tourmaline content the lode contains a lot of chalcocite and the wall-rock alteration consists of a little reddened granite.

(c) Major Prospects

(1) Prospects East and South

By development to the east on the Coronation Lode the Prospects East and South were discovered, as indicated in Figs. (53) and (65).

The Prospect East, shown in Fig. (70), structurally resembles the 'A' Lode to the east of the Hanging-Wall Branch Lode, striking WNW with a

relatively steep SW dip. It has similarly undergone normal faulting through about 5 feet, and has been developed over nearly 400 feet.

The Prospect South, developed over approximately 800 feet, strikes NW-SE with a relatively steep dip, and locally overturns. Unlike the North-West Branch Lode, which it structurally resembles, the relative movements of the lode walls may be evaluated and constitute normal faulting of the same extent as the Prospect East, with which it is complimentary. Mineralogical details of both Prospects are available from Fig. (65).

(2) Prospect No. 1

The Prospect No. 1, which has been developed on two levels for over 900 feet overall, is located as indicated in Fig. (30), and is shown in plan in Fig. (71). With a NW-SE strike, it dips at between 75° and 85° SW and is convex in the same direction.

The displacement of the main central dyke indicates that either reverse faulting through about 5 feet or no relative movement has occurred in the Prospect. Seldom exceeding one foot in width, the fissure is infilled with tourmaline and quartz, and surrounded by a little reddened and kaolinized granite, as shown in Photo. (71) and Fig. (58 upper).

(3) Prospects No's 2 and 3

The Prospects No. 2 and No. 3 are situated to the north of the No. 3 Branch Lode and, as shown in Fig. (9), were developed only on Level 11. Both strike WNW, and whilst the Prospect No. 2 dips at about 65° SW the other is relatively steep. Both structurally resemble the Prospect No. 1 further to the east.

The Prospects, which are very similar, are typically rich in tourmaline and are illustrated in Fig. (131). To the west the Prospect No. 2 was traced

into the killas for a short distance but was not located further west in the x-cut on Level 11 from the No. 3 Branch Lode. Only one dyke crosses the Prespect No. 3 and indicates little relative movement of the fissure walls.

(d) North-South Lodes

(1) Hanging-Wall Branch Lode

The Hanging-Wall Branch Lode, shown in Figs. (52) & (78), was so named owing to its location in the upper levels on the hanging-wall of the main central dyke, as shown in Fig. (52). From a point to the south of the South Pig Lode it has been followed north for 800 feet, junctioning with the South Pig, North Pig, North, 'A' and 'D' Lodes. With a N-S strike it dips east and, as shown in Fig. (43/11), possesses a maximum of 174/70 E. Although the lode was partially stoped, as shown in Fig. (78), it was advantageously employed as a x-cut to the north.

There are numerous planes of shear and signs of mainly vertical movement in the Hanging-Wall Branch Lode. The only evidence, preserved in the form of junctions between the Hanging-Wall Branch Lode and the 'A' and 'D' Lodes which are shown in Figs. (57) & (72), indicates downward relative movement of the hanging-wall through a distance in excess of 5 feet and in a direction inclined to the south at about 80°. Dines observed, however, that the Hanging-Wall Branch Lode, displaces the South Pig Lode in such a manner that reverse movement through an indeterminate amount is indicated.

Where it is not stoped out and is accessible between the North and 'D' Lodes on the lower levels, the Hanging-Wall Branch Lode consists of two or three inches of quartz with occasional tourmaline and a very small amount of jasperoidal hematite. Variable wall-rock alteration comprises discolouration and slight reddening of the surrounding granite.

(2) Wethered No. 2 Branch Lode

The location of the Wethered No. 2 Branch Lode, shown in Fig. (71), is indicated in Fig. (30). With a very variable strike approximating towards N-S in the northern half, the lode varies in dip direction between east and west with an inclination always greater than 80°. Although differing structurally from the Hanging-Wall Branch Lode, it resembles the latter in the small amount of stoping ground.

As a result of the strike of this lode, in which specular hematite is common, it intersects very few dykes, but preliminary measurements indicate that the eastern side probably descended through an indeterminate distance. The relationship of the Wethered No. 2 Branch Lode to the Wethered Lode is shown in Fig. (56 lower).

(e) Guides

As the only major guide in the mine, the North Levant Lode, illustrated in Photos. (66) & (67), junctions with the North and Footwall Branch Lodes as shown in Fig. (63) & (64). It continues to the west and assumes the attitude of the Footwall Branch Lode, as shown in Fig. (63) and Photo. (69), for about 500 feet. Striking NW-SE, it meets the No. 2 Branch Lode where it has been observed on Level 12, as shown in Fig. (102). By following a N-S course the North Levant Lode eventually junctions with the No. 3 Branch Lode whence it reassumes a NW-SE strike.

The North Levant Lode dextrally displaces both the North and No. 2 Branch Lodes for a few feet, but merely penetrates the No. 3 Branch Lode without inflicting horizontal displacement.

The mineralogical and minor structural character of the North Levant Lode, which contains only trace amounts of cassiterite, is apparent from

the above Photos. There is no measureable relative movement of the lode walls and opening appears to have resulted entirely from their simple intermittent separation.

6/6 Faults.

Faults are common in the mine and with horizontal displacements of about two or three feet and a maximum of 10 feet, they may be grouped as follows:- (a) major faults, (b) fault zones, and (c) minor faults.

(a) Major Faults

Six major faults, shown in Fig. (103), occur in the mine and the two most prominent, F_2 and F_5, are indicated in relation to the dykes in Fig. (31). They possess a very regular NE-SW strike, a high SE dip, and are continuous in both the granite and the killas for at least 1,000 feet, over which distance they display variations in the extent and direction of displacement of the lodes.

Their major structural form is indicated by plotting the poles to the planes of the faults, as shown in Fig. (38/1), indicating a maximum of 34/71 SW. Some of the major faults consist of a zone about 30 feet wide in which three or four major fissures possess the same attitude and collectively displace the lodes. Occasionally some, which would otherwise be classified as 'major', tend to strike more N-S and an example from Level 13 of the No. 3 Branch Lode is indicated in Fig. (62).

F_1, shown in Fig. (103), may be traced through the No. 3 Branch Lode, and with less certainty, through the No. 2 Branch Lode. From the Prospect No. 2, F_2 may be traced through the No. 3 Branch, Coronation, No. 2 Branch and Footwall Branch Lodes as far as the Hanging-Wall Vein, but whereas F_3 is in evidence on the No. 2 Branch, No. 3 Branch and No. 1 Lodes, its presence is not indicated on the Coronation and Footwall Branch Lodes.

To the East, F_5 is continuous through the Borehole, Wethered and North Lodes and through the Prospects East and South, as shown in Fig. (53). F_6 is present on the Borehole, Wethered and North Lodes, but may be identified with less certainty on the Prospects East and South. There are no records concerning the North Pig, South Pig, and other Lodes to the south through which F_5 and F_6 might be expected to continue.

A selection of the lode-fault intersections is provided in Figs. (61) and (62). In the western unit of the mine F_1, F_2 and F_3 produce an overall sinistral displacement of the lodes through 5 to 10 feet with occasional very slight drag effects. Sometimes there is a pronounced bending of the lode, usually more prominent on the western side for about 200 feet, which cannot be accounted for by drag effects. This curvature is less pronounced in the vicinity of F_5 and F_6 which have exerted a small dextral deflection upon the lodes.

The direction of relative displacement by the faults, indicated by often highly developed slickensides on the planes of movement, is essentially horizontal. Usually the surrounding granite for several feet is heavily discoloured and/or kaolinized and the fault contains, apart from a little quartz, tourmaline, traces of cassiterite and other minerals occurring in the lode, substantial amounts of calcite and quartz which, from their microscopic examination, appear to have been introduced during and after the main horizontal movements.

Slickensides in the faults indicate not only a horizontal movement, but also an earlier vertical displacement, the evidence of which has been almost completely erased by successive reactivation. Each movement in the faults initiated subsidiary fractures along which a slight displacement, often

undisturbed by later movements, occurred. As successive displacements in the lode fissures gradually became confined to a central fissure, so the later horizontal movements in the faults became concentrated into less planes than the earlier vertical displacements.

Although the identity of an individual lode is recognizable on either side of a major fault, there are significant differences, not so much in the width, but in the mineralogy of the lode on each side.

(b) Fault Zones

> "About 270 feet to the West of the Wethered Shaft a nearly vertical 'guide' or group of 'guides' runs through the country with a course about 5° to 10° to the E of N (Magnetic); .... This is not however a simple cross-course, but apparently consists of a sort of shear-zone traversing the country ...."
>
> .... Collins (1920).

There are two major fault zones in the mine, each about 200 feet wide and containing numerous minor faults. The two most continuous are FZ_1 and FZ_2, the positions of which are indicated in Fig. (103), and with a N-S strike they may be traced over a lesser distance than the major faults. Within each zone minor faults strike between N-S and NE-SW with large local variations and different directions of dip. Some appear to be no more than enlarged joints along which movement has taken place but others are inconsistent with the prevailing joint direction. The dip of the zones is not easily discerned but is most probably towards the east, and the extent of their formation is more variable than that of the major faults.

The western fault zone FZ_1 has been disclosed, as shown in Fig. (64), on Level 12 at the western end of the North Lode from whence it may be traced with diminishing intensity through the Footwall Branch Lode. It is present in the Lodes to the north as a few crossing fractures causing no apparent

displacement or as a zone of slight dislocation of the lode fissure surrounded by heavy kaolinization of the granite as, for instance, on the No. 3 Branch Lode.

For details regarding the other major fault zone, FZ_2, one is more dependant upon the accounts of Collins (1920) and Leggett (1920), on which subject the latter write:

> "Going West of the Shaft (Wethered) on the 6th and 7th levels, there is a zone of 'shrinkage and shear joints'...."

FZ_2 is also apparently characterized by a zone in which movement, mainly horizontal, has occurred along pre-existing joints. In similarity with the major faults, there is evidence in the zones of both vertical and horizontal movement in the plane of the individual faults, and although attended by considerable doubt, there is an indication that the vertical displacements were the earliest. Where there is substantial faulting the lodes often exhibit pronounced changes in their minor structure and mineralogy, especially between the more prominent faults, in an individual fault zone.

Despite their continuity throughout the mine with an individually constant strike and dip, the effect of the major faults and fault zones upon the lodes differs. The horizontal displacements exerted upon the lodes are inconsistent in direction and extent, not only from one fault to another but also on different lodes along the same fault. For instance, one lode may be sinistrally displaced for several feet by a major fault, whilst an adjacent, similarly disposed, lode along the strike of the same fault may be displaced only a few inches and sometimes in the opposite direction. This more often occurs in the case of the major faults, F_5 and F_6, occurring in the Eastern unit of the mine. Individual faults in the fault zones cannot be correlated between neighbouring lodes, even over distances of the order of 100 feet, or from one level to

another on the same lode.

(c) Minor Faults

Minor faults are numerous, and with maximum displacements of 2 feet they do not usually fault the lode out of the drive if it is being maintained in the centre of the development face.

The direction of movement on the minor faults is determined by slickensides which indicate only post-mineralization displacement in a predominantly horizontal direction, with very few signs of re-activation. They are distributed equally throughout the mine and their orientation is indicated in Fig. (38/2). Unconnected with the granite joints, they strike NE-SW and NW-SE, as demonstrated by the maxima of 64/76 SE and 159/74 SW, and are respectively divisible into sinistral and dextral faults. There is no apparent change in either the minor structure of mineralogy of the lodes in the vicinity of these faults which usually contain a little gouge, earthy hematite and calcite.

(d) Lode-Fault Relationships

There are many structural relationships between the lodes and the various forms of faulting, and considering each group separately:-

The major faults:

(1) are concentrated towards the two limits of the mine; three in the west and two in the east.

(2) in the west are more strongly developed and more composite in nature than those in the east along which movement tends to have been concentrated in one main fissure.

(3) would normally be classified as post-mineralization in age with a predominant horizontal displacement, but detailed studies indicate that this movement was preceded by an earlier displacement which

itself presaged and/or accompanied the economic mineralization phases.

(4) frequently coincide with the line of termination of parallel, neighbouring, WNW-striking and curved lodes such as the No. 3 Branch, Coronation and No. 2 Branch Lodes in the west, and the Wethered and North (East) Lodes in the east. If F_5 and F_6 are projected to the south they mark the lines of termination of the Caunter, New and Mundic Lodes.

(5) often coincide in plan with a region of change in the major structure of the lodes; such as a junction between two lode fissures which are collectively known as one lode.

(6) appear to bear no such relation, as detailed above, with the North Pig and Borehole Lodes.

The fault zones:

(1) approximately divide the mine into three equal areas in plan and bear no distribution relationship to the major faults.

(2) often coincide with the lines of termination of some of the lodes. For example, FZ_1 is thus related to the North (West), No. 1 Branch, 'D', and North Pig Lodes, which may be classed either as the relatively steep, SW-dipping lodes or those possessing a marked deviation in strike at their western ends. Similarly, FZ_2 coincides with the line of termination of the Wethered (West) and New (North) lodes, and with the junction between the Central and Eastern sections of the North Lode and with that between two separate lode fissures of the North Pig Lode. It should be noted that the strike of FZ_1 in Fig. (103) is incorrectly drawn and should be N-S, in agreement with FZ_2.

(3) coincide in location with junctions between, and the lines of termination of, all forms of lodes and are hence comparable with the the Hanging-Wall Branch Lode which possesses the same strike direction.

(4) coincide with regions of change in structural attitude, and terminations, of the steep, overturning, complex lodes characterized by the Borehole Lode. The distance separating FZ_1 and FZ_2 is about 1,500 feet and at a similar distance to the east of FZ_2 there is the N-S line connecting the terminations of the Borehole and North Pig Lodes. Similarly, at an equal distance to the west of FZ_1 a N-S line marks the effective termination of the lodes adjacent to the granite contact, especially the No. 2 Branch and No. 3 Branch Lodes.

The minor faults:

(1) bear no major structural relation to the lodes, and are indiscriminately distributed.

6/7 Dykes

The distribution of dykes, of which there are two main major ones, is indicated in Fig. (31). The Main Central Dyke, shown in Fig. (31), is situated a little to the east of Victory Shaft, and the Complex Dyke, shown in Fig. (53), is located at the junction of the Prospects East and South. A major dyke was intersected by the Wethered Lode, and another may be traced through the No. 3 Branch and Coronation Lodes.

Around each, and for nearly 500 feet on each or one side, are clustered several minor dykes which cannot be traced through adjacent lodes and are not indicated in Fig. (31). There are three general spatial groupings of minor dykes as follows:

(a) around F_1, F_2 and F_3,

(b) around the Hanging-Wall Branch Lode,

(c) around, and for over 500 feet west of, F_5 and F_6.

Whereas there is a distribution correlation between the major faults and dykes of all forms, there is no such apparent association with the fault zones.

Some, especially the Main Central Dyke, flatten in depth, as shown in Figs. (31) and (52). Nearly all the dykes, especially those striking N-S or NE-SW, dip to the E or SE, and this allows a rapid evaluation of the direction of movement within the lodes when no records, other than the apparent horizontal deflections, remain concerning the displaced dykes in the older workings of the mine.

The fact that small dykes are frequently encountered on only one side of a lode is often accounted for underground by the non-recognition of the displaced portion, which is understandable under some of the prevailing conditions. However, dykes often occur locally on only one side of a lode.

This may be interpreted as an impounding of the dyke magma by that of the lode or a dilation of the dyke fissure on only one side of the lode fissure, the early existence of which in some form is thereby indicated. When a dyke branches close to a lode an apparent discontinuity of one branch on both sides may be accounted for in the manner illustrated as Stages 2 and 3 in Fig. (101/A).

7. PETROLOGY

"The Cliffs from Pendeen to Cape Cornwall show the finest sections of metamorphosed rock in Cornwall ...."

.... Reid & Flett (1907).

7/1 Killas

The killas exposed in the workings of Geevor Mine and in the overlying cliffs conforms to that occurring throughout the Pendeen-Botallack area, and the petrology of which was described in detail by Reid & Flett (1907) and Bagchi (1947). Original banded, silty, mud-stones were transformed into a low-grade metamorphic assemblage of hornfelses. With a characteristic banded, spotted, and biotitic nature, they were classified by Bagchi (1947) as spotted slates.

There are several varieties of spotting, the most prominent due to the formation of biotite, sericite, and chlorite. Other features of comtact metamorphism are visible nearer the granite with the development of cordierite, staurolite and chiastolite in the underground workings. Around the granite contact the original texture of the killas is almost completely destroyed, and although there are many metamorphic modifications it is impossible to map any distinct zones underground. On the surface the exposure width is too small and the area is complicated by the superposition of metasomatism upon the general metamorphism.

Barclay (1959) observed silicification of the killas on the headland of Pendeen Watch and attributed it to soda matasomatism. To the same process he ascribed the formation of the whitened and heavily silicified rocks of the Avarack, and Lacy (1958) suggested that the latter may be complementary to

the desilicificated hornfelses close to the granite contact. Barclay (1959) similarly accounted for the feldspathization of the killas, in which he recognized the existence of plagioclase (possibly oligoclase) porphyroblasts, west of the silicified area.

Whenever the killas is interbedded with greenstone sills on the cliffs above Levant Mine the contact is marked by the formation of an adinole.

7/2 Greenstone

The complex petrology and metamorphic history of the greenstone in the Pendeen-Botallack area was described by Reid & Flett (1907), Bagchi (1947), Lacy (1958), Barclay (1959) and Hawkes (1958). The latter remarked that "the most widespread changes in the basic rocks (on the NW flank of the Land's End Granite) are the replacement of augite by hornblende, re-crystallization of oligoclase crystals as granular andesine, and the partial alteration of ilmenite to granular sphene. Hornblende veining is common".

The present writer has merely mapped the coastal outcrops, as shown in Fig. (H), employing only a little microscopic work to assist in the field identification of the numerous rock types. The surface distribution of greenstone, consisting of sheared pillow-lavas, south of the Avarack is indicated in Fig. (H). Apart from a small occurrence in the Level 3 adit no greenstone has been observed by the present writer in the workings of Geevor Mine.

Pillow lavas are continuous from a point south of the Avarack, through Trewellard Zawn, and along the cliffs above Levant Mine. Usually the form of the original pillows is still recognizable, as illustrated in Photo. (23), and they are frequently outlined by actinolite which also develops as penetrating veins, shown in Photo. (24). In their less contact altered state the pillow lavas contain albite or albite-oligoclase, hornblende (green), sphene, and iron-oxide, with accessory chlorite, calcite and epidote. Axinite and tourmaline are often developed in numerous fissures.

According to Barclay (1959), the most common modification of these spilitic rocks, which may be compared with those described by Reid & Dewey (1908), is the extensive formation of biotite by addative processes.

Some altered dolerite sills are interbedded with pillow lavas towards the south while the majority of the greenstone around Botallack Head consists, as described by Robson (1953), of epidiorite. Some chemical analyses and early mineralogical details were provided by Allport (1876) and Phillips (1878).

None of the well known greenstone hornfelses, described by Reid & Flett (1907), Tilley & Flett (1930), Tilley (1935), and Reynolds (1947), occur in the vicinity of Geevor and Levant Mines. South of Botallack Mine anthrophyllite-cordierite hornfelses and other varieties containing cummingtonite, plagioclase, spinel, and diaspore outcrop in the cliffs, and a typical cordierite hornfels is illustrated in Photo. (22). Slates at the same locality contain andalusite, cordierite, biotite, and corundum.

The above rocks are very rich in Mg and Fe and are believed by the majority of workers to represent a modified dolerite. Past writers have assumed them to be characteristically situated near to the granite and to be formed from a local re-distribution of Mg and Fe. Calcium is thought to have migrated outwards to form calcium-hornfelses from which the silica has been correspondingly ejected to form the overlying silica-hornfelses. The main role of the granite intrusion was to cause a re-distribution of the elements in the aureole rocks, and it is probable that only potassium was introduced from the granite.

Lacy (1958) postulated a genetic relationship between mineralization in the St. Just area and the formation of the greenstone hornfelses, stating ".... is an area traversed by a plexus of mineral veins that was, in the past, a leading producer of tin. If it be held that fluorine is an important agent in carrying tin, then it may be postulated that this element greatly facilitated the metasomatic processes or was the active agent involved".

Fluorspar occurs in the Geevor Lodes, which may be regarded as typical

of those formed throughout the entire Pendeen-Botallack area, but originated during a relatively late stage of the mineralization period as a sporadically distributed accessory. It is not associated, as in many of the other mining districts of the South-West, with the main cassiterite mineralization phase.

Future workers would probably find it more rewarding to attempt a determination of any possible spatial relationship of the greenstone hornfelses with the configuration of the underlying granite surface, rather than with the occurrence of intense mineralization.

7/3 Granite

(a) Normal Geevor-type Granite

Apart from the fine- and coarse-grained granites of the Land's End Peninsula, described by Reid & Flett (190), several modifications exposed over limited areas were distinguished by Bagchi (1947). He confirmed that the more usual granite occurring in Geevor Mine is the coarse-grained Land's End Granite, G_1, and he described another type outcropping on Carn Eanes.

The present writer has identified within G_1, hereafter known as the Geevor-type, several modifications, the distributions of which are indicated in Fig. (17).

The Geevor-type granite is potassic and chemical analyses are provided in Table (4), from which comparisons may also be made with the granite of New Mill and Castle-an-Dinas Quarries, the latter being situated in the fine-grained granite, G_2. It possesses a clean white appearance, as shown in Photos. (85/D) & (86/A), and any alteration is easily detected by changes in the colour. With coarse-grained, porphyritic, whitish feldspars, it contains visible biotite, muscovite, quartz, and tourmaline. The feldspars frequently possess ill-defined boundaries with the groundmass, and contain inclusions of minute quantities of biotite and quartz which form well-defined zones, as shown in Photo. (85/D).

In thin section the constituent minerals rarely show a perfect development of their crystal boundaries. Phenocrysts of perthitic orthoclase are easily distinguishable and oligoclase-albite occurs in the groundmass. The former is always slightly terbid due to alteration and invariably possesses inclusions of anhedral quartz, orthoclase, biotite and plagioclase. These are often arranged concentrically within the porphyritic feldspar laths, and other

constituents comprise tourmaline, apatite, topaz, zircon, pinite, chlorite and white mica. Carlsbad twinning is common, and the plagioclase is frequently sericitised whilst maintaining a clear rim.

Variously-sized flakes of biotite are pleochroic from reddish-brown to yellowish-brown. Zircon inclusions are surrounded by pleochroic haloes and the biotite is often chloritized, the alteration commencing along cleavages and boundaries with the development of rutile needles. Primary muscovite occurs in the granite but is often an alteration product of the fledspars. Bagchi (1947) remarked that "it is doubtful whether any white mica of primary origin occurs in the granite", but Reid & Flett (1907) reported its presence. It is occasionally evident in localities where it cannot be confused with alteration products and may be classed as a minor, accessory, primary constituent of the Geevor-type granite.

Quartz rarely occurs as a porphyritic constituent, but forms irregularly sized anhedral grains. With inclusions of feldspar and biotite, it usually possesses very irregular and intergrown boundaries with other minerals.

Primary tourmaline, existing throughout the fresh granite, is yellow, orange, or brown in colour and strongly pleochroic, an example being provided in Photo. (117). A blue alteration variety sometimes veins and borders the primary tourmaline, and both types were described in detail by Brammall & Harwood (1925), Scrivener (1903), and Wells (1946).

Fine-grained, greenish-blue tourmaline is produced by alteration of the feldspars but, in common with the above varieties, is easily distinguished from the tourmaline associated with mineralization, illustrated in Photos. (117), (118), & (121). Accessory minerals include cordierite, pinite, andalusite, apatite, topaz, zircon, sphene, rutile and chlorite.

(b) Fine-grained Granite

The fine-grained granite, G_1, covering an area of approximately 7 square miles, is whitish-grey to grey in colour, and is illustrated in Photo. (87/C). A chemical analysis of this specimen is provided in Table (4).

In thin section the ground-mass comprises an equigranular association of quartz and feldspar, the latter being oligolcase or albite-oligoclase. The less common larger feldspars are euhedral or subhedral perthitic orthoclase and are extensively kaolinized. They differ from their counterparts in the coarse-grained granite by being less perthitic and containing fewer inclusions, although the grain boundaries are equally indefinite. Smaller, anhedral grains of albite are present in both the quartz and the larger feldspars. Orthoclase alters to kaolin and fine-grained sericite, whereas the albite forms only kaolin. Biotite with a little secondary chlorite, interstitial orange tourmaline, primary and secondary muscovite, and zircon are also present.

Chemical analyses of the Land's End Granite from different localities were provided by Phillips (1875 & 1880) and Davison (1927 & 1928). The latter attempted to correlate the mineralogical variations in the Cornish granites with the distribution of mineralization. He included a description of the Land's End Granite and provided the following mineralogical analyses of the rock from different localities:

Locality	Quartz & Feldspar	Biotite	Muscovite	Tourmaline
New Mill	55.1%	7.5	1.2	nil%
Sheffield Quarry	58.2	6.2	1.8	2.3%
Lamorna	60.3	8.1	nil	nil%
Geevor	61.4	1.5	5.9	6.1%

(c) Carn Eanes-type Granite

Fig. (17) indicates the distribution of the Carn Eanes-type granite. It was otherwise known as the Pendeen type by Bagchi (1947), who recorded its transitional boundary with the normal Geevor-type. Medium-grained and usually porphyritic, it possesses a typical cream colouration as shown in Photo. (85/A).

The Carn Eanes-type is very similar in composition to the Geevor-type but contains more muscovite, and Bagchi (1947) recorded the groundmass to be richer in plagioclase than in orthoclase. A chemical analysis is recorded in Table (4), and although its distribution has been proved only around Carn Eanes its more widespread occurrence in mine dumps may indicate a greater surface area than is shown in Fig. (17).

(d) Boscaswell-type Granite.

The Boscaswell-type granite is exposed in the main Level 9 cross-cut between Geevor and Boscaswell Downs Mines, and at approximately 1,700 feet it possesses a gradational boundary over about 20 feet with the Geevor-type. Apart from its unusual reddish-brown colour, shown in Photo. (85/B), the Boscaswell-type is similar to the Geevor-type, and its potash and soda content is given in Table (4). Maximum colouration occurs at the northern end of the cross-cut and increases in intensity where the granite is more heavily jointed.

With well-developed porphyritic feldspars, the Boscaswell-type contains coarse-grained muscovite in excess of biotite, thereby differing from the Geevor-type. Examinations of the dumps around Boscaswell Downs Mine indicate that its distribution both in depth and laterally, is probably quite extensive. Recent diamond drilling to the north of Grenfell Lode has disclosed many local modifications of both the Geevor and Boscaswell-types.

(e) Western-type Granite

The inset of Fig. (17) indicates the distribution of the Western-type granite near the contact where it is locally widespread. A determination of its continuity to the south is prohibited by the inaccessibility of the Coronation and No. 2 Branch Lodes in this area.

The granite is illustrated in Photo. (85/C), and shows a similarity, apart from the slight greyish-brown colouration, to the Geevor-type. It is biotite-rich, the only white mica arising from the alteration of feldspars, and has a high topaz content. Potash and soda contents of the Western and Boscaswell-type granites are indicated in Table (4).

The Western-type is most probably a contact modification of the normal Geevor-type. It is separated from the killas by small patches of the latter, with which it is gradational over a few feet, and this feature probably indicates the intermittent local intrusion of the Land's End Granite in this area.

A careful study of the underground workings of Geevor Mine would probably reveal the existence of several additional granite varieties, on the basis of both appearance and mineralogy. Several localized forms have been revealed by diamond drilling and slight variations are always evident within the Geevor-type. The modifications originated before the commencement of primary jointing, and do not affect the development or extent of the lode fissures and mineralization.

7/4 Xenoliths

Xenoliths formed by magmatic stoping of the killas, shown in Photo. (16), are fairly common along the NW flank of the Land's End Granite. Bagchi (1947) based many of his arguments regarding the latter's intrusive nature upon such xenoliths, describing them in detail.

Smaller ones are fairly common in Geevor Mine and have been observed by the present writer to be equally distributed throughout the property, with no apparent increase in abundance towards the granite surface. With an average diameter of less than 6 inches they are typically rounded as shown by Photos. (49), (65) & (75).

All the xenoliths are fine-grained and hornfelsic, containing minerals such as cordierite, andalusite, silimanite, biotite and corundum. They are consequently similar in composition to the killas where immediately adjacent to the granite in the metamorphic aureole. Many different varieties were described by Bagchi (1947), and some chemical analyses were provided by Phillips (1876).

Their sedimentary parentage is mineralogically recognizable and there have been two major processes in their transformation. According to Bagchi (1947), the xenoliths were basified and subsequently granitized, with the resulting formation of gradational zones as shown in Photos. (78) & (87/D). The latter process is characterized by the development of feldspar porphyroblasts which either reflect the local trend of porphyritic feldspars in the host granite or are developed parallel to the surface of the xenolith. Different workers consider that they are due to either mechanical incorporation or replacement.

7/5 Dykes

Numerous early veinlets and narrow dykes with a wide range of direction occur throughout the mine. They possess gradational boundaries indicative of some replacement and are very similar to examples provided by Webb (1946 & 1947). Several are exposed on Level 12 of the No. 3 Branch Lode where they attain a width of four to six inches.

One, comprising nearly 40% quartz, contains fine-grained perthitic orthoclase and porphyritic albite-oligoclase laths which are aligned parallel to the dyke walls. Both feldspars are altered to sericite, secondary white mica, and occasional blue-green tourmaline. The dyke is rich in biotite, pleochroic from very pale brown to dark reddish-brown, which parallels the alignment of the feldspars, and is frequently altered to secondary chlorite and occasionally to brown tourmaline.

Another important dyke rock often present is fine-grained and greyish-brown. It is non-porphyritic and saccharoidal in texture, containing fine-grained, lath-shaped, sericitized orthoclase and albite. Biotite and muscovite are absent, and apart from containing primary orange tourmaline which alters to a blue-green variety, and accessory pyrite, the rock is similar to an aplite.

Most of the dykes vary in width between one and ten feet, possessing well-defined margins with the host granite, and are dilational in origin as defined by Goodspeed (1940). Many of the dyke-rocks are fine-grained and aplitic in composition, possessing a cream colour shown in Photo. (86/E). They are modified by varying amounts of tourmaline and occasional biotite, and usually consist of equigranular, kaolinized, perthitic orthoclase with

quartz, plagioclase, and accessory brown tourmaline and apatite.

With increasing amounts of primary tourmaline and biotite, the dyke rock approximates to a fine to medium-grained granite, illustrated in Photo. (86/C). The primary tourmaline shows no relationship to the proximity of mineralization or any other structural features, and it is zoned in both brown and blue, as shown in Photo. (82). The amount is often very variable and the tourmaline is sometimes concentrated against the dyke walls, an example being provided by the sills shown in Photo. (84).

In other cases the tourmaline results from nearby mineralization and concentrations in the fine to medium-grained original granite or aplite may be related to either wall-rock alteration or structural features. The secondary nature of this blue-green variety is always recognizable and its sporadic distribution is demonstrated by Photo. (86/B).

The secondary tourmaline content of some dykes often becomes intense, as shown in Photo. (86/F), and it is usually an indication, although exceptions occur, of the proximity of a major fissure which is not necessarily economically mineralized.

Whereas the aplite and granite dykes, and their tourmalinized modifications, normally occupy cross and longitudinal joints, later quartz-tourmaline veins, such as that illustrated in Photo. (86/A), occur only in the longitudinal joints and occasionally in the secondary joints. By attaining a maximum width of three to four inches, they differ from the tourmaline-rich, fine-grained granites, typified by Photo. (86/D), which often compose the larger dykes.

Small dykes with a maximum width of 6 inches, and corresponding closely in composition to the normal Geevor-type granite, are fairly frequent in the aureole rocks.

Table (4/1)

The Land's End Granites

Chemical Analyses

	Western Type %	Boscaswell Type %	Pendeen Type %	Geevor Type %	Castle-an Dinas Quarry %	Newmill Quarry %
Sample	(a)	(b)	(c)	(d)	(e)	(f)
SiO_2			73.9	71.2	73.2	72.4
TiO_2			0.17	0.36	0.21	0.31
Al_2O_3			13.0	13.9	13.9	13.3
Fe_2O_3			0.51	0.34	0.55	0.84
FeO			0.96	2.48	0.38	2.31
MnO			0.07	0.14	0.11	0.15
MgO			0.24	0.60	0.34	0.51
CaO			0.45	0.82	0.54	0.81
Na_2O	2.46	3.23	1.47	2.89	2.79	2.70
K_2O	6.20	5.38	6.58	5.55	5.14	5.17
P_2O_5			0.26	0.32	0.26	0.26
H_2O (Total)			1.01	0.83	1.00	0.98
Li_2O						
Cl						
F						
S						
B_2O_3						
Total			98.63	99.43	99.42	99.76%

Table (4/2) The Land's End Granites

Chemical Analyses (Cont'd)

	Botallack %	Chywoon Morvah %	Gready %	Lamorna %	Kaolinized Granite %	Greizen %
Sample	(g)	(h)	(i)	(j)	(k)	(l)
SiO_2	74.54	70.65	69.64	70.17	71.15	69.42
TiO_2				0.41	0.16	Trace
Al_2O_3	14.86	16.16	17.35	15.07	19.4	15.65
Fe_2O_3	0.23	0.52	1.04	0.88	1.32	1.25
FeO	2.53	1.53	1.97	1.79	0.09	3.30
MnO	Trace	Trace	Trace	0.12	0.09	0.39
MgO	Trace	Trace	0.21	1.11	0.45	1.02
CaO	0.29	0.55	1.40	1.13	0.21	0.63
Na_2O	3.49	0.54	3.51	2.69	0.05	0.27
K_2O	3.73	8.66	4.08	5.73	1.44	4.06
P_2O_5				0.34	0.07	0.40
H_2O (Total)	0.87	1.22	0.72	0.88	5.25	0.60
Li_2O	Trace	-	Trace	0.11	0.03	0.81
Cl				0.06	Trace	Trace
F				0.15	0.11	3.36
S				0.04	-	-
B_2O_3				Trace	0.33	0.59
				100.68	100.16	101.75
Less for F and Cl				0.07	0.04	1.41
Total	100.54	99.83	99.92	100.61	100.12	100.34

Table (4/3) The Land's End Granites

Chemical Analyses (cont'd)

	Western type	Boscaswell type	Pendeen type	Geevor type	Castle-an Dinas Quarry	Newmill Quarry
Sample	(a)	(b)	(c)	(d)	(e)	(f)
$(Na_2O + K_2O)$	8.66	8.61	8.05	8.44	7.93	7.87
$\frac{(Na_2O + K_2O)}{Al_2O_3}$			0.62	0.61	0.57	0.59
$(CaO + MgO)$			0.69	0.74	0.88	1.32
$\frac{(CaO + MgO)}{\text{Total Fe}}$			0.67	0.26	1.80	0.54
K_2O/Na_2O	2.52	1.66	4.48	1.92	1.84	1.91
Na_2O/CaO			3.27	3.52	5.17	3.33
S.G.						
Analyst/Ref.	Geochem. Dept. Imp. Coll.	----------				

Table (4/4).

The Land's End Granites

Chemical Analyses (Cont'd)

	Botallack	Chywoon Morvah	Gready	Lamorna	Kaolinized Granite	Greisen
Sample	(g)	(h)	(i)	(j)	(k)	(l)
$(Na_2O + K_2O)$	7.22	9.22	7.59	8.42	1.49	4.33
$\frac{(Na_2O + K_2O)}{Al_2O_3}$	0.49	0.57	0.44	0.56	0.08	0.28
$(CaO + MgO)$	0.29	0.55	1.61	2.24	0.66	1.65
$\frac{(CaO + MgO)}{\text{Total Fe}}$	0.11	0.27	0.53	0.84	0.47	0.36
K_2O/Na_2O	1.07	16.04	1.16	2.13	28.8	15.04
Na_2O/CaO	12.03	0.98	2.51	2.38	0.02	0.43
S.G.	2.66	2.62	2.72			
Analyst/Ref.	Phillips (1875)	Phillips (1875)	Phillips (1880)	Reid and Flett (1907)	Reid and Flett (1907)	Reid and Flett (1907)

8. WALL-ROCK ALTERATION

"The substances known in Cornwall and Devon as Capel may be described a highly altered and usually silicified and tourmalinized bands of country-rock, bordering a more or less distinct fissure or fissure-filling".

.... Collins (1912).

8/1 Granite

(a) Introduction

The Geevor-type granite and the various modifications are equally subjected to alteration arising from tin mineralization. The effects are always visible underground, there being a zone of alteration varying in width from a few inches to a maximum of about 3 feet. A characteristic colouration is imparted to the granite and may be easily recognized even when the drive walls are extensively slimed over. Unaltered granite is visible on both the footwall and hanging-wall in the drives, and the alteration is an asset in day-to-day underground development.

A detailed description of the alteration of granite wall-rock adjacent to tin lodes in the South-West of England was given by Webb (1947), who defined the following forms:- chloritization, tourmalinization, greisenization, sericitization, and silicification. To this list he added the prominent reddening of the granite.

Rao (1952) studied trace element variations in granite wall-rock from South Crofty Mine and divided the progressive alteration into the following zones:

(1) Outer zone of sericitization

(2) Felspathization

(3) Chloritization and inner sericitization

(4) Tourmalinization

(5) Late silicification which he related to the late quartz infilling, termed the 'leader' by Webb (1947).

From published accounts it is possible to summarize the mineralogical changes evident in an average Cornish granite with increasing proximity to a tin lode.

(1) Soda feldspar decreases until it becomes non-existent in the sericite-chlorite zone.

(2) Potash feldspar increases slightly and then gradually diminishes until it is present in only accessory amounts adjacent to the lode.

(3) Quartz increases gradually, attaining a maximum in the chlorite zone, and then diminishes suddenly.

(4) Biotite completely disappears in the outermost zone.

(5) Chlorite increases steadily until it becomes the major constituent of the granite adjacent to the lode.

(6) Muscovite increases slowly, attaining a maximum in the sericite-chlorite zone, and is then rapidly distroyed.

(7) Kaolin is an important constituent only in the outermost zone.

(8) The accessory minerals increase slightly.

(9) The porosity and density of the granite increases in proportion to the alteration.

The above changes aredue to many different factors and some forms of alteration may be absent or only slightly represented. When several are

present they are superimposed upon each other, complicating a determination of the age relationships. An analysis of the forms of wall-rock alteration provides important indications of the history of lode formation and associated ground movements, and of the chemical nature of the contributing mineral solutions.

In Geevor Mine the most impressive alteration of the granite is associated with the No. 3 Branch Lode, and typical examples, indicating its full extent, are provided by Photos. (88/A) & (90). The former demonstrates the perfect development of every zone, with the exception of the outermost one of kaolinization along which the specimen naturally broke.

(b) Mineralogical Changes.

The specimen shown in Photo. (88/A) was divided into eleven equally spaced sections approximately 1 inch long. Thin sections were constructed from each and the remnants were utilized for chemical analyses. The large number of different minerals present prohibited the use of a point counter for modal analyses, and the thin sections were consequently placed in a projector fitted with crossed nicols and projected upon a sheet of white graph paper on which the outlines of the individual minerals were graphically depicted.

Total areas representing each mineral variety were measured with a planimeter and the volume percentages calculated. The results are presented in Figs. (124) & (125/4). The portion between 2 and 7 inches in the latter corresponds to part of the specimen shown in Photo. (88/A), for which modal analyses are presented in Figs. (122) and (123).

Mineralogical changes, appreciated visually by the reader in the above figures, arise mainly through the alteration of primary mineral constituents and the stages in the transformation of each are as follows:-

(1) The porphyritic potash feldspars, which are kaolinized even in the unaltered granite, are altered in the outer zone to fine-grained white mica. This process is concentrated especially along the albite veining, producing small rafts of mica which interlace the feldspar and comprise 50% of the whole.

Potash feldspars gain a characteristic red coloration from which their existence in the zones may usually be determined. Soda feldspars are altered in the outermost zone to fine-grained sericite, imparting a pale green coloration which disappears with continuing alteration more rapidly than the red.

With progressive alteration soda feldspars are replaced by quartz whereas remnants of potash feldspar are replaced by chlorite, forming as fine-grained, spherulitic growths, pleochroic from colourless to very pale green. Elsewhere, potash feldspar remnants are progressively replaced by quartz and accessory amounts of orange and blue tourmaline. They are finally evident only as ghost structures in which the outer rims of the original laths are still visible as shown in Photo. (124).

(2) In the outermost zone primary biotite is completely transformed into secondary chlorite, and small blades of iron-rich material are formed along the cleavage planes. The chlorite, in which the original haloes are preserved, is pleochroic from off-white to greyish-green and is associated with some white mica.

With progressive alteration secondary chlorite is replaced by quartz and a little orange tourmaline. Eventually only the blades of iron material remain and provide a site within the quartz for the commencement of growth of additional spherulitic chlorite. Shown in Photo. (113), it is the characteristic variety arising from intense wall-rock alteration and is also closely associated, as shown in Photo. (119), with the cassiterite mineralization phases.

Dines (1956) described secondary chlorite after feldspar, and Webb (1947) analysed chlorite from South Crofty Mine, concluding that it was daphnite. The latter was also identified by Hallimond (1939) from the Tolgus Mine where it occurs interstitially to quartz. However, there are numerous varieties of chlorite in Geevor Mine deserving further extensive work before their true composition may be stated with any certainty.

(3) Primary, orange tourmaline is veined by a secondary, blue-green variety even in the unaltered granite and this process continues in the wall-rock, as shown in Photo. (117). With increased alteration the central core of orange tourmaline is replaced by quartz. Only the rims of the original mineral remain and provide a site for the eventual growth of parallel, acicular, blue, tourmaline crystals which are oriented normal to the rims. Orange tourmaline, together with topaz, also forms after original biotite.

(4) In the innermost zone very little trace remains of the perthite veining and original feldspar. Albite veining which originated during the early stages of alteration, as reported by Dines (1956), is completely transformed into secondary mica, fine-grained chlorite, and tourmaline.

No remnants of the original biotite or corresponding secondary chlorite are present and its original occurrence may be inferred only from localized concentrations of spherulitic chlorite. Primary orange tourmaline remnants, heavily overgrown with the blue variety, are occasionally visible. Adjacent to the lode the quartz is frequently re-crystallized.

Dines (1956) reported the late formation in the wall-rock of arsenopyrite which precedes the majority of the infilling stages concentrated in the central fissure. As shown in Figs. (88/A) and (90), the arsenopyrite is accompanied by pyrite and chalcopyrite, shown in greater detail in Photo. (100/B). In

the specimen illustrated in Photo. (88/A), accessory cassiterite increases in abundance in the sulphide impregnated zone. Numerous cavities created by the alteration are infilled with minute crystals of colourless calcite.

(c) Chemical Changes

The results of chemical analyses of the specimen illustrated in Photo. (88/A), are presented in Table (5) and in Figs. (126) & (127). They may be related to the mineralogical changes presented in Fig. (125) and are best appreciated by a visual examination. Granite alteration is characterized by an increase in the hydrogen ion content but very little overall change in the oxygen ion.

Webb (1947) studied the chemical changes taking place during wall-rock alteration and from the results obtained, together with those of a mineralogical study, he presented the following conclusions regarding the nature of the mineral solutions causing the alteration and the physical requirements for the latter:-

"1. The extent of fracturing even down to the microscopic scale has an important bearing on wall-rock alteration. The extent of tourmalinization, especially is largely controlled by this factor. Such fracturing determined the nature of the channel-ways along which the incoming solutions moved and also made available enormous specific areas of wall-rock, promoting permeation, reaction and replacement.

2. The wall-rock alteration may be divided into zones.

3. Tourmalinization is concentrated in a comparatively narrow zone adjacent to the channel-way. Providing the other ingredients (principally Fe") are available, boron was precipitated rapidly to form tourmaline - it was given no chance to migrate far.

4. Fe" and (OH) are essential for chloritization, these may migrate further than boron before being 'fixed' in chlorite.

5. The formation of tourmaline or chlorite is not dependant on the temperature, but on the presence or absence of boron.

6. The responsible ore fluids must have contained B, Fe" and OH (and probably Al) - B was precipitated quickly in tourmaline: the remaining Fe", (OH) and (Al?) migrated further to form chlorite; excess iron was deposited in the outer reddened granite zone.

7. Chloritization and tourmalinization released potash which undoubtedly caused sericitization in the outer zone. This zone incorporates the reddened granite zone where iron was also available. It seems probable that some of the potash was also introduced by the vein solutions, but this is doubtful - the little potash feldspar that is found in the vein proper may represent some liberated potash that migrated back into the channelway, instead of out into the wall-rock.

8. The zone furthest away from the vein is characterized by a softening of the rock by kaolinization and sericitization. The final excess of H_2O with more or less potash was probably active in this zone.

9. The tin-bearing ore-fluid contained H_2O, Fe", B, F, possibly some K and Al: Sn, and small amounts of W, Cu, S, As. There is no direct evidence at this stage for the introduction of Si, but in view of the nature of the ore-bearing source and events leading up to the formation of the ore-fluid, it is probable that some silica was present.

10. Fe" in the ore-solutions could not have been derived from adjacent country rock. There is no evidence of zones of leaching at the present level. It must, therefore, be assumed that it was derived from the source, either (a) as an original constituent of the ore-residua, or (b) by deuteric reaction at depth.

11. The bulk of the silica arrived with the later hydrothermal solutions and caused restricted silicification of the earlier altered rocks enumerated above."

(d) Additional Forms

Several supplementary forms of alteration may be considered individually as follows:-

(1) Greisenization: Only a few inches of granite on either side of the fissures are affected by greisenization, as shown in Photos. (43), (56), & (84). Feldspars are altered to quartz and secondary mica, and the process usually affects a large number of joints adjacent to the lodes.

(2) Kaolinization: Although one or two inches of granite in the outermost zone of the normal wall-rock alteration are kaolinized, the process is

sometimes intensely developed, its age of formation varying considerably. Very early tourmaline replacement masses are surrounded by a little kaolinized granite but the most extreme kaolinization, coupled with a discoloration of the granite, often occurs in the vicinity of major faults and fault zones. Especially at junctions of the latter with lodes, the kaolinization covers widths of up to 3 feet, necessitating some ground support in the levels.

(3) Tourmalinization: The first tourmalinization of the wall-rock, with the exception of tourmaline branches, comprised a slight replacement adjacent to major fissures and increased slightly in intensity with the continuance of the mineralization stages. The original granite texture is normally preserved and the tourmaline, characteristically zoned in brown, orange, blue and green, either replaces quartz or feldspar as shown in Photo. (93/B).

(4) Silicification: This is a widespread form of alteration and either affects hitherto unaltered granite or is superimposed on the various other forms which may be previously existing. It usually affects about 6 inches of ground on both sides of a fissure and an example of the product is provided by Photo. (93/C).

(5) Chloritization: Occasionally chloritization is the only form of alteration, the original granite texture, as shown in Photo. (93/A), being preserved.

(6) Discoloration: A process whereby a reddish-brown or grey coloration is imparted to the granite is evident to varying extents throughout the mine. It sometimes results in an intense hematization over a few inches, as shown in Photo. (55). Normally it is less intense, although more widespread, and occurs especially around major faults and fault zones, and their junctions with lodes, as shown in Photos. (74) and (77).

(e) Distribution

The various forms of wall-rock alteration affect the major lodes, prospects, fractures and adjacent joints. In an average cross-cut about 500 feet long there may be up to 20 fractures surrounded by alteration comparable with, or even exceeding, that present around the nearest major lodes. Usually the uneconomic, dislocated joints and fissures show reddening with a little tourmalinization and chloritization, as shown in Photos. (53) & (71). The lodes possess, in addition, all the other forms, either separately or superimposed upon each other, but they are not normally so strongly developed as around the No. 3 Branch Lode where the altered zone characteristically merges into the lode infilling.

Sometimes kaolinization exists alone around less important crossing fractures, as shown in Photo. (70), and along minor prospects, as illustrated in Photo. (71). There is an increase in the intensity of all forms of wall-rock alteration at junctions between lode fissures and some major joints. Displacements of the crossing fractures and their associated wall-rock alteration are usually positive indications, although exceptions to this rule do occur, that alteration preceded the major movements on the lodes.

Only joints and major fissures lying within the strike range of the lodes are substantially surrounded by wall-rock alteration. Some local and regional cross-joints are bounded by belts of hematized, kaolinized and discoloured granite, but rarely show reddening, tourmalinization, and chloritization.

Whereas economic mineralization is frequently terminated around high angle (in plan) lode intersections, and junctions with major faults and fault zones, alteration forms such as greisenization, reddening, chloritization,

and some tourmalinization are continuous, with equal development, for a considerable distance on both sides of such a feature. Other forms, including silicification, major tourmalinization, kaolinization, and some sulphide and cassiterite replacement of the wall-rock, exist on only one side of such major features; that occupied by the economic mineralization.

The common forms of wall-rock alteration are distributed fairly equally throughout the mine but tend to be more intensely developed around the relatively steep, NW-striking lodes in the Western unit. Lodes characterized by the Coronation and Borehole Lodes are less affected, although alteration may sometimes be extensive, as evidenced by Photo. (80). Curved lodes characterized by the Wethered Lode show the least intense overall wall-rock alteration, as shown in Photo. (79), apart from silicification.

The extent of alteration around some prospects and major fissures is comparable with that surrounding lodes of the Coronation and Wethered Lodes groups.

Although areas of maximum wall-rock alteration do not coincide with those of highest lode value, the alteration, apart from that around major junctions, normally attains a maximum overall development midway between the lateral limits of a lode. The intensity of alteration is very little indication of the value of a lode or prospect, but, although a lode of high value may often be bordered by only a little silicified and reddened granite, portions of the lodes containing economic mineralization generally possess a greater degree of wall-rock alteration than those which are uneconomic.

Various individual alteration forms may be mapped qualitatively and quantitatively underground. The present writer adopted this procedure for the No. 3 Branch Lode and the variations in intensity of the different forms,

presented in Fig. (141), may be related to the major structural context and degree of economic mineralization.

(f) Relative Ages

Some alteration preceded, accompanied, and followed major movements along the lodes and faults. Deflections exerted upon one another by the lodes, faults, and other features may be employed to evaluate the relative ages of completion of the different alteration forms. They are superimposed upon each other in a single lode and their age relationships cannot be interpreted without a detailed study of the structural history.

Such an analysis, all the details of which cannot be included owing to the lack of space, permits the various processes of wall-rock alteration to be listed as follows, commencing with the earliest:

(1) Tourmalinization: This minor form was usually unaccompanied by any relative movement of the ground.

(2) Kaolinization: A little kaolinization was normally associated with the above tourmalinization.

(3) Greisenization: This was unaccompanied by any movement of the ground.

(4) Reddening, chloritization, and tourmalinization:
In many cases these alteration forms did not accompany any dislocations of the ground, but since their formation covered an extensive time period some major movements initiated a part of their creation.

(5) Cassiterite replacement and sulphide impregnation: Some, although relatively small, movements in the lodes accompanied these alteration forms.

(6) Silicification: This process accompanied the major movements and infilling phases of lode formation, and was supplemented by less intensive alteration of the above types.

(7) Major kaolinization and discoloration: Each accompanied major, post-cassiterite movements along the lodes, major faults, and fault zones.

There are numerous exceptions to the above order, chiefly arising from localized regeneration which results in apparent inversions.

(g) Application

Identification of the varieties of alteration intersected during diamond drilling permits a tentative interpretation of the structural history of the associated fissures. It is never possible, for obvious reasons, to assess the potential value of an intersected lode from a petrological examination of the associated wall-rock alteration.

Rao (1952) measured the distribution of trace elements in altered granite wall-rock around tin lodes in South Crofty Mine. He demonstrated that although the presence of tin is indicated at a maximum distance of only 5 feet from a lode, associated increases or decreases in other elements may be detected at greater distances.

The width of alteration around the Geevor Lodes is less than that surrounding those of South Crofty Mine but a closer study of the associated petrological and trace element variations may have an important application in diamond drilling at Geevor Mine. An attempt should be made to determine the changes in trace element distribution around a representative tin lode and to discover whether or not there is any relation between such changes and the localized value or extent of the lode.

8/2 Killas and Greenstone

Where the Geevor lodes enter the killas they are uneconomic and in the adjacent granite they possess very little associated wall-rock alteration; merely a little kaolinized and reddened granite with accessory tourmalinization. Within the killas there is little evidence of any substantial alteration. The rock is simply tourmalinized and silicified, producing a hard hornfels which is richer than normal in tourmaline.

In the Level 3 adit there is very little apparent alteration of the greenstone and the 'lode' comprises a simple quartz vein. Elsewhere in the Pendeen-Botallack area an indication of the manner of alteration of the greenstone may be obtained from various published records. Axinite, fluorspar, epidote, and garnet are common alteration products and may be observed at many localities in the cliff section.

Table 5/1

Geevor Mine.

Wall-Rock Alteration of Granite

No. 3 Branch Lode, No. 11 Level. Chemical Analyses

Sample Number	Unaltered Granite	5806	5807	5808	5809	5810
	%	%	%	%	%	%
SiO_2	71.2	43.0	46.3	68.9	61.5	58.8
TiO_2	0.36	0.41	0.27	0.31	0.29	0.32
Al_2O_3	13.9	15.3	10.3	11.8	12.9	14.8
Fe_2O_3	0.34	22.4	22.3	8.5	3.6	2.6
FeO	2.48				7.01	9.06
MnO	0.14	0.39	0.33	0.11	0.20	0.26
MgO	0.60	1.3	0.7	0.9	0.9	1.1
CaO	0.82	0.5	0.5	0.4	0.5	0.5
Na_2O	2.89	0.41	0.12	0.17	0.23	0.18
K_2O	5.55	4.15	2.83	5.48	6.71	6.48
P_2O_5	0.32	0.44	0.28	0.26	0.26	0.3
H_2O (Total)	0.83	3.94	3.24	1.52	2.00	2.86
Total	99.43	92.24	87.17	98.35	96.10	97.26

Analyses by the Department of Geochemistry, Imperial College.

Table (5/2)

Geevor Mine

Wall-Rock Alteration of Granite

No. 3 Branch Lode, No. 11 Level. Chemical Analyses (Cont'd)

Sample Number	5811 %	5812 %	5813 %	5814 %	5815 %
SiO_2	70.6	70.7	71.3	70.0	69.8
TiO_2	0.32	0.30	0.28	0.27	0.33
Al_2O_3	14.1	13.8	13.8	15.1	14.4
Fe_2O_3	0.9	0.7	0.5	0.7	0.8
FeO	3.26	2.77	2.49	1.71	2.05
MnO	0.09	0.09	0.11	0.04	0.02
MgO	0.6	0.4	0.5	0.8	0.9
CaO	0.5	0.5	0.5	0.6	0.7
Na_2O	0.20	0.23	0.35	0.43	0.39
K_2O	7.06	7.58	7.86	7.92	6.03
P_2O_5	0.29	0.28	0.26	0.25	0.28
H_2O (Total)	1.35	1.34	1.49	2.68	3.60
Total	99.27	98.69	99.44	100.50	99.30

Analyses by the Department of Geochemistry, Imperial College.

Table (5/3)

Geevor Mine

Wall-Rock Alteration of Granite

No. 3 Branch Lode, No. 11 Level. Chemical Analyses (Cont'd)

Sample Number	Unaltered Granite	5806	5807	5808	5809	5810	
$(Na_2O + K_2O)$	8.44	4.56	2.95	5.65	6.94	6.66	
Na_2O/CaO	3.52	0.82	0.24	0.42	0.46	0.36	
K_2O/Na_2O	1.92	10.1	23.6	32.2	29.2	36.0	
$(CaO + MgO)$	1.42	1.8	1.2	1.3	1.4	1.6	
$\frac{(Na_2O + K_2O)}{Al_2O_3}$	0.61	0.30	0.29	0.48	0.54	0.45	
$\frac{(CaO + MgO)}{\text{Total Fe}}$	0.50	0.08	0.05	0.15	0.13	0.17	
Rb		150	120	300	400	350	p.p.m.
Zr		100	50	80	50	80	p.p.m.
Y		50	-	-	-	30	p.p.m.

Table (5/4)

Geevor Mine

Wall-Rock Alteration of Granite

No. 3 Branch Lode, No. 11 Level. Chemical Analyses.

Sample Number	5811	5812	5813	5814	5815	
$(Na_2O + K_2O)$	7.26	7.81	8.21	8.35	6.42	
Na_2O/CaO	0.40	0.46	0.70	0.54	0.43	
K_2O/Na_2O	35.3	33.0	22.5	18.4	15.5	
$(CaO + MgO)$	1.1	0.9	1.0	1.4	1.6	
$\frac{(Na_2O + K_2O)}{Al_2O_3}$	0.51	0.57	0.59	0.55	0.45	
$\frac{(CaO + MgO)}{\text{Total Fe}}$	0.33	0.31	0.31	0.80	0.77	
Rb	550	650	600	500	450	p.p.m.
Zr	150	150	100	100	150	p.p.m.
Y	-	40	40	50	40	p.p.m.

9. CASSITERITE DISTRIBUTION

9/1 Introduction

> ".... For it should be borne in mind that the occurrence of the useful metals in veins is not the effect of blind chance, but has been governed by great and general laws, which can only be approached by long and careful research".
>
> .... de la Beche (1839).

Sulphides in the Geevor lodes are eventually marketed as a by-product, but exploration and development are directed towards the discovery of tin. The latter, occurring only as cassiterite, resulted from several superimposed mineralization phases, separated in time, and which may be represented according to their characteristic mineral association; quartz-cassiterite, tourmaline-cassiterite, chlorite-cassiterite, and sulphide-cassiterite. There are additional combinations, such as hematite-cassiterite, and the total tin content of a lode depends upon the extent to which each phase is represented and upon the cumulative effect.

The distribution of the mineral associations resulting from each phase is irregular, and the Geevor lodes, in common with those of South-West England, contain erratic quantities of cassiterite, with a tin content fluctuating both above and below the pay limit.

9/2 Distribution Characteristics

> "The mineral riches of the lodes are in general very unequally distributed, and the workings expose 'sterile' zones, as well as others, which are productive in different degrees".
>
> .... Collins (1912).

(a) Width - Value Relationships

Channel samples are taken across the lode width at 5 foot intervals along the back of all the development levels. The grade is determined from a vanning shovel assay and given as 'A' lb. SnO_2/ton, the total tin content of the lode being expressed as:

'A' lb. SnO_2/ton over 'W' inches (lode width).

or $\frac{WA}{12}$ ft.lb. SnO_2/ton.

N.B. The SnO_2 is sometimes denoted by the term 'Black Tin' or the abbreviation 'B.T.'.

In general the lode width and fissure width are equal, but there are often sections of constant fissure width in which the measured lode width is highly inconsistent, unrelated increases being due to two features:

(a) localized, intensely altered wall-rock which sometimes contains cassiterite.

(b) the inclusion of horses of granite in the lode, resulting from:

(1) fragmentation and the inclusion of wall-rock breccia not far removed from its source.

(2) the branching and probable re-uniting of the lode fissure, with intense alteration of the intervening granite.

(3) the lode may comprise several closely-spaced, parallel fissures.

(4) repeated dense veining of the wall-rock by quartz; as on parts of the North lode, for example.

Inconvenience prevents the use in all major statistical studies of any measurements of the lode width other than those made by the samplers, and any possible errors thereby introduced must be considered. No geological

study may ignore the implications arising from a statistical approach, and similarly the latter may not be divorced from an understanding of the detailed characteristics of each lode and individual component fissures.

To avoid a constant repetition, the terms lb. SnO_2/ton and ft. lb. SnO_2/ton will hereafter be replaced respectively by lb./ton and ft.lb/ton. and/or lode grade and lode value.

When the lode width is equivalent to the fissure width there is a fairly close overall agreement between increases in the lode width and in the lode value. In such cases the value results from a simple infilling of material with a consistent or constantly varying grade. Although the lack of space prevents any illustrations, measurements of the lode width and corresponding lode value figures for entire individual lodes have been plotted against each other on two linear scales, thereby demonstrating the co-variation and providing a mean lode grade figure.

Within the product of a single mineralization phase which is infilling a lode fissure of constant width there is an erratic distribution of cassiterite, as illustrated by the lode grade figures in Fig. (67). A variety of superimposed infilling phases produces a complex relationship between the lode width and the lode value. Each phase, although increasing the fissure and lode widths, may possess an individual tin content of between 0 and 100% .

An early tourmaline-cassiterite phase, shown in Photo. (59), considerably increases the lode value and grade while adding only a few inches to the fissure width. Conversely, a late quartz infilling, shown in Photo. (80), excessively increases the lode width and correspondingly decreases the lode grade without adding to the final value.

With varying fissure widths, the interference of several cassiterite-bearing infilling phases, and the combined effect of structural and tempera-

ture controls, it is not surprising that the Geevor lodes, like those of all Cornwall, are reputed to possess very fluctuating tin contents.

(b) Log-Normal Frequency Distribution

The writer has analysed the distribution of cassiterite in several lodes representing the different structural groups, but the lack of space permits the presentation of only one limited example.

The Wethered Lode is one of these most suited to a statistical study since the fissure width is almost always equal to the lode width. As a wide lode, any localized differences between the two widths are less effective as a source of error.

Only a detailed underground study allows divergencies from the expected results to be accounted for correctly, and the present writer found it necessary to map the majority of the Wethered Lode to a scale of 1 inch to 5 feet, noting the distribution of the several phases of mineralization.

The results presented below are based upon a total of 1,805 individual development samples taken for the full lateral extent of all the levels of the Wethered Lode. No stope or raise samples have been used.

Frequency histograms of the lode width and lode value (ft.lb.SnO_2/ton) sample measurements were plotted as described by Moroney (1951). From the histogram a corresponding lode value frequency curve, presented as Fig. (69/A), was constructed with the following characteristics:

Standard deviation 97.99

Arithmetic mean..... 64.77

Mode 8.5

N.B. In Figs. (69/A) & (69/D), the term 'median' should read 'mode'. The correct median (not shown) lies between the mode and the mean.

This monomodal frequency curve is almost identical to the curves produced by Ross (1950) and Sichel (1947 & 1952) from sampling of the Witwatersrand gold reefs. Sichel termed this curve log-normal, since by plotting the assay values to a logarithmic scale, it becomes, as shown in Fig. (69/C), a normal or Gaussian curve. The log. of the standard deviation, 1.99, is comparable with the values of 2.0 ± 0.4 which were quoted by Sichel (1952).

In common with the frequency curves computed for the Witwatersrand deposits, the Geevor curves show a wide discrepancy between the mode, arithmetic mean and median. As Falini (1956) demonstrated, the disparity may be related to the metal under consideration and to the origin of the deposit, there being a marked difference in the curves, for instance, between hydrothermal gold veins and large, low-grade copper deposits.

Watermeyer (1919) considered that in the estimation of the mean of any values each sample should be weighted according to its frequency, but Truscott (1930 & 1947) demonstrated this assertion to be incorrect, and eventually Sichel (1952) presented a simplified method for the computation of the mean.

The overall value of any Geevor Lode is determined by a minority of high-grade samples which are evident in the long drawn-out 'tail' of the frequency curve. Their relative paucity is indicated by the cumulative frequency curve, shown in Fig. (69/B). From the latter, constructed from Fig. (69/A), the following facts emerge:

(a) about 4% of the samples exceed 300 ft.lb. SnO_2/ton

(b) nearly 70% of the samples are less than the arithmetic mean.

(c) over 50% of the samples are less than the pay-limit figure.

(d) the arithmetic mean is very sensitive to changes in the frequency of samples, numbering 8% of the total, in excess of

200 ft.lb. SnO_2/ton.

Variations in the lode width may be similarly represented, and a corresponding frequency curve with the following characteristics is illustrated in Fig. (69/D):

Standard deviation 13.99

Arithmetic mean 26.56

Mode 22.0

The monomodal, lode width frequency curve, being neither normal nor log-normal, is most aptly described as skew-normal with less discrepancy between the mode, mean and median, compared with the lode value curve.

Although the individual lodes differ in many structural and mineralogical respects their various frequency curves are remarkably similar in form. Lode value frequency curves for the Wethered and No. 3 Branch Lodes, for instance, are in many ways identical.

The curves shown in Fig. (69) were based upon samples taken over the full developed extent of the lode, regardless of value. The same statistical procedure was adopted by the writer, employing only development samples taken along portions of the drives above which the lode was eventually stoped. Comparable results were obtained and, as expected, the frequency curves (not shown) possess a less definite mode, an increased mean, and a decreased height when constructed to the same scale.

(c) Application to Valuation

At Geevor Mine it is current procedure to reduce what are regarded as random, unusually high values according to a 'system' which is highly individual and non-systematic. The subject of cutting random high samples, which should be approached from the view-point of "why are they cut" rather than "it is good practice to cut them", was discussed theoretically by Watermeyer

(1919), Truscott (1930), Bath (1948) and Palini (1956). The latter concluded:

"In mine sample interpretation there is the rather common practice, which is regarded as prudent, of 'cutting away' or reducing the frequencies of the very high grades ... Provided that this danger (errors in the underground sampling) can be excluded, in other words, provided it can be assumed that the sampling was honestly carried out, then obviously the striking off (or arbitrary cutting) of the higher grade frequencies cannot lead to results which are satisfactory in the long run. The very existence of the high grade samples demonstrates, indeed, that in relation to the sample volume adopted, high grade portions do exist in the deposit and these portions .... can contribute appreciably to the general average grade".

Sichel (1952) considered the problem of over-sampling and remarked that errors may result from loss in mining, tonnage left underground, waste, and various other factors. He referred to the practice, which he deplored, of cutting high values in order to remedy apparent over-sampling. Sichel (1952) correctly pointed out that if such practice is founded upon the surmise that isolated high-values are the result of over-sampling, then over-sampling must be assumed to apply to all the samples taken underground which should be correlated accordingly.

As pointed out by Sichel (1952), there is a statistical justification for cutting an isolated high value if it is suspected that the sampling operation during its cutting was in error. Alternatively, it may be reduced if the value is considered to be a freak with a chance of occurrence of less than one in ten thousand.

At Geevor Mine the underground sampling is reasonably efficient and any errors locally introduced by variations in the rock friability, density, cassiterite grain size and many other factors, produce no overall bias. In addition, any possible errors would be introduced in the sampling of both low and high values. Losses of cassiterite and gains in other minerals during the vanning shovel assay operation must also be taken into account, but the general overall effect provides no justification for the cutting of only high

samples.

Jackson (1947), discussing gold valuation on the Witwatersrand, concluded that only when there is a suspected error in the sampling practice or the assay technique should random high values be reduced, and that otherwise it is bad policy.

Published literature on this subject concerns only the Witwatersrand but valid comparisons may be made between Geevor Mine and the examples quoted by the various writers. This is because, although concerning different minerals and geological contexts, tin distribution in Geevor Mine and that of gold in the Witwatersrand possess the same statistical characteristics, upon which comparisons may then be based.

About 4% of the total development samples in Geevor Mine are considered to be exceptionally high and are consequently reduced. This figure, generally constant for the mine and, with certain reservations, over individual lodes, cannot be considered as including only freaks. This conclusion is substantiated by Sichel (1952) who, in discussing the Witwatersrand deposits, stated "If the number of high samples is month by month more or less the same - say 2% of the total number of samples - then the first point (the probability of there being a freak occurrence) cannot be taken into consideration".

Jackson (1947) pointed out that the occurrence of high values may usually be accounted for geologically on the Witwatersrand by the presence of a "pay shoot" or "narrow streak". Similarly, random high lode values at Geevor Mine usually result from the existence of a vertically-elongated ore-shoot arising from a number of mineralization phases which are normally localized at fissure intersections.

A recent example has been afforded by development of Grenfell Lode in which bunches of high value ore are elongated in a highly inclined direction

governed by the attitude of the lines of intersection of component lode fissures. However random an isolated high value on Grenfell Lode may appear, its vertical extensions into the unworked, blocked-out ground above and below, the estimated value of which is based on level development samples, is greater than its extent of influence along the level, as evidenced by adjacent sample values which may be only a fraction of the value of the high sample. The indiscriminate reduction of high values causes a serious under-valuation which correspondingly increases with the true lode value.

Alternatively, random high values on the Wethered Lode are less important since high value ore in the latter is localised by changes in dip and bunches of ore are elongated in a horizontal direction. Consequently, isolated high values are more justifiably reduced.

It is possible to recognize the major structural and ore distribution characteristics of a lode under rapid development and to thereby forecast the orientation of the major and localized ore-shoots and courses. The relative importance of out-of-place high values may then be appreciated more accurately and an "a priori" knowledge applied.

Development samples are utilized in the valuation of potential stoping areas on all the lodes. Since an estimation of the tonnage and grade of ore reserves should be as accurate as possible with any given number of samples, the decision whether or not to reduce apparently random high values must be considered seriously, and trial valuations should be made from both uncut and cut values for comparison. On the Witwatersrand, with which it has been demonstrated that comparisons are valid, the practice of reducing values has been discontinued following theoretical and practical investigations by Sichel (1952) and numerous other writers listed in the latter's publication.

Preliminary estimates of a mine call factor at Geevor Mine exceed 100%; a figure of which the only virtue is its 'conservatism'. An effort should be made to determine a realistic factor which will indicate losses incurred in the mining and underground transport of the ore. The effect will be revealed of such practices as the tipping of waste development rock down the ore-passes and the leaving of ore on the stope walls when a convenient parting plane exists within the lode. Otherwise the management will continue to delude itself by the mathematical adjustment of the observed samples, and losses of ore which would be brought to light will remain unrectified.

Jackson (1947) discussed the subject generally with reference to the Witwatersrand, concluding:

"It follows that only under certain conditions can the reduction of high values really be justified. Some mining engineers will not allow high values to be reduced under any circumstances whatever and there is much to be said for this. Such a policy may result in a greater discrepancy between the gold 'called for' and that 'accounted for', but it is far better to have such a discrepancy based on actual results, than a closer comparison brought about by adjustment".

and finally:

"On some mines reduction is allowed only in the case of exceptionally high values in development sampling; on other mines values are cut to a considerable extent and therein lies the danger of abuse. Some Mining Engineers favour a system of cutting so-called high values merely for the purpose of being conservative; others use this system in an endeavour to make the gold 'called for' by the sampling agree with the gold 'accounted for' by the Reduction works. This, of course, is utter folly for in so doing they overlook the possibility of other errors being hidden which could permit the loss of a certain amount of gold to pass unnoticed. In any case, no cutting or discounting of values should be permitted by anyone other than the person directly in charge of the sampling, and quite definitely, the method adopted should by systematic and not haphazard".

9/3 Ore Shoots and Courses

"Both these lodes (the North Pig and South Pig) as a whole are exceptionally remarkable for their consistency of productiveness over lengths of thousands of feet, and average between 28 and 4 inches in width".

.... Leggett (1920).

(a) Introduction

In most of the lodes there is a well defined demarcation between the payable and non-payable ground. Stoping sections indicate the major extent of payable ground and, to a limited degree, the effects of temperature and structural control upon tin distribution. For example, that of the North Pig Lode, shown in Fig. (81), reflects the major zoning apparent throughout the mine.

Within any major course of payable ore, the form of which is indicated by a completed stoping section, there are well defined shoots of high value ore separated by patches of relatively low-value, although payable, ground. The immediate recognition of these ore-shoots is imperative both during major lode development and exploration, and in the interpretation of the structural controls which cause their localization.

No stoping sections indicate the presence or location of high-value areas above the pay-limit and a graphical distortion of the extent of ground in excess of the latter is caused by blending different ore grades and the removal of small patches of individually non-payable ground to be added to high grade ore.

A further disadvantage entailed in the sole use of such sections is that stoping of a particular lode must be completed before an interpretation of the overall payable ore distribution is possible. Any graphical method of representation of the cassiterite distribution must be based upon the level samples as soon as the development of a lode commences.

(b) Graphical Representation

Variations in the lode grade or lode value of a blocked-out area may be graphically represented on a linear scale, the abscissa being provided by the level drives on a longitudinal lode section. This technique is illustrated in Fig. (85) which shows the lb./ton figures from samples over the developed portions of the Wethered Lode represented on a section of the latter.

Fluctuations in the cassiterite content are clearly visible, being preserved in the representation, but an overall visual appreciation or measured record of the orientation and magnitude of any ore-shoots, courses and bunches is not easily obtained.

An alternative method (not illustrated) employed by the writer consists of contouring, on a longitudinal lode section, the figures evaluated in the estimation of stoping blocks for the reserve calculations. Although, by this method, the form of ore-shoots above the pay-limit and the intervening relatively low-value areas may be approximately appreciated, minor variations in value within localized areas are no longer evident since the mean is based upon too large an area. Any variations in the lode value which are not naturally random but due to structural controls are too effectively meaned out and almost completely disappear.

Attempts to contour the various metal contents of fissure veins have been made by many writers including Mills (1950), Koch (1956), Koch & Link (1960), and Gross (1956). The only such attempt to graphically represent tin variations was madeby Turneaure (1935) who illustrated the distribution of 'high grade ore' and the 'limits of ore' in one of the Bolivian Llallagua tin veins.

Lode Contour Diagrams

9/4

(a) Introduction

An attempt was originally made by the writer to contour the individual level development samples in conjunction with raise and stope samples, but this technique was prevented by the high localized fluctuations and by the low number of stope development samples in relation to those taken along the levels and raises. For this same reason, and because of the high standard deviation, it is impossible to correlate separate valuations based on level and raise sampling or, alternatively, on stope sampling.

Although the tin content of a lode fluctuates considerably the cassiterite is not randomly distributed throughout the lode as a whole. If a small number of samples were taken in order to estimate the average value they would have to be spaced at equal intervals throughout the whole lode and not systematically concentrated over any portion of the lode. The standard deviation and arithmetic mean of the lode value, determined from any number of equally spaced samples taken over portions of a lode, progressively vary.

A determination of the standard of the mean to indicate the minimum number of samples required for a reasonable estimation of the lode value over part of a lode must be based upon the standard deviation over that portion, and not upon the standard deviation over the whole lode, which includes both stoped and unstoped areas.

The average level interval is about 100 feet and if only level development samples are employed in lode value contouring the arithmetic mean must be taken over a minimum development distance of 100 feet. When the oreshoots tend to be oriented in a vertical direction this interval may sometimes be reduced to 50 feet, but for the Wethered Lode, for instance, it

must be maintained at 100 feet.

The arithmetic mean of 20 development samples over 100 feet is a fairly reliable estimate of the correct value. Although unsuitable for valuation purposes, it provides a sufficiently accurate indication of the average value of a length of ground for geological interpretation, for which purpose only the contoured diagrams produced by the present writer were intended.

(b) Production

The following procedure has been evolved by the writer in order that the distribution of cassiterite in the lodes may be graphically demonstrated from zero to about 300 ft.lbs./ton. Although the contour diagrams do not indicate the extremely localized fluctuations in tin content (the standard deviation over 100 feet sections) they accurately define the orientation and size of ore-shoots, courses and bunches.

For the more recently developed lodes records are maintained of the 5 ft. development samples before the random high values are reduced and where possible these figures have been employed in the determination of the arithmetic mean over 100 ft. level intervals. For some of the older lodes, such as the North Pig and No. 2 Branch Lodes, the 5 ft. development sample records are no longer readily accessible, but longitudinal lode sections to a scale of 1 inch to 30 feet are available and show the extent of stoping and the averages of pairs of 5 ft. samples as lode width and lode grade figures. These incorporate reduced samples but this fact is not of relative importance since the results are employed only for geological interpretations.

Development samples from either the longitudinal lode sections or the development sheets were utilized on a standard calculating machine to determine arithmetic means of the lode width, grade, and value over 100 ft. sections. The computed means were superimposed upon longitudinal lode sections to a

scale of 1 inch to 100 feet, and contoured in the standard manner. An example of the graphical technique is provided by an original lode value contour diagram of the Footwall Branch Lode illustrated in Text Fig. (3).

Lode width, lode grade and lode value contour diagrams have been presented in this thesis to a scale of 1" to 400 ft. for the following lodes and major prospects:

The 'A', Borehole, 'C', Coronation, 'D', Footwall Branch, Hanging-Wall Branch, New, North, North Pig, North West Branch, No. 1, No. 1 Branch, No. 2 Branch, Wethered, and Wethered No. 2 Branch Lodes, and the Prospects No. 1 East, and South.

(c) Application

Like those of many of the abandoned mines in the South-West, the lodes of Geevor Mine become, in the minds of those persons who have been acquainted with them progressively richer with time.

One of the most important immediate applications of the contour diagrams is to provide an overall appreciation of the tin distribution throughout the mine, together with variations above the pay-limit, which cannot be obtained from a diagrammatic or model representation of the stoped-out portions of the lodes.

Parts of the lodes containing more than 100 ft.lb.SnO_2/ton are indicated in Fig. (68). Owing to their either recent development or very early exploitation the distribution of cassiterite in the South Pig, Caunter and Footwall Branch Lodes is not included in Fig. (68). Distortion arises from the flatter lodes exposing a greater area in plan than the steeper, near vertical, and overturning lodes. There is a fair distribution of higher value ore throughout the mine and such notions that "the lodes are richer near the contact" or that the "old Pig Lodes were the richest" are shown to

have very little verification.

Comparisons between the major structural characteristics of the lodes are visually provided by Figs. (48), (49) & (97). Although the major ore-shoot on the North (West) Lode is comparable with major courses occurring in the No. 2 and No. 3 Branch Lodes, the relatively steep WNW-striking lodes, taking into account the relative sizes, appear to contain more extensive, consistent courses or shoots of higher value ore than the structurally, equally well developed, flatter lodes.

Major faults and fault zones, indicated in Fig. (103), coincide in plan with lines connecting the terminations of high value areas. The higher value mineralization of the No. 3 Branch Lode is terminated against F_1, and that of the Coronation (West) Lode against F_2, whilst the latter, together with F_3, marks the end of the high value mineralization on the No. 2 Branch Lode. The southward continuation of F_3 may be correlated with the mineralization of the No. 1 Lode, whilst F_5 loosely marks the terminations of higher value ore on the Wethered and North (East) Lodes and may be similarly related to the Prospect South and North Pig Lode.

An even closer relationship is shown by the fault zone, FZ_1, which coincides in plan with the terminations of higher value ore on the No. 3 Branch, 'D', No. 2 Branch, and North (West) Lodes. Further east, the Hanging-Wall Branch Lode bears a similar relation to the high value mineralization on the 'C', Coronation (West), and North Lodes, but FZ_2 bears little immediately visible association with the extent of high value mineralization.

Lode junctions are not generally the sites of widespread cassiterite enrichment, although there are often localized increases which are not visible in Fig. (68). Major higher value areas are usually situated midway between the lateral limits of a lode, or, when the mineralization is confined

between another lode and a major fault, between the two features concerned.

A model of the Geevor Mine workings, shown in Text Figs. (1) & (2), has recently been constructed. It is invaluable in the planning of underground exploration and major development when a rapid appreciation of the local complexities of lode structure, which can never be adequately gained in a comparable time from a mine plan alone, is necessary.

A further supplementary model to a suitable scale (say 1 inch to 100 feet) showing only the form of the lodes, and uncomplicated by the individual level drives and cross-cuts, would have an important application. Changes in the extent of cassiterite mineralization, shown by the lode value contours presented by the present writer, could be depicted upon a materially continuous form representing the detailed attitude of the lodes. The correct effect would not be gained by superimposing any legend depicting the stoped areas or variations in the tin content of the lodes upon the mine workings of the existing model, or on another of the same design.

The practical application of the contour diagrams in the everyday development of individual lodes is so obvious that it requires no further amplification. Contour diagrams, such as that illustrated in Text Fig. (3), should be maintained by the resident geologist for all the lodes under development.

(d) Interpretation

The contour diagrams allow a visual and graphical comparison between both the lode width and tin content and also between the latter two features and the structural variations, especially dip and strike, within the individual lodes.

Conolly (1936) provided a useful graphical technique for contouring the minor structural characteristics of a fissure vein, combining both the dip and strike into one diagram. The result resembles a topographical contour map with respect to a fixed reference plane (comparable with sea level) which

is individually selected for each vein.

This method has been applied by the present writer to the No. 3 Branch and Wethered Lodes as shown in Figs. (84) & (85) respectively. The choice of a correct reference plane is very important since slight changes in its attitude greatly alter the amount of information obtainable from the final diagram. This is demonstrated by the three Conolly diagrams of the Hanging-Wall Branch Lode constructed from different planes, as shown in Fig. (78).

Changes in the major lode structure may often be related to variations in the tin content of the Geevor lodes, but within structurally favourable portions changes in the supplementary minor structures equally affect the value. For example, the economic ore on the Wethered Lode is mainly confined to the relatively straight central portion, within which variations in the tin content are susceptible to slight changes in the lode dip and strike. In order to interpr : such small, but critical changes in the minor lode structure the present writer devised a technique for the production of a curved (in plan) reference plane, but the method is so tedious that, except only for the most detailed studies, its everyday use is quite impracticable. Without its occasional employment, however, overall major changes in the attitude of a lode mask the less obvious inflections.

Even when a lode is fairly constant in attitude and may be interpreted with a uniform reference plane, the choice of a correct plane is tedious. The present writer has found it more convenient to first construct Lode Dip and Lode Strike diagrams which individually demonstrate variations in each of these features.

If indications of structural control are provided by these diagrams, examples of which are illustrated in Fig. (84), one may then construct a

Conolly diagram, the choice of reference plane being guided by the lode structural maximum obtained as illustrated in Fig. (43), and by the preliminary interpretations of the Lode Dip and Lode Strike diagrams.

The production and utilization of the contour diagrams makes possible a correct interpretation of the form and attitude of the many ore-shoots, courses and bunches, together with any relation that they may bear to lode and fissure intersections, branches, faults, the granite contact, and numerous other features.

9/5 Detailed Distribution

"Apart from the difficulty experienced in following them, owing to the large number of branches thrown off, the two Pig Lodes, so far worked, exhibit one very noticeable and favourable feature, namely a remarkable consistency or uniformity of productiveness which has allowed their being stoped away continuously over lengths of many hundreds of feet. Many lodes carry payable ore only in shoots, separated from each other by lengths of unproductive ground of greater or less extent, which have to be left. On the Pig Lodes practically no such bars of unproductive ground are met with, except where the lode is split up and disordered".

.... Collins (1920).

No written description, however lengthy, replaces a detailed examination of the contour diagrams themselves. The individual lodes are briefly described below, but a comprehensive appreciation of the cassiterite distribution in each may be obtained only from the diagrams.

To attain a more convenient brevity the terms iso-dips, iso-strikes, iso-widths, iso-grades, and iso-values will be employed to denote respectively the contour lines in the lode dip, lode strike, lode width, lode grade, and lode value diagrams.

(a) The 'A' Lode - see Fig. (72).

Most of the cassiterite mineralization is confined to the west of the intersection with the Hanging-Wall Branch Lode although payable ground also extends to the east. A poorly-defined ore-shoot possesses the same inclination to the SE as the line of intersection of the Hanging-Wall Branch and 'A' Lodes. Its attitude and dimensions are reflected by the lode width, grade and dip contours, with an apparent agreement between the localities of high lode value and areas of relatively low lode dip.

Compared with the other Geevor lodes, the 'A' Lode is neither extensive nor rich, with only one small area exceeding a mean value of 100 ft.lb. SnO_2/ton.

The lode width is variable, with averages of 18 inches and 9 inches for the upper and lower fissures respectively.

(b) Borehole Lode - see Fig. (73)

The lode width, grade, and value diagrams of the Borehole Lode indicate a close agreement with the structure, which is illustrated by the Conolly diagram. To the west a well defined ore-shoot is localized by the line of intersection, inclined to the SE, of the individual lode fissures comprising the Borehole Lode. The base of this ore-shoot, which widens and increases in value in depth, has not yet (1962) been located since it lies on, or below, Level 14.

Elsewhere throughout the lode there is a poor agreement between the regions of high value and high width. Bunches of higher value ore are concentrated where there is a reversal of the direction of dip. The average lode width is about 19 inches, but when the diagrams were constructed, the Borehole Lode was not exceptionally rich, except in the lowest level.

(c) The 'C' Lode - see Fig. (74).

Most of the economic mineralization on the 'C' Lode, of which the average width is 18 inches, is confined to the west of the line of intersection of the latter and the projection of the Hanging-Wall Branch Lode. The iso-values bear some relation to the lode structure which is indicated by the Conolly diagram, but it is impossible to state categorically that the higher value ore is confined to the relatively steeper or flatter portions of the lode. Considering the extensive driving on the 'C' Lode it is not rich and only a small percentage area maintains an average value in excess of 100 ft. lb. SnO_2/ton.

(d) Coronation Lode - see Fig. (75).

Of the two major areas of relatively high value ore in the Western section of the Coronation Lode, the less important is situated between, and elongated in the same direction as, the line of intersection (not shown) of the upper and lower fissures and that of the Coronation Lode and Coronation Footwall Branch.

The other high value area, with no well-defined elongation, is confined between the lines of intersection (not shown) of the Coronation Lode with the 'D' and Hanging-Wall Branch Lodes, and particularly, except in the upper levels, to the west of the latter. Each area is reflected by corresponding increases in the lode width and value.

The junction of the Western and Eastern sections of the Coronation Lode is characterized by a widespread increase in the lode width but is not directly associated with a bunch of ore confined to the west of the junction. An additional ore-shoot, associated with a low lode width area, is situated between, and with the same inclination as, the intersections of the Coronation Lode with the Wethered and North Lodes.

The Western and Eastern sections are comparable in value, with approximately 15% of the total lode area exceeding a mean value of 100 ft. lb. SnO_2/ton, but with very few portions exceeding the figure of 200.

(e) The 'D' Lode - see Fig. (76).

A major course of ore, divisible into two sections, is confined to the west of the intersection with the Hanging-Wall Branch Lode. The component ore-courses are inclined at about 20° to the NW although the lower limit of economic mineralization is roughly horizontal.

The extent of mineralization is very sensitive to changes in the structure of the lode, but although the major course is situated in an area of constant dip, high value ore is situated in areas of both relatively high and low dip. In contrast to the Borehole Lode, changes in the direction of lode dip result in the development of impoverished areas. In the centre and lower portions variations in the value are directly reflected by the width.

The lode possesses an extensive area of high value, almost one third of the lode area averaging a value in excess of 100 ft.lb.SnO_2/ton, despite the relatively low average width of 16 inches.

(f) Footwall Branch Lode - see Fig. (77) and Text Fig. (3).

The Footwall Branch Lode during March 1961 and December 1961 is illustrated in Fig. (77) and Text Fig. (3) respectively. A lode value diagram in the former, constructed from arithmetic means evaluated over 100 ft. lengths, demonstrates the tendency of the ore to form bunches. Only Text Fig. (3), which employed means over 50 ft. lengths, demonstrates the formation of ore-shoots, particularly along the line of intersection of the Footwall Branch Lode and Hanging-Wall Vein.

This association with a lode junction is the reverse of that demonstrated by the smaller bunches of ore formed nearer the North Lode and which are situated mid-way between the lode junctions. Although the Footwall Branch Lode is not yet fully developed, it appears comparable in overall value with the Coronation Lode. Continued development west on the upper levels will, as shown in Text Fit. (3), indicate the full extent of the ore-shoot localized around the junction with the Hanging-Wall Vein.

(g) Hanging-Wall Branch Lode - see Fig. (78)

While the three Conolly diagrams illustrate the influence of lode structure upon the extent of mineralization, the stoped areas are generally

confined to those of relatively high dip, and are situated between the 'A' and 'D' Lodes and between the South Pig and North Lodes. The upper limit of economic mineralization is inclined to the north at about 10°.

The Hanging-Wall Branch Lode is not comparable in extent with many other lodes, but for its size it contains a large amount of well-defined stoped ground. The average lode width, except over a section between the 'A' and 'D' Lodes, is comparable with that of the New Lode.

(h) New Lode - see Fig. (79).

Higher value areas in the New Lode occur as bunches which constitute a course of ore inclined to the NNW at about 15°.

The projection (not shown) of the North Pig Lode fissure (west of the North-West Branch Lode) divides the New Lode into two sections. In the Southern section high values, which are reflected by an increased lode width are concentrated in the areas possessing a high lode dip. To the north, regions of relatively low lode dip are more favourable to economic mineralization. The intersection between the New Lode fissure and that of the Western section of the North Pig Lode is characterized by the occurrence of higher values.

Bearing in mind the different extent, the New Lode is comparable with the Coronation Lode in value, but is narrower with a mean width of only 10½ inches over the whole developed area.

(i) North Lode - see Fig. (80).

In the Western section of the North Lode a major, centrally-situated ore-shoot is confined between the North Pig and Footwall Branch Lodes above Level 10, and localized around the junction with the South Pig Lode, as shown

in Text Fig. (3). It is inclined to the SE at the same angle as the lines of intersection between the North Lode and the immediately adjacent lodes, and is situated in a region of relatively high lode dip.

An additional, equally important ore-shoot in the Western section is associated with, and assumes the same inclination as, the lines of intersection of the North Lode with the North Pig and Hanging-Wall Branch Lodes. It is not directly related to any areas of relatively high lode dip but, in common with the other ore-shoot, its upper limit is situated beneath a point at which the lode dip decreases.

Both major ore-shoots are reflected by corresponding increases in the lode width and lode grade. With a high average width of about $23\frac{1}{2}$ inches, the North (West) Lode has been one of the major producing sections of the mine, comparable with only the No. 2 Branch and No. 3 Branch Lodes.

A relatively small, horizontally-elongated, bunch of ore in the Central section is not situated in a region of relatively high lode dip, but beneath, at a point where the dip decreases below the average. It is not reflected by any pronounced increase in lode width, although the average width of the Central section is $19\frac{1}{2}$ inches.

The lode structure and mineralization distribution of the North (East) Lode, of which the average width is 22 inches, are very similar to those of the Wethered Lode. A major, horizontally-elongated course of ore is confined between the junction with the Coronation Lode and the major fault to the east. Its length is more than twice its vertical extent, and whilst the lower and middle economic portions of the lode are situated in an area of relatively high lode dip the upper limit of the ore-course coincides with a sudden decrease in the dip, again in similarity with the Wethered Lode.

(j) North Pig Lode - see Fig. (81).

According to both major structure and mineralization distribution, the North Pig Lode is divisible into four sections:-

(a) between the No. 2 Branch and North Lodes;

(b) between the North Lode and North-West Branch Lode;

(c) between the North-West Branch and New Lodes;

(d) to the east of the New Lode.

Although each section is different, the North Pig Lode as a whole, possesses some general characteristics of major ore distribution. Courses of ore, corresponding with each of the major structural divisions of the lode, comprise bunches and shoots of higher value which tend to be elongated in a direction which is more or less vertical but inclined slightly to the SE. They correspond only partially, but more perfectly in the west, to the areas of high lode width and grade.

There is usually no increase in the lode value at a junction of two component lode fissures, except at the intersection of the North Pig Lode and North-West Branch Lode, where the latter is a structural continuation of one of the component North Lode fissures. In the Eastern section, to the east of the junction with the New Lode, areas of high Lode value, which are not always reflected by increases in the width, are situated in the regions of relatively high lode dip.

(k) North-West Branch Lode - see Fig. (82).

Between the junctions with the North and North Pig Lodes, there is a small bunch of ore, reflected in corresponding increases in the lode width and grade.

(l) No. 1 Lode - see Fig. (70).

A small ore-shoot, with a corresponding increase in the lode width, is inclined at a high angle to the SE, and its situation is related only to changes in the lode strike.

(m) No. 1 Branch Lode - see Fig. (82).

In an area of relatively high lode dip a small bunch of ore is confined, with the exception of the upper levels, to the west of the junction with the North Pig Lode.

(n) No. 2 Branch Lode - see Fig. (83)

In common with the 'D' Lode, the No. 2 Branch Lode contains a major course of ore, with subsidiary bunches, which is inclined at about 20° NW in the same direction as the granite contact. Both the upper and lower limits of the ore-course possess a similar inclination but the superimposed bunches are slightly elongated to the SE and parallel with the line of intersection of the No. 2 Branch and North Pig Lodes.

Most areas of high lode value are associated with increases in the lode grade, but there are several unrelated lode width anomalies. Most of the high value areas coincide in position with those of relatively low lode dip, but there is a closer correlation with the two major faults and with variations in the strike, as indicated by the plan of the workings. The effect of a change in the direction of dip upon the extent of mineralization is inconsistent, and the average lode width is low, being about 14 inches over the completely developed area. The No. 2 Branch Lode was an important producer with almost one third of the lode possessing an average tin content in excess of 100 ft.lb.SnO_2/ton, and several areas exceeding a figure of 250.

(o) No. 3 Branch Lode - see Fig. (84).

The No. 3 Branch Lode is characterized by a major course of ore inclined, in the western half, to the NW in common with the granite contact but at an angle of only 20°. The lower limit of economic mineralization is inclined at a less angle than the upper one. Economic mineralization is terminated abruptly at the granite contact in the west, as indicated by the stoping section (not shown), and to the east by the projection of the Hanging-Wall Branch Lode.

Within the major ore-course there are three bunches, reflected in corresponding increases in the lode width and grade, although there are some anomalies in the latter near the granite contact. The bunches are confined, as shown in Fig. (141), between the major faults, the North Pig Lode, the major fault zone FZ_1, and the Hanging-Wall Branch Lode. They are localized in the intervening areas by intersecting fissures making a small angle in plan with the lode.

There is an ill-defined agreement between the major lode structure, the cassiterite distribution, and changes in lode width, some of the latter being due to intensive wall-rock alteration.

The No. 3 Branch Lode deserves its reputation as the richest lode in the mine, since over 40% of the blocked out area possesses an average value in excess of 100 ft. lb. SnO_2/ton with some parts exceeding a figure of 300.

(p) Prospect East - see Fig. (70).

The Prospect East is not sufficiently extensive to present any deductions but it is noticeable that the highest values are localized around the Complex Dyke.

(q) Prospect No. 1 - see Fig. (71).

The lode is very similar to the Grenfell Lode when the latter was first contoured on Levels 8 and 9, and for several other reasons development may prove to be rewarding, although limited, in depth.

(r) Prospect South - see Fig. (70).

Areas of high values, reflected by increases in the lode width, are mainly concentrated where the dip is relatively high and are possibly limited in the upper levels by a decrease in the lode dip.

(s) Wethered Lode - see Fig. (85).

In common with the North (East) Lode, which is structurally similar to the Wethered Lode, the latter contains a major ore-course with a horizontal extent over twice that in the vertical direction. It is limited between the junction with the Coronation Lode in the west and the major faults F_5 and F_6 to the east, although most of the economic ore is confined to the east of the junction with the Wethered No. 2 Branch Lode.

The coincidence between the high value, which is reflected by the lode grade and width, and relatively high dip areas may be appreciated from the Lode Dip and Conolly diagrams. Subsidiary, vertically-elongated, minor ore-shoots, also associated with regions of relatively high dip, occur in the lower part of the the lode. The average lode width over the developed area at the time of construction of the diagram is $25\frac{1}{2}$ inches, and, in common with the North (East) Lode, the ore-course is terminated more rapidly in the upper than in the lower portions of the lode.

(t) Wethered No. 2 Branch Lode - see Fig. (71).

The upper limit of the only bunch of ore, which is terminated to the south against the North Lode, is inclined to the north at about 10°. Despite the major structural differences between the Hanging-Wall Branch and the Wethered No. 2 Branch Lodes, the ore in both is concentrated in areas of relatively high lode dip, and each has yielded ore of a comparable grade and value.

9/6

Summary

According to their major and minor structure, overall movements, mineralization distribution, and mineralogy, the Geevor Lodes may be divided into six groups, signified by their most typical member:

(a) 'D' Lode group, including the No. 2 Branch and No. 3 Branch Lodes.

(b) Coronation (West) Lode group, including the Footwall Branch, North (West), and 'C' Lodes.

(c) New Lode group, including the North (Central), South Pig (Central), and Coronation (East) Lodes.

(d) Borehole Lode group, including the North Pig and Grenfell Lodes.

(e) Wethered Lode group, including the North (East), South Pig (East), and Caunter Lodes.

(f) North-South group, comprising the Hanging-Wall Branch and Wethered No. 2 Branch Lodes.

Many smaller lodes and prospects may be assigned to the above groups, but often with little certainty since they possess conflicting characteristics, often due to the small extent over which they are at present exposed or economically formed. Nevertheless, a structurally similar, subsidiary class, consisting of the 'A' (Lower) Lode, the Prospect No. 1, the Prospect between the 'D' and Coronation Lodes, and the South Pig (West) Lode, could be added to the 'D' group.

(a) 'D' Lode Group

This group of lodes, characterized by the relatively high SW dip and fairly constant NW-strike, possess major ore-courses inclined at about 20° to the NW under the structural and temperature zoning influence of the granite contact.

Within these courses bunches of ore are localized at low angle (in plan) intersections, and are situated midway between the junctions with other lodes and with major faults and fault zones.

All the lodes of this group, which are the most consistently rich in the mine, have been subjected to movements equivalent to an overall reverse faulting through about 5 to 10 feet, in a direction possessing a high SE inclination. However, the high value ore is concentrated in areas of both relatively high and low lode dip, and may often be related to changes in the strike. Each lode occasionally reverses its dip direction, to the detriment of the value in the NE-dipping section. The bunches are generally terminated below the point of dip inversion. Ore-shoots are neither common nor associated with lode junctions and similar structural features.

Wall-rock alteration is very variable and often intense. In the latter case it constitutes a major proportion of the lode width and grades into the infilling of a very narrow central fissure. The value of the lodes is highly susceptible to the presence of major faults, fault zones, and lode junctions, between pairs of which the higher value bunches are usually situated mid-way.

The lodes have been subjected to several mineralization phases, and although sulphides are fairly common, the later phases in which quartz predominates are not well represented.

The 'D' Lode group exists mainly in the Western unit of the mine. It is only partially represented in the Central Unit by such minor lodes and Prospects as the 'A' Lode (lower), 'D' Lode (East of the Hanging-Wall Branch Lode), Prospect No. 1, Prospect between the 'D' Lode and the Coronation, and South Pig (West) Lode. The above are structurally similar to the major group, and, like the 'D', No. 2 Branch, and No. 3 Branch Lodes, their horizontal developed extent (not their associated ore-courses and bunches) is greater than their vertical

extent, but they are of relatively low production importance and are small in size.

(b) Coronation (West) Lode Group.

The lodes of this group are similar in strike to those of the 'D' Lode group, but possess a relatively low SW dip. Their strike range is greater and the lodes are more curved in plan. Each has been subjected to movements corresponding to normal faulting through about 10 to 20 feet. The direction of movement is inclined to the SE and equivalent to most of the lines of intersection between other lodes and members of this group.

With the exception of the North (West) Lode, the lodes are not so productive as those of the 'D' Lode group although they are approximately $1\frac{1}{2}$ times the average width of the latter and their fissure width constitutes a high percentage of the lode width. Stoping is necessarily more selective and the ore occurs more often as elongated bunches or major shoots, in which increases in the lode value are reflected by corresponding rises in the grade and width. They are inclined in the same direction as the overall relative movement of the lode walls.

In each lode the horizontal extent of major economic mineralization is greater than that in depth and the effect of temperature zoning is obvious. Major ore-shoots with a large vertical extent are confined between adjacent high angle intersections (in plan) with other lodes, and are often localized along the line of junction with additional lodes which make a relatively small angle of intersection. The vertical extent of economic mineralization in each lode is usually greater at the western end.

Their localized value is not very susceptible to changes in strike, and the higher values are usually located in areas of relatively high lode dip, the ore shoots being terminated directly below points at which the dip substantially

decreases. The productive capacity of this group of lodes, with the exception of the individual ore-shoots, is not comparable with the 'D' Lode group in which the values are more consistently high.

With less intense wall-rock alteration than around the lodes of the 'D' Lode group, the values are concentrated, with a few exceptions such as that illustrated in Photo. (80), in the lode infilling. Post-cassiterite mineralization phases, resulting in the formation of quartz, calcite, siderite and fluorspar are common.

Most members of the Coronation (West) Lode group are situated in the Western unit, but are slightly in evidence in the Central unit. In common with the lodes of the 'D' Lode group, the extent of economic mineralization is related to the presence of the Hanging-Wall Branch Lode. Owing to its low value the 'C' Lode is an exception in this group, but the possibility should be entertained that the major producing area of the lode, possibly at depth, has not yet been located.

(c) New Lode Group

With a SW and S dip, the lodes of the New Lode group possess a wide strike variation between nearly N-S and nearly E-W, and for the latter reason the North (West) Lode could probably be included. Their dip is variable but at times is relatively flat and is comparable with that of the Wethered Lode group. However, the strike is very irregular over short distances and the lodes often tend to be predominantly curved towards their eastern and western limits. Strike changes, in contrast to those on the Borehole Lode, are continuously visible from one level to another in plan and are due to the combined effect of the component lode fissures possessing the same overall variations in strike as the complete lodes. Lines of intersection of component lode fissures, and the junctions between individual lode sections, are always inclined to the S.E.

The group is normally developed in the Central unit and the western part of the Eastern unit, and the members show very little evidence of zoning in value along their strike. Despite their large extent when fully developed, their overall value, although economic, is low.

Possessing numerous branches, the lodes are normally faulted through about 5 to 20 feet in a direction inclined to the SE at the same angle as the lines of component fissure intersections. The ore occurs as bunches which are sometimes, although equally often not, related to increases in the lode and fissure widths.

High angle intersections (in plan), under which category junctions between lodes of the same group may be placed, usually terminate the higher values which may exist in either lode on one side of the intersection.

The ore-bunches, with no dominant elongation direction, are confined between pairs of intersections and in areas of both relatively steep and low lode dip. They show a preference for areas of consistent lode strike, and tend to be terminated below points at which the dip increases or decreases rapidly.

The lodes are continuous into the members of the Coronation (West) and Wethered Lode groups existing in other units, and with which for practical mining purposes they are continuous. They are characterized by the presence of post-cassiterite, quartz-rich, mineralization phases, and those typical of the North Levant Lode are very much in evidence.

(d) Borehole Lode Group

The lodes of the Borehole Lode group are structurally more complex and composite than any others in the mine, and each comprises several lode fissures which may be reduced to four planes of movement. Upon dividing a lode into its integral fissures it becomes apparent that the vertical and horizontal

dimensions of the extent of economic mineralization are of the same order.

The higher value ore occurs either as irregularly shaped bunches in the centre of the individual component lode fissures, or as ore-shoots localized along the lines of intersection of the latter. Bunches are situated in areas of either relatively flat or steep dip. Several ore-shoots are reflected in increases in the lode width but the bunches, which are sometimes located at the points of inversion of lode dip on the Borehole Lode, may be associated with either local increases or decreases in lode width. A widespread increase in lode width is consequ ntly not always indicative of a rise in the lode value.

Whereas the lodes of other groups are paralleled in their attitude by the surrounding joints, those of the Borehole Lode group are usually steeper than the joints which are, nevertheless, always present, as shown in Photo. (84).

Zoning effects are very conspicuous along the overall strike of the lodes, which have been subjected to several phases of infilling, with the general exception of the later quartz-rich phases. Wall-rock alteration is very changeable in intensity and form, varying from widespread alteration to only a little kaolinization of the walls.

Wherever there is a marked change in the lode strike there is often a continuation beyond the point of inflection of several joints and fissures along the original strike direction. The component fissures lead naturally into one another and each should be thoroughly investigated during development. Fig. (119) shows the important overall continuity of this group of lodes, and the importance of their persistent development is immediately evident to even the most casual observer. Although the component fissures are not exceptionally high in value their combined extent contributes to their overall productive importance.

(e) Wethered Lode Group

With a very curved outline and a relatively very flat SW dip, the members of the Wethered Lode group possess an average WNW-ESE strike, and are convex in plan to either the SW or NE. High value ore always occurs as a major horizontally-elongated course, the length of which is more than twice its vertical extent. Since the ore-courses, which show no effects of zoning, always possess a 'root' the final fully developed length of the lodes is only $1\frac{1}{2}$ times their total depth.

Each lode is normally faulted through about 10 feet, and the high values, including the root of the ore-course, are localized in areas of relatively high dip, the upper limit being situated beneath an area of decreased dip.

Courses are limited between high angle lode intersections (in plan) and major faults, such as F_5 and F_6. Within such limits the lode strike is slightly more constant, although still convex, but the localization of the high value areas shows no preference for any particular strike direction, as in the case of the lodes of the 'D' Lode group.

The lode strike shows a constant rate of change but on a very minor scale the lodes tend to comprise, as noted by Collins (1920), numerous short, variously-striking sections which together result in the curved outline.

Each contains the results of several mineralization phases and quartz is a major constituent, to a greater extent than in any other lodes. Calcite, siderite, fluorspar, and many different forms of low-temperature quartz are common, with numerous vughs and relatively little wall-rock alteration.

Occurring only in the Eastern unit of the mine, the Wethered group lodes are comparable in productiveness with those of the Coronation (West) Lode group, but are not so extensively developed laterally. The ore is always

concentrated into one major course, and the width of the lodes of the former group, when fully developed, is about 23 inches and among the highest in the mine.

(f) North-South Lode group

The Hanging-Wall Branch and Wethered No. 2 Branch Lodes, despite their major structural differences, possess comparable production records, with very variable widths and values. Their economic portions are confined between, and terminated against, high angle lode intersections.

Each lode exerts a strong influence upon the extent of mineralization in the lodes of other group with which it junctions, with no enrichment along the line of intersection of any of the lodes concerned. Like the other lodes of the mine the Hanging-Wall Branch and Wethered No. 2 Branch Lodes have been subjected to several periods of movement, resulting in each case in an overall downward displacement of the hanging-wall.

Zoning effects cause the inclination of the upper zone of economic mineralization to the north. The lode value and wall-rock alteration are extremely variable, and the two lodes are among the least productive in Geevor Mine.

Numerous prospects and crossing fractures could be included on structural grounds in this group, but do not qualify because of their lack of economic mineralization.

(g) Application

The lodes of the Pendeen-Botallack area have been grouped in Figs. (18) and (119) according to their average dip and strike respectively. With the use of plans and available stope sections of the relevant mine workings, and appreciating that some lodes may not have been fully developed, further

structural classifications may be made.

By employing published accounts of the mineralogical characteristics of the same lodes the present writer has placed them in the groups outlined a above. In this way it is possible to provide a clear portrayal of the lode characteristics in the Pendeen-Botallack area thereby utilizing an "a priori" knowledge in all exploration and development.

10. MINERALIZATION

"With respect to the external appearance of St. Just, nothing can present a more forebidding and discouraging aspect to a stranger, than the barren and rocky country on which he will enter at the distance of 3 miles from Penzance, and which will accompany him all the way to St. Just; and if, on his arrival there, he shall expect, from the description which I have given, to find any of the minerals so prominently situated as to salute his eyes at once; or if he shall suppose that those objects which are especially worthy of notice in a geological point of view, are to be discovered and examined in the space of a few hours; he will be greatly mistaken and disappointed; for very few, either of the minerals or the veins, are to be found in situ, but by diligent, patient, and persevering search ...."

.... J. Carne (1822).

10/1 Introduction

Cronshaw (1921) concluded that the complete mineralization of the lodes of the Camborne-Redruth district had resulted from several distinct phases. He listed ten, commencing with quartz, feldspar, wolfram, and arsenopyrite, and concluding with calcite. Weston-Dunn (1923) preferred to contemplate a single mineralization phase but he was outnumbered in his views by the majority who, like Lees (1914), concluded that the complete formation of the lodes arose from several phases, each accompanied by movements of differing extent and form.

As stated by Dines (1956), the detailed mineralization sequence may vary in the individual lodes and mines of South-West England, but the order of deposition of the component minerals is similar to the vertical order of arrangement of the mineral zones. He concluded that:

"Wolfram, cassiterite, and mispickel precede chalcopyrite which is followed by blende and galena, while the later metallic minerals are siderite, haematite and pyrite. The gangue minerals show a similar correspondence with the depth zones, being formed in the order; tourmaline, feldspar, chlorite, fluorspar, barite, and carbonates; quartz persists through nearly all the stages of mineral deposition. Fluorspar, though occasionally present as a primary

constituent along with cassiterite and chalcopyrite, occurs also as veins filling the last opening of the fissure, its usual position in the depth zones being in the upper part of the copper zone and in the lead-zinc zone."

Hosking (1951) outlined the main mineral components of the Cornish tin lodes and concluded that their entire infilling and associated wall-rock alteration arose from a series of mineralization surges, accompanied by changing temperature conditions.

The complete formation of the Geevor lodes similarly resulted from a series of well-defined phases. The first affected several parallel fissures and joints around the potential lode fissures. Succeeding phases, each accompanied by dislocation and movement, were increasingly concentrated in a central fissure which is now regarded as the lode. Displacements associated with each phase reveal the complex age relationships and a detailed study indicates that the Geevor lodes resulted from the following main mineralization stages, each comprising several component phases:

(a) Preliminary phases, mainly comprising wall-rock alteration.

(b) Economic phases, producing cassiterite and associated minerals.

(c) Supplementary phases, comprising the main sulphide, quartz, and succeeding phases.

Each phase possesses different spacial, mineralogical, and depositional characteristics, which are governed by the individual prevailing temperature and structural conditions.

10/2 Preliminary Phases

The rise in vapour pressure of the accumulating mineral solutions at depth in the St. Just area initiated the ascension of boron-rich gases. The consequent stages of wall-rock alteration were continuous into the first

infilling stages which gradually became dominant.

(a) Tourmaline Branches

Ground Movements were not a pre-requisite for the ascent of the boron-rich gases. They produced, especially at low angle (in plan) intersections between major fractures and potential lode fissures, intense tourmalinization of the granite which retains its original texture although the feldspars are completely replaced.

Such tourmaline branches, shown in Photos. (75) & (76), are common on the No. 3 Branch Lode, where they attain a vertical extent of the order of hundreds of feet and a horizontal one of only about 20 feet. They occur especially on the Wethered and Borehole Lodes where they provide, owing to their higher porosity, a site adjacent to the lode for the deposition of later cassiterite and sulphides. Otherwise, the tourmaline branches contain only trace amounts of cassiterite and do not justify any development. Fawns (1905) reported their occurrence in North Levant Mine where they were surrounded by a little kaolinized granite.

(b) Main Wall-Rock Alteration

Phase 1 in Fig. (140) embraces the majority of the wall-rock alteration forms previously listed, with the exception of heavy kaolinization, and discolouration. Innumerable fractures, of which the lode fissures are only a small percentage, were affected by some, or all, of the main forms including tourmalinization, chloritization, and reddening of the granite. Silicification is widespread but resulted mainly from the later economic mineral phases.

The main alteration phases were accompanied by some movements but these were so small as to prevent their evaluation at the present day.

(c) Sulphide and Cassiterite Impregnation

The order of occurrence of the cassiterite replacement and sulphide impregnation phases, shown in Fig. (140), is uncertain and at times is reversed. The effects of the sulphide impregnation process are illustrated in Photos. (41) & (42). Comprising arsenopyrite, chalcopyrite, and pyrite, the sulphides are formed as replacement products and by the infilling of cavities, often creating a spongy form shown in Photos. (88/A) & (100/B). This process is most common on the No. 3 Branch Lode and, although it occurs on the North Pig (West) and Borehole Lodes, it is rarely seen elsewhere in comparable and equally consistent quantities.

In its most intense form the sulphide impregnation affects only a few inches of wall-rock and is superimposed upon the innermost zones of wall-rock alteration. Arsenopyrite formed first in the wall-rock, mainly as a replacement product of feldspar remnants. It was succeeded by pyrite and chalcopyrite which increasingly tended to vein the rock and infill small cavities, in lieu of replacing the pre-existing minerals. With the exception of occasional pyrite, the sulphides are anhedral and the chalcopyrite invariably contains accessory tetrahedrite, enargite, and sphalerite.

In contrast to those resulting from the later phases, sulphides impregnating the wall-rock are not extensively altered to chalcocite and bornite, although there is frequently a secondary green colouration under conditions of more than average water flow. Arsenopyrite is sometimes altered to hematite, creating a characteristic hematization of the wall-rock.

The cassiterite originating by replacement of the wall-rock is extremely fine-grained and zoned in brown and white, as shown in Photo. (114). At its maximum development it affects only a few inches of granite and forms a very inconsistent boundary with the cassiterite-free rock, the degree of

fracturing of which is an important factor in the localization of this process.

Cassiterite may replace earlier arsenopyrite whenever its introduction is superimposed upon sulphide impregnated wall-rock. Chalcopyrite and pyrite, however, are usually later than the cassiterite grains round which they are moulded.

Dines (1956) reported a specimen of wall-rock from Level 11 of the North Lode to contain 17% by weight of cassiterite. An additional specimen, shown in Photo. (104/A), possesses, apart from albite veining, a substantial cassiterite content resulting from the replacement of feldspar.

This type of cassiterite mineralization, although sometimes causing a local high lode value, rarely produces consistently economic ground, but provides occasional high assay values which encourage continued level development.

(d) Tourmaline Infilling

Very slight movements accompanying the main alteration and impregnation phases rarely resulted in any significant cavity formation. As the dislocations continued slight openings were created in the major fissures and surrounding joints. These were immediately infilled with fine-grained tourmaline, constituting the first mineral infilling phase, and bordered by some tourmalinization of the granite.

With an increasing influx, the tourmaline attained a maximum infilling width, grading into altered wall-rock, of six inches. The tourmaline was fine- to medium-grained, zoned in brown, orange, green and blue, and set in a matrix of quartz, an example being provided by Photo. (104/C).

10/3 Economic Phases

Fig. (140) shows a grouping under economic, of Phases 5 to 9 inclusive. With the exception of the first and the addition of early wall-rock replacement, these have contributed the entire tin content of the Geevor lodes.

(a) Feldspar-Arsenopyrite

The first major movements and dislocation of the potential lode fissures, and the surrounding joints, permitted the formation of openings with a maximum width of about 6 inches. Arsenopyrite and salmon-pink feldspar immediately infilled the cavities. As indicated in Fig. (128/A), this mineral assemblage more normally accompanies a pegmatite association, and according to Hosking (1951) it demonstrates that the process of mineralization is the "concluding phases of igneous activity". He noted that feldspar-arsenopyrite-quartz veins, which are fairly common in Cornwall, often pass at less depths into hydrothermal lodes, or that the two forms are telescoped vertically and/or laterally.

No wolfram is associated with Phase 5, or any other mineralization phases in Geevor Mine, but important comparisons are valid between this early, deep infilling and some of the feldspar-quartz-arsenopyrite assemblages of South Crofty Mine.

The composition of the feldspar, which is occasionally massive, as shown in Photo. (54), is uncertain owing to its eventual, almost complete replacement by quartz and sometimes by cassiterite. Preliminary work indicates orthoclase, and it either forms as laths, shown in Photo. (116), or possesses an adularia habit. Earlier tourmaline was brecciated and recemented, as illustrated in Photos. (76) & (102/D), by the feldspar-arsenopyrite association. The arsenopyrite often succeeds the feldspar, as shown

in Photo. (98), and partially replaces it.

The infilling exists not only in the lode fissures, where it attains its maximum development, but also in several parallel veinlets which are common around most of the lodes. Feldspar and arsenopyrite are a characteristic mineral association in the lower limits of the tin zone.

(b) Quartz-Cassiterite

Further relative movements of the lode fissure walls initiated the introduction of the first major cassiterite phase; a fairly simple infilling of quartz and cassiterite, shown in Photo. (101/C). Cassiterite is sporadically distributed as bunches in the quartz, which attains a maximum width of about 6 inches.

The quartz-cassiterite phase was sometimes preceded by barren quartz which fragmented the pre-existing tourmaline and altered wall-rock in a similar manner to that shown in Photo. (63). Upon this earlier structure quartz and cassiterite are superimposed in conjunction with shearing in the manner shown in Photo. (81), although the latter is not an illustration of the exact case in question.

When the quartz-cassiterite phase of infilling is superimposed upon an earlier feldspar-arsenopyrite association, both the quartz and cassiterite replace the feldspar, an example being provided by Photos. (105) & (106). Such cassiterite is very fine-grained and tends to streak and mottle the feldspar, the original nature of which is nevertheless recognizable in hand specimen despite its almost entire eventual replacement by quartz.

The quartz-cassiterite phase introduces a fine-grained cassiterite, shown in Photo. (115), which often replaces earlier euhedral arsenopyrite,

as illustrated in Photo. (123). As evidenced recently by development on the Hanging-Wall Vein and parts of the Grenfell Lode, this early cassiterite phase is often sufficiently developed to alone result in economic mineralization. When superimposed upon the feldspar-rich phase it occasionally provides localized payable ground, as demonstrated recently by the Prospect between the 'D' and Coronation Lodes on Level 10 and by the Prospect No. 1 on Level 13.

The arsenopyrite of the feldspar-rich phase often forms, by decomposition due to the action of the quartz-cassiterite phase, an earthy reddish-brown hematite, providing the quite common hematite-cassiterite association, illustrated in Photos. (94/A), (103/E) & (125).

(c) Tourmaline-Cassiterite

Continued movements along the lodes, concentrated into a single central fissure and its branches, initiated the introduction of a tourmaline-cassiterite phase, an example of the product being illustrated in Photo. (58). Both mineral constituents are typically fine-grained, the former occurring as bluish-green, acicular crystals illustrated in Photo. (117). In the occasional absence of the preceding infilling phase the association is superimposed upon the earlier medium-grained tourmaline infilling and wall-rock replacement, as shown in Photo. (118).

The tourmaline-cassiterite combination is economically important and often forms a banded, alternating structure in the lodes with other cassiterite associations. A visual underground estimation of a lode's potential must include a thorough identification of the age of the tourmaline which is invariably present, since the products of different tourmaline-bearing phases have a wider vertical extent of distribution than those of the tourmaline-cassiterite phase.

(d) Chlorite-Cassiterite

The economically most important infilling phase is that represented by the succeeding chlorite-cassiterite association, examples of which are provided by Photos. (94/B), (103/A), (104/B), & (104/F). Cassiterite constitutes a large proportion of the association by volume, as shown in Photo. (119), and is set with chlorite in a matrix of quartz.

The chlorite is spherulitic, fine-grained, and pleochroic from colourless to green, with an appearance and composition very similar to the variety formed during intense wall-rock alteration of the granite. Hosking (1951) suggested that chlorite occurring in the Cornish wall-rocks is pro-chlorite whereas Webb (1947) concluded its identity to be laphnite. Many varieties are associated with tin mineralization in Cornwall from individual localities alone and a large amount of laboratory work is necessary before their thorough identification may be completed. Additional varieties occurring in Geevor Mine, the first associated with cassiterite, are shown in Photos. (120) & (126).

Accessory sulphides, comprising chalcopyrite and pyrite, accompanied the tourmaline-cassiterite and chlorite-cassiterite infilling phases, and were frequently replaced during later mineralization stages, now being visible only as rim relics shown in Photo. (121).

The chlorite-cassiterite phase is economically more important than the preeceding associations but of far greater value than any single mineral association is the more common tourmaline-chlorite-cassiterite phase shown in Photo. (122). This results either from the cumulative effect of intermittent, alternating tourmaline-cassiterite and chlorite-cassiterite phases, or from a composite phase in which the cassiterite is equally associated with both tourmaline and chlorite.

(e) Sulphide-Cassiterite

The last, major, cassiterite mineralization phase comprised an association with chalcopyrite and some pyrite. Although not so productive and more sporadically distributed than the tourmaline-cassiterite and chlorite-cassiterite associations, the sulphide-cassiterite phase produces localized, important increases in the lode value since the cassiterite contributes a high percentage by volume to the total assemblage.

This association occurs on all the lodes, although the most notable locality comprises the lower levels of the Borehole Lode, from which a typical chalcopyrite-cassiterite infilling is illustrated in Photos. (92) & (95). It must not be confused with the mineral assemblage which results when cassiterite is superimposed upon the sulphide impregnation phase; this is sometimes similar when observed underground.

Chalcopyrite and pyrite of the sulphide-cassiterite phase are deposited around subhedral or euhedral cassiterite. A little accessory, pale green fluorspar sometimes moulds around both the cassiterite and primary sulphides. The chalcopyrite, frequently replaced successively by bornite and chalcocite, contains ex-solution sphalerite, bornite, enargite, tetrahedrite and chalcocite. The latter often completely replaces chalcopyrite, forming a characteristic chalcocite-cassiterite association. Fine-grained cassiterite is set in a chalcocite matrix and the whole forms veins two or three inches wide in many of the lodes between the surface and level 15.

10/4 Supplementary Phases

"According to Henwood the Narrow or Crowns Lode varies in width from 2 to 12 feet, but the other lodes are small. The minerals occurring in them are limonite, quartz, vitreous copper ore, oxide of tin, arsenic, antimony, amethyst, atacamite, aragonite, bismuthinite, pharmacosiderite, blende, black and purple copper ore, blue carbonate of copper, cobalt, cobaltite, chalcybite, malachite, native copper, cuprite, diallogite, manganite, magnetite, mispickel, erythrite, fahlerz, galena, gothite, native silver (mentioned by Borlase as having been found in 1753), specular iron ore, smaltite, stannite, jasper, vivianite, and pyrrhotite.

.... Reid and Flett (1907).

(a) Sulphide Phase

The cessation of the cassiterite-bearing phases was marked by a period of relative quiescence, after which extensive relative movement of the lode fissure walls again commenced. The sulphide phase, Phase 10 in Fig. (140), resulted in the introduction of massive chalcopyrite and pyrite, followed by primary chalcocite, as shown in Photo. (51).

The chalcopyrite, illustrated in Photos. (99) & (100/A), exhibits a large number and variety of ex-solution and replacement textures. Ex-solution bodies of sphalerite, bornite, enargite, tetrahedrite, and chalcocite are frequent, together with accessory covellite and marcasite. Famatinite has been identified from the No. 3 Branch Lode and the presence of wittichenite is suspected.

Pale green or grey fluorspar is often closely associated with the sulphide phase and may be relatively earlier or later than the chalcopyrite and pyrite. Examples are provided by Photos. (107/B) & (107/D), and pale green fluorspar is shown in visible association with chalcopyrite and cassiterite in Photo. (95).

Chalcopyrite is altered to bornite and chalcocite, many of the textures being described in detail by Hammond (1958). Numerous other supergene minerals

originating from the components of the sulphide and sulphide-cassiterite phases include malachite, chalcanthite, chrysocolla, langite, limonite, and hematite. A characteristic green staining, shown in Photos. (50), (51), (52), & (65), originates from the copper content of the lodes and is present throughout the mine. Native copper occurs in the Borehole and Grenfell Lodes and a botriodal variety of chalcopyrite is shown in Photo. (102/B). The latter's supergene nature has been confirmed by its occurrence as a coating on large quartz crystals originating during the late quartz mineralization phases. Well formed covellite crystals are present in the Borehole Lode, and most drives in all the lodes possess a coating of fine, acicular gypsum.

Chalcopyrite and pyrite were succeeded by a phase of primary chalcocite mineralization, developing crystals up to $\frac{1}{2}$" long, as opposed to the more massive variety forming as an alteration product of earlier chalcopyrite. The primary chalcocite contains ex-solution blebs of covellite which impart a characteristic blue colour, as described by Edwards (1954). Both hypogene and supergene chalcocite are of equal importance and the combined chalcocite content of the Geevor lodes is of the same order as the chalcopyrite content. On the No. 3 Branch Lode primary chalcocite is set in a matrix of calcite, and possesses some unusual replacement characteristics, being partly altered to bornite.

Sphalerite, a common accessory mineral of the sulphide phase, becomes, in the upper parts of the Wethered Lode, a dominant mineral of the same phase, with an appearance illustrated in Photo. (101/B). A later infilling, consisting predominantly of sphalerite and shown in Photos. (61) & (100/B), also occurs in the same area.

Phase 10 is characterized by massive sulphides, with only green fluorspar as a gangue constituent. It therefore differs from the later quartz phases in

which any sulphides occur only in accessory quantities.

Diamond drilling into the country rocks from Level 11 of the No. 3 Branch Lode, as shown in Fig. (12), revealed small quantities of chalcopyrite, pyrite and pyrrhotite in quartz veinlets. These occurrences probably represent the westerly structural continuations of the main No. 3 Branch Lode fissure.

A small cube of galena has been recorded from Level 7 of the North Pig Lode (Victory Section), providing the only noted occurrence of this mineral in the mine. Chemical analyses of the flotation residues from the Geevor Mill, presented in Fig. (129), indicate the existence of bismuth, nickel, and cobalt, but the corresponding minerals have not been identified by the present writer in polished sections of the ores.

Numerous secondary iron varieties, like those of copper, deserve a systematic analysis before their identity may be stated with certainty. Encrustations and stalactitic growths with the appearance of limonite are evident in many of the lodes where they are sulphide-rich and the water flow is excessive.

Like those of the other mines of the area confined to the granite, the Geevor lodes do not possess a large variety of minerals in comparison with the lodes situated in the country. Details of minerals occurring in the Pendeen-Botallack mines have been provided by several writers, being summarized by Dines (1956).

The minerals of Levant Mine were listed by Reid & Flett (1907) as follows:-

> "The lodes are narrow in comparison with those of other districts, but contain a variety of minerals such as bismuth, bismuthinite, carbonate of bismuth, malachite, native copper, fahlerz, arsenate of iron, argonite, gothite, garnet, gypsum, native silver, gold, scheelite, tetrahedrite, cuprite, and mispickel".

No wolfram has been recorded from any of the mines in the Pendeen-Botallack area, but Russell (1920) reported the occurrence of scheelite and phenacite, from Wheal Cock. The present writer has identified gilbertite from the dumps

of Levant Mine (confirmed by Sir A. Russell).

(b) Quartz-Phase

The previous phases, concluding with the sulphide phase, were initiated through relative shear of the lode fissure walls, with no appreciable cavity formation apart from that resulting from the relative movement of the walls of irregular fissure planes. From Phase 11 inclusive the succeeding infilling phase, indicated in Fig. (140), were accompanied by relative movement of the fissure walls, or substantial stress relaxation with consequent tensional opening, or a combination of both effects.

Numerous forms of infilling grouped under the quartz phase may be defined according to the accessory minerals associated with each. These mainly comprise sulphides (chalcopyrite and pyrite) and purple fluorspar, of which an example is provided in Photo. (107/A). Tourmaline, chlorite, cassiterite, and the preceding mineral associations are also present but originate from the pre-existing lode material.

Each phase is characterized by abundant quartz, constituting over 90% of the total infilling as shown in Photos. (62), (79), (80), & (82). It is either massive with a maximum width of 2 feet, or banded as shown in Photos. (59) & (60). In the latter case, the final fissure width arising from such an intermittent quartz introduction is comparable with that produced by a single massive infilling.

Goethite and micaceous hematite (confirmed by X-ray analysis), the latter possessing the underground appearance of gold paint, were introduced in the final quartz phases. With the succeeding quartz phases vughs became more numerous in the centre of the lodes and contain quartz with well-developed rhombohedra. These sometimes attain a height of 2 inches, and are shown in Photos. (58), (109),& (110/A).

The only previous phase containing noticeable vughs, although small, was that characterized by the early feldspar-arsenopyrite infilling in the lower levels of the No. 3 Branch and North Pig (West) Lodes.

The quartz phases are well represented throughout the lodes of the Coronation (West), New, and Wethered groups in contrast to the lodes of the Borehole and 'D' Lode groups which exhibit a narrow infilling, as illustrated in Photos. (41-47 inclusive). In the former groups of lodes there are numerous forms of late quartz mineralization, including jasper, chalcedony, opal and amethyst, as shown in Photo. (109). The chalcedony is often botryoidal and alternations of the different varieties produce zoned quartz crystals similar to those shown in Photo. (109).

(d) Calcite-Siderite Phase

The completion of the last quartz phases signified the discontinued formation of large openings in the lode fissures. Succeeding phases, although accompanied by some movement, did not produce any substantial increase in the lode width. Fine-grained calcite and siderite were deposited in existing vughs in the flatter lodes, and frequently coated quartz crystals which show well developed prisms illustrated in Photos. (108/B) & (108/D).

Calcite usually occurs as pale pink to white rhombohedrons attaining a maximum size of about $\frac{1}{8}$ inch. They are occasionally thin and tabular, when they form a fibrous interlocking mass, shown in Photo. (108/A), characteristic of the St. Just area.

Calcite is less frequent in the steeper lodes where it forms only small veinlets through the pre-existing lode material in the manner illustrated in Photo. (48). Otherwise, as shown in Photos. (49), (52) & (88/B), it is massive and grey-brown in colour.

Small rhombohedral crystals of siderite with curved faces and about 2 mm. long, shown in Photos. (88/D) & (96), coat free surfaces in the lodes. Elsewhere, rhombohedrons up to ½ inch in size occur only in the lodes of the Coronation (West), New and Wethered groups.

(d) 'North Levant Lode' Phase

Two phases of infilling, each visible in Photos. (68) & (69) and separately in Photos. (66) & (67), produced the complete North Levant Lode. Frequent vughs in the quartz of both generations are infilled with jasper and earthy hematite. The effect of this mineralization phase is evident throughout the mine in the lodes of the Coronation (West), New, and Wethered groups, examples being provided by Photo. (58) and Fig. (66). The characteristic quartz-jasper association is illustrated in greater detail in Photos. (110) & (128).

(e) Uranium Mineralization

Pitchblende in Geevor Mine was first described by Ostle (1951) who related it to "an increase in the sulphide content of the siliceous leaders ". He placed the pitchblende with bornite and chalcopyrite in a paragenetic sequence, and provided details of its occurrence in the No. 1 Branch, North Pig, Coronation, 'C' and No. 3 Branch Lodes. The distribution of uranium mineralization in the western part of the mine is indicated in Fig. (139), and it is noticeable that the 'uranium-shoots' differ in inclination from those of the cassiterite-bearing mineralization. In the No. 3 Branch Lode, however, it agrees to some extent with the trend of lode infilling indicated in Fig. (141).

Recently Darnley (1959 & 1960) completed an age determination upon uraninite which he collected from the Geevor Mill. The results of 290 ± 7 m.y. agree fairly well with estimates of the age of the tin-copper mineraliza-

tion.

Uraninite has since been observed on the Footwall Branch and Borehole Lodes, not only indicating a more extensive distribution than was previously considered but also demonstrating its occurrence in the lodes of all groups. In a specimen from the North Pig Lode, Darnley (private communication, 1961) has recently identified coffinite, thereby raising some interesting questions regarding its age relationships with the main tin-copper infilling. It is not improbable that there were at least two phases of uranium mineralization, differing in form, associations, extent and age in the different lodes. One example is provided by Photo. (106); a specimen obtained from the No. 3 Branch Lode at the locality shown in Photo. (48).

10/5 Conclusions

(a) Paragenesis

The successive mineralization phases have been diagrammatically presented in their chronological order from Phases 1 to 13 in Fig. (140). Although this is a simplification of the sequence of events it provides a general picture of the changing characteristics of mineralization.

There is a marked lack of uniformity in the development of each phase throughout both the mine and individual lodes. Their incomplete representation, coupled with merging and repetition, results in localized overlapping in their distribution and a reversal of the usual order of initiation.

Standard paragenesis tables for Geevor Mine are quite misleading unless their construction is based on a far more extensive mineralogical study than that completed by the present writer in the time available. Paragenesis tables were originally prepared for the individual lodes, but continued underground and laboratory examinations invariably indicated that all the phases are represented to some extent, however small, in each lode. Paragenetic sequences are more advantageously evaluated, especially for Phases 9 and 10 in which arsenopyrite is followed by cassiterite, then by the remaining sulphides, and eventually by the supergene products in a standard sequence.

While the major faults and fault zones exhibit only a minor development of the early forms of wall-rock alteration, and contain trace amounts of cassiterite except in the immediate vicinity of the lodes, they commonly contain calcite and a little siderite. The Hanging-Wall Branch and Wethered No. 2 Branch Lodes possess the development of the same mineralization phases, but on a less extensive and more varied scale, as the other lodes. The Wethered No. 2 Branch Lode is less variable than the Hanging-Wall Branch

Lode, probably owing to its incomparable underground development, and contains a large amount of specular hematite.

(b) Temperature of Formation

For practical purposes it is convenient to define the various phases of cassiterite mineralization according to their individual mineral associations as opposed to distinguishing between pneumatolytic and hydrothermal ore. If such a discrimination is necessary, the cassiterite originating through replacement of the granite wall-rock should be placed in the pneumatolytic category, whereas the succeeding cassiterite phases may be classed as hydrothermal.

Little (1960) determined the apparent formation temperature of Cornish cassiterite from inclusion techniques, but provided no specific locality or mineralization details. He arrived at a result of between 300° and 500° C, over which temperature range he defined hydrothermal mineralization.

Gavelin, Parwell & Ryhage (1960) ascertained the isotopic composition of several sulphides from Cornwall, demonstrating a wide range of formation temperature. They allotted a specimen of "chalcopyrite from Geevor Mine" to the "high temperature zone". Considering the wide variety of sulphide mineralization in Geevor Mine very little emphasis may be placed on this analysis alone, although it may be viewed in perspective against the results of further analyses of sulphides from Cornwall and other localities.

It may be concluded that most of the cassiterite in Geevor Mine arose from high temperature hydrothermal mineralization, and that the lodes demonstrate a temperature range of mineralization from Phases 5 to 13 of between 500° and 100° C.

(c) Mode of Cassiterite Transportation

Hosking (1951) outlined the numerous past suggestions regarding the nature of the ascending, tin-bearing, ore-fluid. Cassiterite has been suggested, on the basis of its mineral associations in different localities, to have been transported as a stannic fluoride, halide, borate (due to the association with tourmaline), arsenide, sulphide, stannate, thiostannate, and as a combination with silicic acid.

As each suggestion is made on localized evidence by one writer it is refuted by others because the particular cassiterite mineral association which is quoted differs from that at the locality with which they are individually acquainted.

The fact that cassiterite occurs in close association with quartz, tourmaline, chlorite, and sulphides is undisputed. Whether it ascended in a form of combination common to all phases, possibly as stannate solutions, or as different forms for each main cassiterite phase, is debatable. Any further discussions without the necessary laboratory work would be based upon only a healthy imagination.

(d) Cassiterite Variations

Scrivenor (1919) described pleochroism in cassiterite and numerous other writers, such as Bond (1930), have noted colour variations between cassiterites of different origin. Gotman (1938) particularized the diverse physical, optical and spectrographic characteristics of cassiterite from several separate localities, whilst Venugopal (1952) and Borovisk & Gotman (1939) measured variations in the trace element content of the mineral. Both approaches were combined by Kun (1959) who studied cassiterites from the Congo and related their physical properties to their trace element content.

The present writer originally intended to devote some time to the application of the latter techniques upon Geevor cassiterite. Accordingly, the No. 3 Branch and Wethered Lodes were systematically channel sampled and the remaining lodes selectively sampled, a 100% pure cassiterite concentrate being produced in each case. Unfortunately the programme could not be completed but it permitted a study of colour changes in the mineral throughout the lodes.

Prisms and pyramids are equally developed in the normally transparent cassiterite. It developed as equi-dimensional grains in which some of the crystal forms are apparent, and the characteristic twinning is often present. Inclusions, comprising tourmaline, sometimes impart a cloudiness to the cassiterite.

As a concentrate, the mineral possesses a colour range from very pale grey to transparent steel-grey with several shades of brown. In thin section it varies from colourless, through grey, yellow and pale brown, to dark brown. No colour shows any predominance in a particular lode or lode group but the variations may be related to the individual cassiterite mineralization phases, being summarized as follows:

(a) Cassiterite replacement of the wall-rock: Very fine-grained and mottled, with colours varying between pale brown and white.

(b) Quartz-cassiterite phase: Very fine-grained and mottled, with a pale brown colour.

(c) Cassiterite replacing hydrothermal feldspar: Similar to that originating from the quartz-cassiterite phase.

(d) Tourmaline-cassiterite phase: Medium-grained and coloured in combinations of white, brown and yellow, the latter always in the centre of the cassiterite grain.

(e) Chlorite-cassiterite phase: Relatively large-grained (maximum size of 1 mm.), and zoned in white, brown and yellow.

(f) Tourmaline-chlorite-cassiterite phase: Relatively large-grained and always zoned in white, grey, brown and very bright yellow (in the centre).

(g) Sulphide-cassiterite phase: Relatively medium-grained, with a very variable colour range.

N.B. The terms fine-, medium-, and large-grained are relative and do not denote any particular grain size. An appreciation of the size range may be gained from Photos. (111-128).

Where the No. 3 Branch Lode traverses the killas the associated cassiterite is relatively fine-grained, mottled, and white to brown in colour, showing an indication of originating during the quartz-cassiterite phase.

10/6 Mineral Zoning

(a) Introduction

Dewey (1922, 1925) recognized the existence in both plan and section of tin, copper, lead-zinc and iron zones in South-West England, and he provided the first comprehensive description, outlining their correlation with depth changes. The relation of the zones to the upper surface of the major granites was outlined Rastall (1923), further information being summarised by Davison (1927).

The history of many mines proves that not only were the different mineral zones never completely represented but also that they were not necessarily parallel to the granite surface. Dines (1933) consequently postulated both vertical and lateral migration of the ore fluids from certain restricted emanative centres, resulting in the upper zone possessing a wider lateral distribution than the lower one.

Dines (1933) believed that the form of the mineral zones was controlled by the isogeothermal surfaces. He considered that during the intrusion period they were parallel to the granite surface, but with time and the advent of mineralization they increasingly tended to flatten out. As pointed out by Hosking (1951), the form of the isogeothermal contours derived by Dines (1933) agreed very closely with the theoretical derivation by Schneiderholn (1934).

Weston-Dunn (1923) preferred to explain the vertical and lateral mineral zoning in the South-West by differentiation of the ore-fluid during its single ascent of the lodes under the effect of temperature.

Some writers, such as Barnes (1956), still work upon the basic assumption of a single mineralization phase, with separation of the components under the influence of temperature, pressure, and several other physical and chemical factors.

As described by Hosking (1951), who concluded that the mineralization resulted from several surges, the effect of the isogeotherms must be considered upon the individual phases. The upper and lower limits of mineralization would be controlled by the form of the isogeotherms and within the range of deposition of a single phase there would be only a little supplementary zoning. The problem of zoning must be approached with a prior recognition of the occurrence of several mineralization phases, such as outlined by Cronshaw (1921), employing the methods adopted by Kutina (1957).

Hosking (1951) demonstrated that under a changing temperature gradient and other factors, the time interval between successive phases is critical in deciding their spatial distribution. Under differing conditions various effects such as telescoping of the accepted zones and the inversion of their usual vertical order are thereby explained.

In the opinion of Webb (1947), however, a combination is possible in practice of the two effects favoured by the different schools of thought. He considered that not only was the ore-fluid at any one time "undergoing extra magmatic differentiation during the course of its ascent up the lode fissure", but also that "the ore-forming fluid leaving the source was not identical throughout the period of lode formation".

In an idealised case the order of arrival of the minerals is equivalent to their order of occurrence with decreasing depth of deposition. The earliest minerals are located at the deepest horizons and the youngest are situated in the upper regions. By this means generalized representations of the mineral zones were constructed by Mac.Alister (1906), Cronshaw (1921), Dewey (1922), and Davison (1936). The latter writer (1927) summarised all the current views, his conclusions being reproduced as Fig. (128C).

Webb (1947) constructed a scheme of zonal distribution, reproduced as Fig. (128B). Hosking & Trounson (1959) modified and added to the former's earlier (1951) schematic illustration presenting the table reproduced as Fig. (128A).

(b) Mineral Zoning in Geevor Mine

The complete mineralization of the Geevor lodes resulted from several phases, diagrammatically outlined in Fig. (140), to which the ideas of Dines (1933) and Schneiderholn (1934) must be individually applied. The main NW-SE crests in the now-eroded granite surface in the Pendeen-Botallack area are reflected in the attitude of the plunging arch of the tin zone, shown in Fig. (118).

With the completion of lode fissure formation and the main wall-rock alteration phases the introduction of the infilling mineral associations demonstrate the following features:-

(1) With the mean temperature and temperature gradient of the granite slowly decreasing with time the vertical range of distribution increased.

(2) The cassiterite-bearing phases followed closely upon one another and were at times mineralogically gradational. When unaffected by local structural controls, the horizon of maximum mineralization of the individual phases slowly decreased in depth.

(3) During the last cassiterite-bearing phases the balance between decreasing temperature and time duration was such that the position with respect to the granite surface, of the horizons of maximum mineralization were static in the approximate centre of the present economic tin zone.

(4) After the completion of the economic phases greater time intervals separated the successive phases, the duration of which increased. The diminished temperature gradiant and overall temperature of the granite allowed the greatest vertical range of distribution.

Although the economic phases commenced their introduction with a theoretically correct depth distribution with age this effect was slowly decreased and from Phase 9 onwards they became telescoped and reversed in distribution with respect to the earlier phases.

A combination of time duration and rate of temperature decrease caused most of the sulphides to be deposited within the tin zone, the maximum sulphide content sometimes occurring in the lowest horizons of the lodes. The copper content of a lode therefore provides no criterion by which to judge whether the lode in question is being developed in its upper or lower horizons.

(c) Individual Lode Zoning

For the above reasons care must be exercised in evaluating the upper and lower regions of a lode. In every-day development it is important to distinguish the 'tops' and 'bottoms' of the lodes. In so doing one must distinguish between members of particular lode groups and consider the position of the lodes upon the flanks of the arched tin zone.

For the purposes of distinguishing between the tops and bottoms one may consider the three most different groups of lodes; namely, the 'D', Coronation (West), and Borehole Lode, groups which may be considered individually as follows:-

1. 'D' Group

(i) The bottom of a lode is indicated by a common association of feldspar and arsenopyrite or arsenopyrite alone, brecciating earlier tourmaline.

(ii) The tops possess a greater mineralogical variation, containing tourmaline, quartz and sulphides.

2. Coronation (West) Group

(i) The bottom is indicated by the presence of massive fine- to medium-grained tourmaline, supplemented by tourmalinized wall rock. Massive feldspar and the later quartz phases may also be represented.

(ii) The tops demonstrate a general decrease in the mineral assemblages normally occurring in the most productive parts of the lodes.

3. Borehole Group

(i) The bottom may be indicated by a minor development of the feldspar-arsenopyrite phase or by the presence of a simple quartz-cassiterite phase surrounded by large-scale reddened and hematized granite.

(ii) The tops are usually indicated by the occurrence of medium-grained tourmaline or quartz-tourmaline, often surrounded by a narrow zone of heavily hematized wall rock.

The above generalizations are necessarily based upon a study of the lodes at present accessible or under development. They may be influenced by local factors and would probably vary if an overall view of the lodes were possible.

Not only do the gangue and economic minerals illustrate a temperature zoning throughout the individual lodes but the wall-rock alteration also possesses marked variations. Evidence has recently been provided by a

detailed study of the No. 3 Branch Lode, the results of which are graphically presented in Fig. (141).

A more accurate appreciation of the mineralogical characteristics of the tops and bottoms of the lodes must in future be obtained, providing a very important application in underground development and in the interpretation of diamond-drill intersections.

11. LODE FORMATION

"The vein-fissures of the tin- and copper-bearing lodes of Cornwall were generally the result of forces acting subsequently to the solidification of the elvans, but operating in the same general direction as those which caused those rocks to be erupted".

.... Phillips (1875).

11/1 Introduction

The following summary of the history of formation of the lodes and post-mineralization features depends upon a close study of the structures in conjunction with the order of introduction of the mineralization phases. Numerous results, gathered from surface outcrops and underground exposures, have been correlated but the space available prohibits the inclusion of all the details, some of which have been briefly mentioned in previous sections.

(a) Coincidence in Attitude of the Lodes and Joints

".... and it is therefore probable that the lodes of this district have been formed on lines of joints enlarged by dislocation"....

.... Whitley (1865).

There is a constant similarity in structural attitude between the Geevor lodes and the granite joints of both primary and secondary origin. This may be visually appreciated in all the underground workings where the lodes are enlarged and dilated joints, as shown in Photo. (56).

On Carn Eanes the various joints, the attitudes of which are graphically illustrated in Fig. (36), have been dilated and subjected to slight movements allowing the selective introduction, demonstrated by Fig. (39), of quartz and tourmaline. Most of the infilled joints strike WNW and NW and dip SW. They are supplemented by others striking between E-W and N-S. The agreement in attitude between these joints and the lodes, represented in Fig. (43), is

further demonstrated by the coincidence of the two respective principal maxima in each case in the first quadrant.

Interpretations cannot be based entirely upon stereographic representations of the joints and lodes, and must be supplemented by direct underground observations. Stereograms indicate only the very strong agreement in structural attitude between a majority of the two features. A study of the infilling and dislocation of joints at separate localities may be usefully employed in an evaluation of the structural and mineralogical history of formation of the Geevor lodes.

From a combination of statistical and underground studies it is apparent that most of the Geevor lodes were formed by movement along, and enlargement of, primary and secondary granite joints. The attitude of the lodes has been substantially controlled by that of the joints and their existence in the present form is dependant to a very large extent upon the heavily jointed nature of the granite before the onset of the wall-rock alteration phases. The intense jointing sufficed to accommodate the increasing stresses during the mineralization period and the formation of new fissures was not necessitated.

(b) Individual Lode Groups

Immediate comparisons are possible between the attitude of the granite joints and the separate lodes, and may be summarised as follows:-

(a) 'D' Lode Group:

The lodes coincide in attitude with the longitudinal primary joints.

(b) Coronation (West) Lode Group:

The lodes also agree in attitude, with greater variations than those of the 'D' Group, with the longitudinal joints.

(c) New Lode Group:

The lodes coincide in strike direction and range with the secondary granite joints, and in some cases with the longitudinal joints.

(d) Borehole Lode Group:

Parts of the lodes agree with all varieties of the longitudinal and secondary joints. Other sections show a marked variation in attitude from the surrounding joints.

(e) Wethered Lode Group:

Sections of the lodes agree in strike with the secondary joints and occasionally with other forms.

(f) North-South Lode Group:

The Hanging-Wall Branch and Wethered No. 2 Branch Lodes lie within the wide range of strike and dip of the local cross-joints.

Similar comparisons are also valid between the attitude of the main faults and fault zones and the granite joints:

(a) Main Faults:

These coincide in attitude with the regional cross-joints.

(b) Fault Zones:

The overall attitude of the fault zones is similar to that of the North-South group of lodes but the individual zones do not agree in attitude with the surrounding local cross-joints.

Within the zones the separate component faults agree in strike with the surrounding local and regional cross-joints.

With the exception of some sections of the lodes included in the Borehole and Wethered groups, the Geevor lodes may always be related to the localized prevailing attitude of the surrounding joints. Their origin, together with that of the major faults and fault zones, lies in the primary and secondary joints of the granite. By large-scale movements and dislocation of the ground in the Geevor Mine area the joints become enlarged and subjected to mineralization to such an extent that they now constitute the economic tin lodes.

11/2

Stage 1

(a) Stress distribution changes

The major and minor structures in the Geevor Mine area upon the completion of the granite consolidation stage are summarized in Section 5/5. After the formation of the secondary granite joints, the vapour pressure of the accumulated mineral solutions at depth increased and became a dominant stress, eventually constituting the maximum principal stress, P_1. The latter was directed upwards in a predominantly vertical direction, with a high SE inclination towards the centre of the granite mass.

The previous NW-SE maximum principal stress gradually decreased in relative intensity becoming subordinate to P_1 and equivalent to an intermediate stress, P_2. The earlier minimum stress, P_3, maintained its relative intensity, directed in a NE-SW direction.

With originally very little difference in relative intensity between P_1 and P_2, and each fluctuating, the consequent small movements were in all directions. Only minor dislocations of the joints were initiated, the stresses being accommodated by movement along the pre-existing joints instead of by the initiation of new fractures. These displacements permitted the commencement of the pneumatolytic mineralization phases, previously listed as the preliminary phases.

The various forms of alteration affected those joints which were not only the most numerous but also the better developed. These included the longitudinal and secondary joints. The regional and local cross-joints, more directly under the compressive influence of P_2, were, with few exceptions, unaffected by alteration. The increasing vapour pressure initiated slight movement of the order of a few inches. This amounted to a jostling of the

numerous blocks of ground which was confined between those joints along which movement occurred.

(b) Granite Surface Irregularities.

In the relatively flat-topped portions of the granite, at a distance of about one mile from the present granite surface exposure, the continued increase in P_1 was accommodated by a general dislocation of all the joints, creating an irregular pattern of movement, unless a particular set was locally excessively developed.

The two major granite crests, which localized the emanative centre in the Pendeen-Botallack area, were supplemented by subsidiary undulations on their flanks, possessing the same NE-SW and NW-SE directions. Additional N-S undulations were localized along the main NW. flank and their direction is reflected by minor folding in the country rocks and by the attitude in plan of the granite contact, shown in Fig. (H).

The relative extent of local development of the N-S and NE-SW undulations is probably reflected at the present day by the strike of the adjacent granite contact along the coastline. For instance, south of Spearn Consols Mine the N-S undulations, reflected by the 17°- trending minor folds shown in Fig. (34), are better developed. In contrast, in the Geevor Mine area both sets of undulations are equally well developed.

Localized variations in the stress distribution attained their maximum intensity around, and below, the surface undulations.

(c) First Displacements

The increase in the vertical stress due to the confined mineral solutions eventually became so intensive relative to P_2 that major movements occurred throughout the area. Owing to the vertical orientation of P_1, the

direction of movement was predominantly vertical but was controlled by the prevailing relative intensities of the principal stresses, and the dip of the longitudinal and secondary joints. Movements were concentrated beneath the undulations and occurred along whichever joints most closely approximated in strike to the trend of the undulations, and were sufficiently well-formed to allow displacement. With the diminishing presence of an undulation the associated displacements were similarly diminished and terminated against longitudinal and secondary joints.

Movements associated with the NE-SW undulations occurred along regional cross-joints whereas those associated with the N-S undulations were mainly along local cross-joints, which show less agreement in attitude with the associated belt of movement.

The undulations were concentrated along the NW flank of the Land's End granite within a distance of about one mile from the present line of outcrop of the granite contact. With increasing proximity to the latter they increased in intensity and development.

In the NE-SW belts of dislocation the movement was localized along a maximum of two or three regional cross-joints, with a belt of movement attaining a maximum width of about thirty feet. Within the N-S belts, because the movement was not so easily accommodated among the diversity of joints, regions of ground developed with a width of 200 to 300 feet, in which displacement occurred along a multitude of assorted planes, eventually constituting an overall movement similar to that localized along the NE-SW belts.

Each major plane of dislocation was inclined to the SE, and especially in the western part of Geevor Mine they underwent reverse faulting through

about 10 to 15 feet, evaluated from deflections exerted upon the granite contact. The direction of movement is indicated by slickensides which are diagrammatically illustrated in Fig. (46/2).

Since the belts of movement sustained post-mineralization movements they are now represented in Geevor Mine by the major faults and fault zones, the attitude of the former being indicated in Figs. (38/1) & (40/6). The locations of the major faults and fault zones are shown in Fig. (103), and they form the boundaries between which block-faulting occurred. A major block of ground bounded to the west by F_1, F_2 and F_3, and to the east by F_5 and F_6, was thrust upwards through a distance of about 10 to 15 feet. The processes is illustrated as Stage 1 in Fig. (101A).

Similar movements also affected the better-developed cross-joints thereby providing a continuation of the process by which some of them were initially created. Numerous planes were subjected to similar, although less extensive, movements, but they are now not so evident having been unaffected by the mineralization and post-mineralization stages.

The extent of movement was most intense at the eastern and western extremities of the present developed area of the mine, those displacements in the centre being less extensive, although in the same direction.

Minor horsts and garben were developed between F_1 and F_6, and the inclinations of the various planes of movement resulted in both normal and reverse faulting. The direction of movement is now frequently difficult to decipher since most of the planes have been subjected to later movements which tended to obliterate the previous evidence.

Such movement planes are apparent throughout the whole of the granite of the Pendeen-Botallack area, with both N-S and NE-SW directions. Only those

with the latter direction, originating from the regional cross-joints, are evident in the country rocks and are reflected in the occurrence of both guides and joint distributions, which are illustrated in Figs. (40/1-5). The N-S planes are not present owing to the non-existence of the local cross-joints in the country rocks.

The blocks of movement confined between adjacent planes of movement were not approximately rectangular owing to interference between the N-S and NE-SW belts of dislocation. The blocks possessed a triangular shape in plan, the third side being provided by well-developed longitudinal or secondary granite joints. The blocks were irregular in both volume and area (in plan), and either remained relatively static or were subjected to a downward or upward overall displacement.

"Whether these lodes are formed along simple joints, or whether along lines of fracture accompanied by dislocation of the walls, is not always clear, but probably both modes of formation are represented".

.... Reid & Flett (1907).

(a) Introduction

Continued block faulting movements could eventually no longer sustain the renewed build-up of vapour pressure, which had been initially released by the faulting, with the production of wall-rock alteration. The triangular blocks of ground created during Stage 1 were confined between planes of movement trending N-S and NE-SW, thereby being elongated in the same directions.

A continued increase in the vertically-oriented maximum principal stress, P_1, decreased the length of the maximum axis in plan of the blocks of further faulting along planes, within the range of attitude of the longitudinal and secondary joints.

The form of these second faults depended upon the scale and frequency of development of the joints, a feature which varied throughout the mine with respect to the distance from the steeply inclined contact. It is convenient to describe separately the movements during Stage 2 in the three mine units. Although apparently artificial, these divisions are based upon structural factors.

(b) Western Unit

To accommodate the almost vertical stress, P_1, directed from the SE, movement took place along those joints which had already been subjected to wall-rock alteration and complied with the requirements of suitable attitude.

Although the secondary joints were present in the Western unit, movement occurred most easily along the longitudinal joints, which were better developed than any others owing to the proximity of the steeply dipping granite contact. About 10% of the joints possessing wall-rock alteration were subjected to some movement.

Slight, intermittent movement, as a preliminary to the later dislocations, permitted the entry of tourmaline into the major joints. The more important displacements, sufficiently extensive to allow infilling, commenced in the relatively steep fissures now represented by the lodes of the 'D' Group. The feldspar-arsenopyrite association tended to selectively affect the steeper lodes, along which movement proceeded first owing to the local inclination of the granite surface, shown in Fig. (91). The lodes of the 'D' Group therefore possess a higher average, final value than those of the Coronation (West) Group which were equally affected by only the later cassiterite phases.

As shown in Fig. (94), the displacements constituted the movement of wedges of ground defined by the planes of the lodes. Individual wedges attained a maximum width at their base of 500 feet, the apex indicating the direction of movement through about 10 or 15 feet.

Cavities were created by relative movement of the irregular fissure walls, as described by Emmons (1943) and illustrated in Fig. (105), thereby providing a path for the ascent of the mineral solutions and a locality for their deposition.

By wedge faulting the triangular blocks of ground were divided into further sections, roughly elongated in an E-W direction, parallel in plan, and possessing an approximately equal width. Relatively steep and flat lodes were alternately subjected to reverse and normal faulting, as shown

in Figs. (91) & (94). To the east and west the wedges of ground were terminated against the previous planes of movement during block faulting in Stage 1, as shown diagrammatically in Figs. (100), (101), and Stage 2 of Fig. (101).

Along an individual lode the extent of relative displacement varied because some was often accounted for by movement of the regional and local cross-joints. An example is provided by the No. 3 Branch Lode, shown in Fig. (141), along which the amount of relative movement in the lode, accounted for by wedge faulting, varied between the limits now defined by the major faults, the North Pig Lode, and the Hanging-Wall Branch Lode.

Some of these terminating planes are now easily distinguished owing to the effect of later movements but many are evident as only small fractures which have sometimes not been subjected to any further displacement. They are surrounded by a little reddened granite, or more often by 'rotten' and kaolinized ground. Despite their present nondescript appearance they were of critical importance during the mineralization phases, since the overall value of a lode is proportional to the relative displacement of its walls. This fact should be recognized in all underground development, and the mapping of such features is of equal, if not greater, importance than the customary mapping of the lodes.

Ore-shoots and bunches were usually localized mid-way between the termination planes which form a high angle (in plan) intersection, greater than 45°, with the lodes.

Depending upon whether the individual lodes were subjected to reverse or normal faulting, the values are generally confined to regions of relative increase or decrease in the lode dip, as diagrammatically illustrated in Figs. (106) & (108). Impounding of the ascending solutions in the lodes of

the Coronation (West) Group occurred beneath points at which dip substantially decreased. The same effect is illustrated by those of the 'D' Group in which solutions were impounded below points of change in the dip direction from SW to NE .

Occasionally slight enrichment occurred up to 5 or 10 feet on either side of a terminating plane, but of greater economic importance are the intersections, now apparent as lode branches, which make a small angle (in plan) intersection with the lodes. By creating greater brecciation and cavity formation along the line of intersection, which follows the direction of P_1 and plunges SE, large-scale enrichment formed a vertically-elongated ore-shoot.

The solutions ascended along the lines of intersection, the attitude of which was controlled by the original direction of P_2 during the period of formation of the secondary joints, by the inclination of the terminating planes, and by the direction of the prevailing maximum stress, P_1.

Temperature control of the extent of mineralization caused the cassiterite and associated gangue minerals to be deposited within the vertical limits of the wedges. Consequently, intersections between lodes of the two different groups at the wedge apices have not been investigated by underground development. By comparison with other areas of the mine it is likely that the intersections comprise a belt of heavily jointed and dislocated ground, the major movements being dissipated along several joints and fractures.

(c) Central Unit

In the Central unit the longitudinal joints were less well developed and were subsidiary to the secondary forms. The latter possessed a greater strike range which produced a more complex variety of ground movements

than in the Western unit. Triangular blocks, formed during Stage 1, were further dissected into smaller blocks with the same three-sided form, now confined between the lodes and the previous terminating planes, one of which is indicated by the Hanging-Wall Branch Lode.

Movements along the set of flatter secondary joints formed the Coronation and North Lodes of the New Lode Group by normal faulting. Complimentary reverse faulting occurred along any sufficiently-developed longitudinal joints. Movement along two or three fissures was necessary to compensate for the extensive displacement along the North and Coronation Lodes, which comprised about ten to fifteen feet. Small intervening lodes thereby formed from the longitudinal joints and include the Prospect No. 1, the 'D' Lode (West of the Hanging-Wall Branch Lode), the A (lower) Lode, and the Prospect between the 'D' and Coronation Lodes. There was also some movement along fissures which now constitute parts of the North Pig and South Pig Lodes. Fig. (92) illustrates the directions of relative displacement along the lodes defining the more complex wedge faulting shown in Fig. (95).

The initial movements creating the lodes of the Central unit occurred simultaneously to the equivalent displacements in the Western unit. In similarity, the earlier economic phases are predominantly represented on the small steeper lodes. The major phases are predominantly represented on the small steeper lodes. The major phases are concentrated, with the exception of the 'C' Lode, along the major lodes of the New Group. The degree of economic mineralization is dependent upon the vertical and lateral extent of relative displacement within the lode fissures.

In the Western and Central units the relative displacements of the lode fissure walls during Stage 2 are evidenced by early slickensides, the

orientation of which is illustrated in Fig. (46/1). Although they were usually distorted and substantially obliterated by later movement they are apparent on a detailed examination.

In common with those of the Western unit the extent of mineralization in each lode is subjected to structural and temperature controls and confined between the apices of the wedges within the area sofar developed. Future exploration and development at depth around the Prospect No. 1 and the 'D' Lode may disclose economic mineralization around a wedge apex.

The usual structural controls of mineralization are common to the lodes of both the Central and Western units. Widespread temperature control is evident to an equal extent, but the localized effect of the granite contact, apparent in the early mineralization and final extent of payable ground in the lodes of the 'D' Group, is not comparable.

Bunches of ore are localized between lode intersections, and major ore-shoots confined between such junctions, are formed along the lines of intersection between lodes and branches which possess a small crossing angle (in plan). Impounding of the solutions was also an important factor in ore localization on both the lodes of the New Lode Group and the steeper lodes comprising the subsidiary class of the 'D' Lode Group.

Individual lodes and some component sections of others reflect the development of the secondary granite joints. Their attitude may be employed in a graphical determination of the stress distribution originally creating the secondary joints, as shown in Fig. (44/1-4). Such determinations yield the results illustrated in Fig. (45/4) which show a good agreement with those based upon an analysis of jointing in the country rocks and in the granite, and upon the minor folding in the former. Further determinations, illustrated

in Fig. (44/5-11), are not valid since, although producing similar results as shown in Fig. (45/5), they are based upon lodes derived from a variety of joints in addition to the secondary forms.

Major blocks of ground created during Stage 1 are confined to the east and west of the Hanging-Wall Branch Lode which, unlike the majority of the terminating planes, was selectively mineralized simultaneously with the adjacent lodes. Its low dip and consequent different relation to the prevailing stress distribution allowed its preferential mineralization as opposed to the major faults and fault zones. Complex mutual interference and structural control of the extent of mineralization between the Hanging-Wall Branch Lode and the lodes with which it junctions was initiated, to be further complicated during Stage 3 by selective movements along the separate lodes. Several additional termination planes were simultaneously mineralized to such an extent that they now rank as unpayable prospects.

(d) Eastern Unit

Neither the longitudinal nor the secondary joints were well developed in the Eastern unit compared with those in the other units, and the maximum stress, P_1, could not be adequately accommodated by movement along the pre-existing joint planes.

The Eastern unit therefore, demonstrates a similarity in this respect to the remainder of South-West England, throughout which new fissures were initiated under the increasing stress distribution, according to the principles outlined by Anderson (1942) and illustrated in Fig. (41). A conjugate set of SW and NE dipping fractures, possessing different dips from the joints, was created, and the prevailing stress distribution, partly reflected by the detailed attitude of the Borehole Lode, may be graphically analysed as shown

in Fig. (47). The results are in close agreement with previous estimates of the stress distribution and indicate the high SE plunge of P_1.

The formation of this major supplementary fracture system allowed movement under the dominant vertical stress to be accomplished more easily, with displacement along a combination of the new conjugate fractures and the earlier longitudinal and secondary granite joints. The consequent formation of the Borehole Lode, as demonstrated in Fig. (104), was repeated forming the other lodes of the Borehole Group including the Grenfell Lode, parts of the North Pig Lode, and some Prospects in the Eastern unit.

The formation of major lines of dislocation, now indicated by the lodes of the Borehole group, was assisted by both the pre-existing joints and by undulations in the new-eroded granite surface. The latter trended NW-SE parallel to the main granite crest which extends through the vicinity of Spearn Consols Mine.

By this means the extensive, NW-trending, steep and overturning lodes, illustrated in Fig. (18) and complying with the characteristics of the Borehole Lode Group, were localized and propagated by incorporating sections of previously-formed lode fissures and original granite joints, thereby extending with economic contents for considerable distances. Their discovery and persistent development during the 19th century was a major factor in the exploitation of the Pendeen-Botallack area. The importance of pursuing the western extensions of such lodes occurring in the Eastern unit of Geevor Mine should be recognized.

Junctions between component lode fissures dipping SW and NE in the lodes of the Borehole Group often create intense fracturing and a consequent increase in the lode value. Within the individual fissures the usual structural

controls of mineralization are evident, especially these arising from the steeply plunging intersections of major fissures and branches.

The complete formation of the Borehole Lode slightly post-dated the first displacements along the potential lode fissures in the western and Central units, as evidenced by the different mineralogy over the localized sections. Overall movement along the Borehole Lode, shown in Fig. (93), is reflected in a tendency towards the occurrence of wedge faulting and various other complex forms, as indicated in Fig. (96)

One set of the conjugate fissures is partly reflected in the dip of the Wethered and North (East) Lodes, but the lodes of the Wethered Group, which are represented only in the Eastern unit, were not completely created until the commencement of Stage 3.

11/4 Stage 3

(a) Introduction

The initial stages of formation and mineralization of the lode fissures, were followed by further intermittent increases in the compression, and changes in the stress distribution caused continued movements along the fissures. The consequent surges of mineralization produced a repetitive infilling and localized complex lode structures, bearing signs of the various movements.

A gradational change from Stage 2 to Stage 3 was marked by the introduction of the chlorite-cassiterite and sulphide-cassiterite phases. Successive movements in the individual lodes were not always identical in direction to the original displacements, either normal or reversed. Cassiterite of the successive phases was not localized in the same areas of the lodes since normal faulting was sometimes superimposed on reverse faulting, as shown in Figs. (107) & (109). Some of the lodes therefore demonstrate a localization of cassiterite in areas of both high and low lodedip within an individual lode fissure.

The planes of termination of successive movements frequently altered, and throughout Stages 2 and 3 most of the lodes were subjected to about five periods of movement.

Following the introduction of most of the sulphides, late quartz phases, indicated in Fig. (140), were commenced through a relaxation of the all-round stress, especially of P_3. The effect of gravity was sometimes comparable in intensity with P_1, and the general lines of movement and termination planes were approximately the same as those of Stage 2. The relaxation and associated effects sometimes influenced a greater strike length but the maintenance of an effective horizontal stress, P_2, was sufficient to prevent the infilling

of the termination planes by the late quartz phases or any regenerated earlier phases.

The stress relaxation constituted Stage 3, and the resulting effects may be considered in each of the mine units as follows:-

(b) Western Unit

All the lodes of the Western unit suffered a downward movement of their hanging-wall, constituting normal faulting. The overall relative displacement of the walls of the lodes of the 'D' Group was consequently reduced from about 10 to 5 feet, and throughout the lodes of the Coronation (West) Group it was increased from 10 or 15 feet to nearly 20 feet.

Slickensides and quartz infilling indicate that all the lodes were affected but only those of the Coronation (West) Group demonstrate the substantial development of late quartz infilling. The nature of the movements is illustrated in Fig. (98) which indicates the initial wedge faulting being followed under stress relaxation by all-round normal faulting, as is similarly illustrated in Figs. (100/C) & (101/C).

(c) Central Unit

Stress relaxation, the introduction of late quartz phases, and some regeneration of the earlier economic mineral associations, affected most of the lodes of the Central unit. The economically small, steep lodes were subjected to only minor amounts of movement and infilling in contrast to the lodes of the New Group.

Normal faulting tended, as in the Western unit, to erase the effects of the earlier reverse faulting in the smaller lodes. They consequently demonstrate a small, final, overall reverse movement varying between zero and

five feet. In contrast, the New Lode Group of lodes indicate an overall normal faulting through about 15 to 20 feet.

(d) Eastern Unit

During the transition period between Stages 2 and 3 the lodes of the Wethered Group were created, reflecting the tensional relaxation in their overall strike. They were infilled by the late economic phases in the absence of any early main wall-rock alteration effects. Continued intermittent relaxation had the pronounced effect of considerably widening the lode fissures and allowing the entry of the late quartz mineral associations.

No predominantly new fractures were created during this stage of formation of the Wethered Group lodes, apart from some possessing a very low dip. Whenever possible the lode fissures were propagated along the flatter members of the longitudinal and secondary joints, and along some fissures created during the formation of the Borehole Group lodes during Stage 2.

Their relatively late infilling is evidenced by the lack of localized zoning in a NW-SE direction. The main structural control comprised a localization of the values between high angle (in plan) structural intersections and in areas of relatively high dip, being terminated below those of decreased inclination.

Late quartz phases originating during Stage 3 are very rarely represented on the lodes of the Borehole Group. Throughout all three mine units the extent of representation of the late quartz phases is indirectly proportional to the mean dip of the individual lodes.

11/5 Post-Mineralization Movements

(a) Shear Movements

The conclusion of the late quartz phases, marked by the deposition of a little calcite and siderite, was followed by a major period of quiescence, of an unknown time duration, during which no movement or mineralization took place.

As the stresses diminished the vertically directed maximum principal stress, P_1, together with P_2, ceased to operate and a major principal stress was instituted in a NE-SW direction, that previously occupied by P_3.

Horizontal movements along the previous planes of termination displaced the lodes, creating the major faults and fault zones. Some of the lodes experienced relative shearing of their walls whenever their strike allowed movement to take place. For this reason cassiterite on the No. 3 Branch Lode is sheared, and horizontal slickensides are formed in the centre of the lode. Such signs of post-mineralization movement are present in many of the lodes and the orientation of the slickensides is illustrated in Fig. (46/3).

Similar horizontal slickensides, obliterating most traces of the previous vertical sets, were also created on the planes of termination (major faults and fault zones) as shown in Fig. (46/4). In general the whole of the Geevor Mine area underwent slight horizontal movement along all possible major fractures and lodes as the ground readjusted itself to the changing stress conditions.

As shown in Figs. (61) & (62), movements along the major faults in the Western unit produced a sinistral displacement of the lodes whilst

in the Eastern unit the latter underwent a less extensive dextral displacement. In each case the total movement varied between zero and a maximum of 20 feet. The Hanging-Wall Branch Lode and many of the other less economically important termination planes produced similar results, and the latter are now evident as small crossing fractures exerting a very small horizontal displacement upon the lodes.

(b) Guides

This discrepancy in displacement and the shearing action to which the granite was subjected between the eastern and western limits of the mine created major tensional fractures. By intermittent infilling with the mineral associations now characterized by the North Levant Lode, the tensional fractures formed characteristically banded, quartz-filled fissures with numerous vughs and no cassiterite.

They are equivalent to the guides of the Pendeen-Botallack area and are represented in Geevor Mine by the North Levant Lode, shown in Fig. (102). Their sigmoidal outline complies with the theoretical conditions for the production of tension fissures under shear stress. Whenever possible the tensional opening was created by dilation of the existing lode fissures. For this reason the North Levant Lode intersects, and continues with, the Footwall Branch Lode to the west until the latter changes its strike as shown in Text Fig. (3).

Tensional dilation and infilling frequently affected the planes of termination created during the earlier stages and the guides erroneously appear to have exerted a structural control upon the extent of mineralization. Possible controls may have been exerted by the fracture in question before it was subjected to enlargement and infilling to become a guide.

(c) Minor Faults

The late NE-SW stress was also accommodated by the creation of small post-mineralization faults inflicting a horizontal displacement upon the lodes. They form a conjugate set, as demonstrated in Fig. (38/1-2), and may be utilized in a graphical determination, as shown in Fig. (38/3), of the stress distribution operating at the time of their formation.

They differ from small branches and crossing fractures, along which post-mineralization movements may have occurred, in exerting no control upon the extent of mineralization and are not associated with any local increases in the value or width of the lodes which are identical in appearance on both sides of the faults.

The processes horizontal displacement along the main faults and the formation of the conjugate minor faults are shown diagrammatically in Fig. (100) & (101) and as Stage 3 in Fig. (101A).

11/6 Control of Mineralization

"as far as is known, all the ores are connected with joints or fissures of some sort, and the variety of forms the bodies of ore may assume is mainly dependant on the nature or form of the fissuring".

.... Reid & Flett (1907).

(a) Structural Control

The main effects of Structural control upon the extent of mineralization have been outlined in previous sections. Major ore-courses and bunches are confined between high-angle (in plan) intersections between the lodes and numerous other structural features. They are frequently localized along the steeply plunging lines of low-angle (in plan) intersections as shown in Fig. (112/B).

Slight changes in the dip within an individual lode are critical and, depending upon the phase of mineralization represented and the group of which the lode is a member, may cause either enrichment or impoverishment, or both, in the local value.

In the lodes of the Wethered Group the control of mineralization by the lode dip is most obvious, producing horizontally elongated ore-courses as shown in Fig. (112/C). Once their full extent within a lode has been determined by underground exploitation further development should be directed towards locating the 'rrot' of the ore-course.

The major forms of structural control in Geevor Mine are diagrammatically summarized in Fig. (111). The principles involved apply equally well to the remainder of the Pendeen-Botallack area. Structural control in Geevor and Levant Mines by termination planes, now evident as guides and major faults, is illustrated in Fig. (113) and was outlined in a previous publication (Garnett, 1961), which is included in Appendix 11 of this thesis.

Intersecting lodes exert an important, mutual, structural control upon the extent of mineralization in each. The original, major, secondary fissures were often dissipated in the Western unit during the formation by developing a marked curvature and finally assuming a N-S or E-W strike. Such portions act as planes of termination to lodes situated immediately to the west.

In the country rocks the equivalent of the major faults in the granite form through early movements along the primary regional cross-joints. The fissures were eventually infilled with quartz and wall-rock fragments, and are also known locally as guides - not to be confused with the tensional forms confined to the granite. The latter forms were not created in the country rocks owing to their less brittle nature compared with the granite.

A correct recognition of the complex structural controls is vital in every aspect of exploration and development in the mine. Changes in the structure of the lodes and their association with other features, with the exception of the post-mineralization minor faults, exert a well-defined structural control upon the values.

This fact should be taken into account in all day-to-day development. Although the controls may not be recognized by those directly concerned in development they nevertheless exist, and the possibility of their occurrence should not be disregarded, but should be investigated on every occasion.

The basic fact should be appreciated that in every case the mineral solutions, contributing to the final value of a lode ascended the paths which offered the least physical resistance to their passage. Such phenomena as the apparent faulting of the Coronation Lode by the Complex Dyke, as shown in Fig. (65), are hence explained by the simultaneous mineralization of the dyke fissure which acted as a plane of termination to the Coronation

Lode and the Prospects to the east.

(b) Temperature Control

Geevor Mine lies on the flank of the NW-plunging, arched tin zone shown in Fig. (118), and the local attitude of the arch is reflected by the extent of mineralization, indicated by Fig. (81), and in the several transverse sections.

Comparisons between the horizons of maximum mineralization in neighbouring lodes should be based upon a recognition of the extent to which the several cassiterite phases are represented, detailed comparisons being valid between only members of the same lode groups.

Localized temperature control effects are more evident in the individual lodes near the granite contact, as shown in Fig. (112/A). An overall temperature zoning effect in Geevor and Levant Mines is represented in Fig. (114).

(c) Petrological Control

> "These phenomena seem to me capable of explanation by the fact that a lode deposit is not determined so much by the nature of the adjacent rock masses as by the structures displayed by those rock masses ...."
>
> J. B. Hill (1902).

The workings of Geevor Mine are confined to the granite, the local modifications of which exerted no petrological controls upon the extent of mineralization. Where the killas has been penetrated in the west by the No. 3 Branch Lode the latter has been proved to be uneconomic owing to the following factors:

(1) With the exception of a minor representation of the quartz-cassiterite mineralization phase, the majority of the lode values in

the immediately adjacent granite are the immediately adjacent granite are derived from the replacement of wall-rock and earlier hydrothermal feldspar. The former process cannot take place in the killas, and the ascent of the hydrothermal feldspar was impeded by the planes of termination which are now evident as major faults.

(2) Movement along the main No. 3 Branch Lode fissure is partly dissipated in the killas along major fractures and the lode is less well-defined. The petrological influence may be reduced more accurately to a structural control.

(3) Several planes of termination operating during Stages 1, 2 and 3, and now indicated by the existence of major faults and guides, shown in Figs. (115) & (141), occur on both sides of the contact. Movements in the plane of the lode were terminated by these features, thereby progressively reducing the extent of mineralization upon approaching the contact from both sides. The planes of termination are not due to the presence of the country rocks but were caused by the sudden increase in the inclination of the granite surface during consolidation.

Fig. (115) indicates a possible petrological control of mineralization in Levant Mine by the greenstone series. If no sympathetic uparching of the country rocks occurred during the intrusion of the granite the series will appear in section with the form X-Y. If the more likely uparching may be assumed, the distortion would be greatest near the granite and the series would possess a form similar to that indicated by X-Z.

In the latter case the upper limit of stoping on the Levant North Lode shows a strong relation to the attitude of the greenstone series. Whether the greenstone exerted a chemical effect upon the ascending solutions, or

whether the final effect was a structural one arising from the non-propagation of fissures in the greenstone, will be decided in future only by detailed underground work.

The cessation of mineralization in the Geevor lodes at the granite contact is not in any way associated with greenstone which is relatively absent. The major lodes of the Western unit occupy enlarged longitudinal joints which are not present in the country rocks. The continuance of the 'same lodes' to the west of the several major faults is governed by the likelihood of the propagation of a similarly-oriented fissure as a suitable continuation. Only lodes of the Borehole group will be directly continuous through the contact.

11/7

Conclusions

"Different Judgements serve but to declare
that Truth lies somewhere, if we knew but where."

The preceding analysis of the history of formation of the Geevor lodes provides an indication of the structural complexity of the St. Just mining district. Webb (1947) was the first to put forward a comprehensive account of the area and he summarized his views as follows:-

"Furthermore the St. Just lodes are narrower, steeper and not as sheeted as the E-W fractures; they also appear to follow the local joint trend. On the assumption that here, as elsewhere, a vertical force was built up by the ore fluid, the writer explains the St. Just fracture pattern as being due to a retarded relaxation of the Hercynian compression. In other words, when the ore fluids beneath St. Just were seeking to escape, there was still in operation an effective Hercynian compression. These forces, though perhaps not greatly exceeding the directive force behind the ore solutions, must have been slightly greater during the initial formation of the fracture system. Because little actual distortion occurred, the lodes would be essentially joint planes which have been widened, especially in the later stages, by the pressure of the solutions, dissolution of the wall-rock, etc. With continued relaxation of the horizontal compression, it is possible that the vertical pressure from below became dominant, but by this time fractures had already formed and any further movement would take place largely along these earlier planes. Final settling under gravity may be assumed. The essential absence both of pronounced sheeting and of re-opening of the vein, implies a less complex sequence of upheavals and is in accordance with the ideas put forward above. There is no reason to assume any age difference between these lodes and the E-W lodes of St. Ives and Carnmenellis. The Hercynian compression relaxed unequally along the E-W belt".

As one of the major mining fields of the world, relatively nothing is known about the economic geology of Cornwall, apart from the first-hand accounts of men such as Henwood (1843) who was a century in advance of his time. With regard to the structural aspects of mineralization too little is known and too many conclusions have been arrived at.

The various lode tin deposits of Cornwall are similar in as much as they are a source of tin and copper and the localization of the mineralization is controlled by structural, temperature and petrological factors.

They originate from a common source and bear a mineralogical resemblance to one another.

Each mining district of Cornwall should be considere individually and accepted views should be approached with a prior assumption of their factual nature. Each conclusion arrived at by past workers should be re-considered in the light of new evidence and one can do no better than to quote the words of Francis Bacon:

> "If a man will begin with certainties he shall end in doubts; but if he will be content to begin with doubts he shall end in certainties".

--- oOo ---

Text Fig (1).



Geevor Mine Model

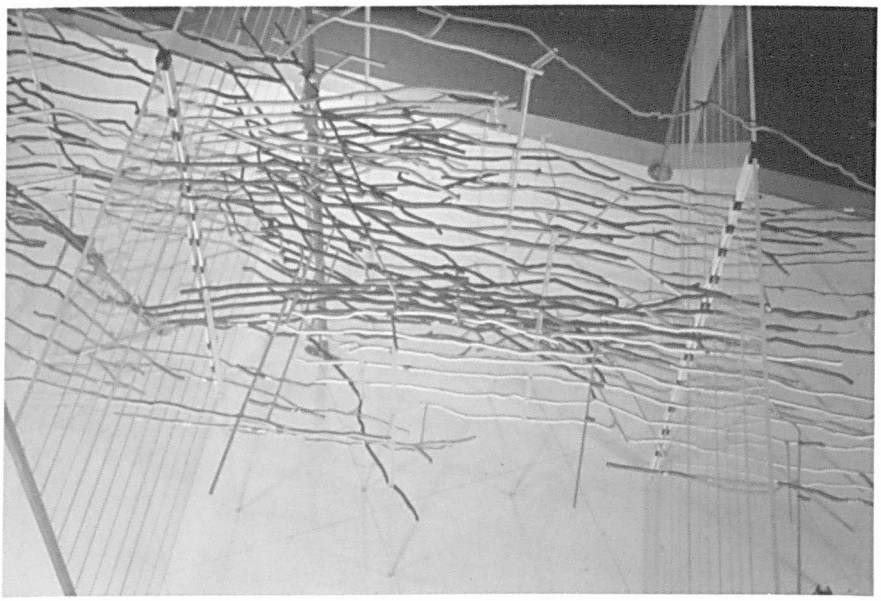
Agfacolour, 1/30th., fll,
@ 8 ft., with 4 x 200 Watt and
2 x 80 Watt bulbs, and one F.F.1.
blue bulb (G.No.85).

All the development levels and cross-cuts between Carn Shaft and the granite contact in Geevor Mine are represented to a scale of 1:600 by their outline on 3/16" hardboard. Most of the workings, which are brought up to date at regular intervals, are supported by 3 sets of 3/16" perspex strips with depths equivalent to the corresponding level intervals. These are fixed by six $\frac{1}{2}$" brass uprights, and the development ends are supported by $\frac{1}{4}$" diameter perspex rods and $\frac{1}{8}$" perspex arms.

The complete model is mounted upon a white hardboard base with grids at 600 ft. intervals. Different colours indicate the individual lodes and the cross-cuts are painted yellow. Faults and dykes are depicted on the model and all diamond drill holes, with their intersections, are represented by suitably painted 1/16" diameter metal rods.

Geevor Mine Model

A Section of the Workings



Agfacolour, 1 sec, f14 @ 5½ ft., with 4 x 200 Watt and 2 x 80 Watt bulbs.

Part of the workings of Geevor Mine are viewed towards the SSW from above the 'C' Lode. The method of support of the numerous level drives is visible, and faults and dykes are diagrammatically represented on a white background.

The relationship of the 'D' Lode (dark green) and No. 3 Branch Lode (white) to the Hanging-Wall Branch Lode (purple) is demonstrated. To the East of the latter the junction of the Western and Eastern sections of the Coronation Lode (red) plunges SE. The main level 9 cross-cut is terminated north of the 'C' Lode, down the dip of which the foreground view is inclined.

GEEVOR MINE.

NORTH BODY (FOOTWALL BRANCH).

LONGITUDINAL DIAGRAM.

FT. LB. SnO_2 / TON.

CONTOUR OF :- FT. LB. SnO_2 / TON.
LEVELS EMPLOYED :- 9-13-15.
INTERVALS OF :- 50 FT.
REFERENCE PLANE :- —
SCALE :- 1" = 100'.
DATE :- 1/JAN. 1962.

LEVEL	DEPTH BELOW COLLAR OF VICTORY SHAFT.
#3	260.00. FT.
#5	410.00.
#6	490. 00.
#7	590. 00.
#8	665. 00.
#9	765. 00.
#10	865. 00.
#11	974. 60
#12	1089. 25.
#13	1206. 23.
#14	1321. 18.
#15	1433. 69.

GEEVOR.

		DATE.
DRAWN BY	INITS.	R.G.T.
TRACED BY	INITS.	R.G.T.

PLAN OF LEVELS

100 FT.

FOOTWALL BRANCH LODE.

NORTH LODE.

NORTH LEVANT LODE.

OLD WORKINGS

JUNCTION OF SOUTH PK LODE AND NORTH LODE.

LONGITUDINAL SECTION.

POTENTIAL

ACTUAL JUNCTION H.W. VEIN & FW. BR. LODE.

STICK TO H.W. VEIN

HANGING WALL VEIN LODE

FOOTWALL BRANCH LODE

STICK TO FW. BR. LODE

APPARENT JUNCTION H.W. VEIN AND FW. BR. LODE.

MAIN WESTERN FAULT F_2.

NORTH LEVANT LODE RUNS WITH FLUKER LODE ???

FAULT F_2

LODE SPLITS IN HERE

NORTH LODE IN FAULTED HERE

NORTH LEVANT LODE OUT

NORTH LODE (WESTERN EXTENSION)

FOOTWALL BRANCH LODE

FZ_1

F_2

HANGING WALL VEIN LODE

JUNCTION OF H.W. VEIN AND FW. BR. LODE.

FOOTWALL BRANCH LODE

R.N.T. GARNETT. M.T.60.
JAN 1ST. 1962.

Off-Shore Mineral Exploration

Appendix I

> "Perhaps when the veins are exhausted, which lie within the boundary of our sea-girt peninsular, we shall turn our attention to those that extend in the same direction beneath the bed of the ocean."
>
> ..... J. Hawkins (1818).

During July 1960, two square miles of the sea-bed between St. Agnes Head and Cligga Head on the north coast of Cornwall, as shown in Fig.(114), was geologically explored using aqua-lungs. Depth soundings for the area were compiled into a bathymetric chart to which further detail was added as required, by the use of a small portable echo-sounder. The chart shown in Fig.(147), indicated the existence of several major rock outcrops on the sea-bed.

When weather conditions were suitable spot dives were made to selected parts of the sea-bed which were located by means of the sextant chart shown in Figs.(145) & (146). The divers worked in pairs obtaining a sample of each outcrop located. With a mean diving depth of 55 feet it required an average of 10½ minutes underwater at each location to complete all the necessary work. To facilitate the detection of outcrops an aqua-plane was also used and a diver towed underwater for distances of up to ½ mile by this means. All the information was logged on the sheets illustrated in Fig.(149).

The bedrock outcropped over approximately 40% of the

sea-bed in the area examined. The coastline was bordered by a belt 1/3 of a mile wide in which all the bedrock was covered by sand as shown in Fig.(148). Beyond this belt the outcrop samples were of the Gramscatho division of the Devonian. Variations were detected in the degree of alteration of the killas and the aureole of metamorphism, shown in Fig.(150), was successfully traced out to sea.

Although no lodes were detected on the sea-bed the coastal area lies within the belt of tin-copper mineralization which is associated with the Cligga and St. Agnes granites, as shown in Fig.(143), and has been extensively worked for these metals in the past.

The work was conducted in order to indicate the potential of a geologist fitted with underwater diving equipment in the prospecting of potentially mineralized off-shore areas in South-West England and other parts of the world. The techniques have an important practical application in limited areas, and also over larger extents if employed in conjunction with geophysics and other off-shore prospecting methods.

The initial investigation of the '40 Backs' in Levant Mine was conducted in 1960 by the team engaged in the St. Agnes area work, and an account of the results is included as a reprint in this Appendix. A reprint is also provided of an account of the work in the St. Agnes district described above.

The Royal Institution of Chartered Surveyors

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Off-Shore Mineral Exploration

by R. H. T. GARNETT, D.I.C., B.SC.(ENG.), A.R.S.M., F.G.S.

The following paper was presented at a general meeting of mining surveyors held in Nottingham on Saturday, 26th November, 1960.

INTRODUCTION

Apart from a few notable exceptions, the majority of the mineral deposits at present being worked throughout the world were discovered as outcrops at the surface during the early part of the 20th century. The likelihood of a prospector discovering further outcropping deposits decreases with each succeeding year if such areas as the Arctic lands and equally inaccessible regions be excluded. The days of the old-time prospector are quickly departing and his place is now being taken by another new mining specialist—the mineral exploration engineer. D. Williams states that " the finding of new deposits, mostly concealed beneath a thick mantle of overburden, is becoming ever more difficult without recourse to scientific prospecting based on imaginative geological reasoning, aided by aerial photography and modern techniques of geochemical and geophysical exploration." This is the role of the prospecting engineer who brings into the industry entirely new techniques and new ideas. Such a man must not allow his imagination to be limited by existing conceptions. For instance, prospecting engineers have, in the past, thought of overburden as a mantle of rock overlying the mineral deposit. It is better thought of as a covering through which the deposit is detected and which must be penetrated in the majority of cases before recovery of the deposit may commence. On this basis, overburden may refer either to the land surface or to the oceans and if the discovery of further mineral deposits is to continue at a pace demanded by ever-increasing world mineral consumption then the prospecting engineer must regard both the land and the seas as potential exploration areas.

The first major advance comes with the realization of this fact and with the first attempts to probe beneath the waters which cover 70.8 per cent. of the earth's surface. A growing interest in the potential of the sea has been aroused through the science of oceanography. Although the latter is not a new subject, it is only now that its importance is being fully recognized and several international bodies are at last being created to foster research. The primary interest of such organisations is the fauna and flora of the sea from which man may one day reap his harvests of food. Little thought has so far been given to the mineral potential of the sea ; in solution, as sediments, or beneath the sea floor.

One of the first indications of the scale of the so far unexploited deposits came with the off-shore oil drilling around the coast of the U.S.A. and in 1945 the President of the United States claimed as additional national territory an area four times the size of Texas ; the sea-bed, subsoil, and waters of the continental shelf as far as the drop-off line which is defined as a depth of 600 feet where the shelf commences to decline into the depths. The distance to the drop-off line is variable but in the off-shore oil producing areas is as great as 200 miles. Since that time, off-shore activity in the mining industry has increased considerably and many countries have laid claim to the waters and deposits of their continental shelves.

Off-shore deposits, with the exception of minerals held in solution, may be classed as existing in the form of either sediments on the sea-bed or deposits beneath the latter. In both cases the exploration and development may be the result of continuing development beyond the coast of deposits that have been proved and worked on land. On the other hand, eventual production may be the result of prospecting in virgin off-shore areas when no signs of mineralisation exist upon the adjacent shore. Whatever the history the engineer must develop a prospecting technique and a method of recovery.

PAST AND PRESENT OFF-SHORE MINING ACTIVITY

The mineral potentialities of the sea are now being recognised for the first time although records of off-shore activity are provided by both Pausanius and Aristotle, who mention the existence of small mines for gold and copper which penetrated for a distance under the sea, the former being eventually flooded by the gods as an act of revenge upon man for his impudence in trespassing. In that once great mining field of the south-west of England are to be found the disused tin-copper mines of Botallack and Levant in the St. Just field. The workings of the latter extended 5,000 feet out to sea from shafts on the cliffs and to a depth below the sea-bed of over 2,000 feet. The Wherry Mine at Penzance is another example. Here small veins of tin exposed in a dyke at low water were first worked around 1700. After several attempts a shaft was sunk to a depth of 26 feet

and surrounded by timber walls above the sea-bed to prevent the entry of the water at the high tide when the collar of the shaft was 20 feet below the water surface. This enterprising mine, however, was finally brought to a standstill in 1792 when a vessel broke loose from its moorings during a storm and smashed into the headframe of the shaft.

Such attempts at submarine mining did not pass unnoticed. In 1818 Hawkins wrote "Perhaps when the veins are exhausted, which lie within the boundary of our sea-girt peninsula, we shall turn our attention to those that extend in the same direction beneath the bed of the ocean ; nor, when we consider the increasing depth of our mines, can that period be very distant. Our submarine works will then form a new epoch in the history of mining, and by calling forth still greater exertions of skill and industry, demonstrate in a more striking manner, the powers of the human intellect. . . ." Outside the mining region of the South-West of Cornwall it has not been uncommon for seams of coal to be worked well beneath the sea and when Hawkins was writing in 1818 coal mines in Whitehaven had long extended their workings beyond the coast.

The first major advance was made in 1922 when off-shore drilling for oil commenced in Venezuela and by 1929 wells were being sunk in 60 feet of water. Off-shore exploration for oil, as opposed to drilling, was commenced on the Louisiana continental shelf in 1938 and by 1947 the first off-shore oil was being produced. Ten years later the number of off-shore wells drilled and completed was 665, according to Crosthwaite, and up to 1959 there were 75 companies engaged in off-shore oil exploration in the U.S.A. alone with a total investment of £714 million. Elsewhere, oil companies have been equally active with the result that the oil was first struck in the Persian Gulf in 1951. Off-shore drilling commenced in Borneo in 1954, and in Trinidad in 1955.

In 1949 the Humble Oil Company were drilling for oil in 50 feet of water and at a distance of 7 miles from the coast of Louisiana when 200 feet of sulphur-bearing limestone were intersected. On the basis of eight drill intersections of the deposit at an average depth of approximately 2,000 feet recovery of the sulphur is planned by the Frasch process at a cost of 30 million dollars. Although the boundaries of the deposit have not yet been delineated on two sides, the proved deposit is already the third largest in the United States.

For many years now the existence of manganese nodules on the ocean floors has been known, but has caused little industrial interest owing to the fact that land supplies fulfil all requirements. However, it has recently been found that such nodules contain, in addition to 20 per cent. manganese, an average of 0.5 per cent. of nickel, cobalt, and copper. J. L. Mero has evaluated the cost of dredging operations in depths in the region of 4,000 feet and concludes that a deep-sea hydraulic dredge would lead to mining costs of the order of 3 to 5 dollars per ton.

Sand and gravel has not, until recently, been recovered in any tonnage from beyond the low water mark, but in 1955 thousands of tons of sandfill for a highway were pumped from the floor of New York Harbour, and in Toulon cement for naval bases has been mixed with sand dredged from the sea-bed following the direction of divers. In the Bristol Channel 1½ million tons of sand and gravel were taken from the sea bed during 1959. Dredging is by suction pump to a maximum depth of 50 feet of water and up to a distance of 12 miles from the shore. At other localities around the coasts of Britain large tonnages are being recovered from the sea-bed annually.

In a similar manner the attention of the tin dredging companies is now being focused upon the potentialities of the sea-bed sediments. In Indonesia off-shore surveys in conjunction with the drilling of bedrock and the overlying strata have been conducted to facilitate the exploration and recovery of submarine tin-placers. According to van Overeem the bulk of the tin in this field is found in the submerged valley floors where sediment thickness varies between 0 and 150 feet beneath a water depth of from 10 to 90 feet. As the world's alluvial deposits are gradually exhausted companies must consider not only the possibility of prospecting for the original tin lodes from which the alluvial tin was derived but also of investigating the off-shore sediments.

Iron ore exposed on Bell Island in Eastern Canada is now being worked from below the sea, and production is coming from points approximately 3 miles off-shore and 2,000 feet below sea-level following the development of the bedded deposit in that direction. J. C. Pierce states that production has now attained the figure of 2,800,000 tons annually, and that the same company is working coal in Nova Scotia 4 miles off-shore and 2,000 feet below sea-level. Recent papers have also stressed the need for off-shore exploration in the United Kingdom by the National Coal Board. In the past the seawards exploration of coal seams worked upon the land and dipping under the sea has always been by underground driving and boring, but recent off-shore operations in the coalfields of Northumberland and Durham, and the Lothians and Fife have been very successful. They have shown that there is only one reliable method of proving the off-shore extensions of coal seams ; by drilling through the sea-bed combined with geophysical devices.

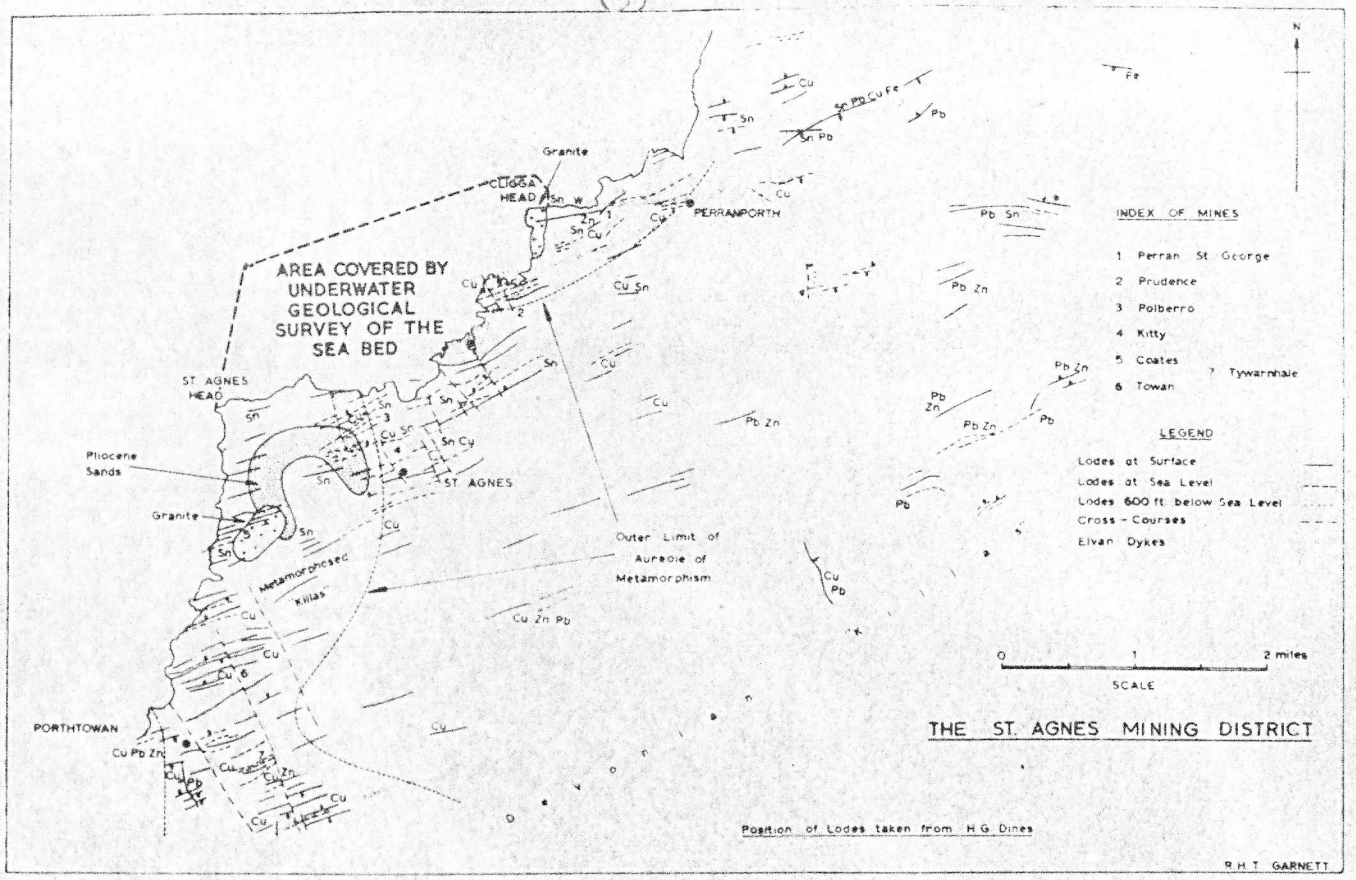
An ever-increasing number of organisations are conducting research upon sea-bed geology and the improvement of techniques whereby the necessary information is made available. Extensive studies by a number of the American Universities are being made in many branches of marine geology, especially off the Californian coast. Marine geology is now taking its rightful place in British Universities, especially Bristol, Liverpool, and Imperial College (London), and recent work upon the projected Channel Tunnel has been followed by complete geological studies of the English and Bristol Channel sea-beds.

OFF-SHORE EXPLORATION

In the exploration of off-shore deposits it is essential that the amount of information obtained concerning all aspects of the deposit should not be less than the information required concerning a land deposit before its development is commenced. Apart from economic factors, the majority of the decisions regarding the eventual working of a deposit are based upon geological knowledge and it therefore follows that it is necessary to obtain the maximum possible geological information before proceeding further.

With respect to sea-bed sediments, the geophysical methods of exploration will provide information regarding the depth of overlying water, the depth of the sediment, and the configurations of the bed-rock. Details of the tonnage, distribution, grade, and positioning of the economic mineral within the sediments can be obtained only by drilling, coring, dredging and diving. Also to be considered are the distance of the deposit from the nearest land, the mining and dressing methods, transportation costs, and the market potential.

Lode and seam deposits present more serious problems but in a like manner such factors as the depth of water to the bed-rock, the depth of the deposit below the bed-rock, and



The St. Agnes Mining District showing the extent of completed off-shore exploration

the major geological structures may be investigated by geophysical methods. The above, and additional information such as the nature of the deposit, the nature of the bed-rock, the configuration and limits of the deposit, the minor geological structures, and the expected tonnage and grade (where applicable) may be derived from a combination of methods involving geophysics, drilling, coring and diving. In addition to the economic factors that have to be considered when examining sediment deposits the problem of underground exploitation of the mineral lodes from the adjoining land must be examined. The iron ore deposit mentioned earlier is worked by room-and-pillar methods and a minimum cover of 200 feet exists between the workings and the sea-floor bed-rock. Depending of course upon the nature of the overlying strata, it would appear that 200 to 250 feet should be the minimum cover allowed for undersea mining. A recent case of workings close to the sea-bed has been investigated by the writer in Cornwall. The workings of the Levant Mine were known to have approached to within only 30 feet of the sea-bed during production and it was feared that since the closure of the mine in 1930 the sea had entered into the workings causing the flooding. A team of divers under the direction of the writer made a detailed examination of the sea-bed. Guided by fluoresceine which had been introduced into the workings through one of the mine shafts, the divers discovered a breach in the sea-bed coinciding exactly with abandoned stopes located from old mine plans. It is evident that the formation of a cavity in the sea-bed was assisted by the percolation of water through the overlying rock and by the pressure differences existing between the once air-filled workings and the sea-bed at a depth of 45 feet below water surface.

GEOPHYSICAL METHODS OF EXPLORATION

For all off-shore work it is necessary to know the depth of water at all points. Depth soundings were originally made with a weighted line or wire until the development of the echo-sounder. An impulse is beamed from the boat on the surface, is reflected by the sea-bed, and is received again by the boat, the time interval being proportional to the depth of water. The instrument exists in many forms but the most important is the continuous recording type in which all depth measurements are automatically recorded on a continuous sheet which eventually takes the form of a profile, often exaggerated, of the sea-bed.

A development of the latter is the inclined echo-sounder which, by the same principle, permits the beaming of the energy to the sea-bed at a pre-determined angle. Small scarps on the sea-bed therefore provide a strong reflection as opposed to surfaces sloping away from the beam which give very little reflection. The results, when continuously recorded, take the form of an inclined view of the sea-bed enabling the observer, in the absence of any sand covering, to interpret within limits the characteristics of the sea-bed outcrops located. This instrument has been used with success recently in both the English and Bristol Channels.

By replacing the intermittent, high-frequency source of the echo-sounder with a low-frequency sound source under water a penetration of the sediments and bed-rock has been achieved. Such an instrument, known as the sparker, continuously records echoes reflected from a large number of structures and produces a record of both the sea-bed profile and the major geological structures underlying the bed-rock.

The sparker has achieved results in water depths of 2,400 feet and sea-bed penetrations of 1,500 feet in lesser depths.

Major geological structures are also revealed by the use of the gravimeter by which precise measurements are made of the variations in the force of gravity at fixed points throughout an area and interpretations based upon the resulting gravity contour map. An investigation of this nature was made in the Persian Gulf by Cousteau on behalf of an oil exploration company by lowering the gravimeter to the sea-floor and recording the measurements in the boat above. In a similar manner measurements may be made of the vertical and horizontal components of the earth's magnetic field and since rocks of differing types possess varying magnetic susceptibilities, indications may be obtained of the changes in rock type at depth. The magnetometer may be employed for off-shore purposes in either an airborne survey or a sea survey in which the instrument is selectively towed behind a boat or installed upon the sea-bed.

Upon the principle of the different speeds of energy through varying rock types a charge of explosive may be detonated upon the sea surface and the echoes from structures beneath the sea-bed received at a series of equally-spaced recorders on the surface, with the time interval between initiation of the energy and its receipt being measured. This technique has a wide application in all forms of off-shore exploration.

SEA-BED SAMPLING METHODS

All off-shore geophysical methods are incomplete if the necessary petrological and mineral grade information cannot be supplied. Off-shore drilling furnishes sub-sea bed details and, although a costly operation, it has been used extensively in the oil industry. The National Coal Board have employed drilling in their off-shore work and it will in the future be utilised to a far greater extent in the search for metalliferous deposits. However, it is at the moment limited to the region 100 to 150 feet of water depending upon the conditions.

Samples of sea-bed sediments may be obtained by the use of various coring devices. First developed in 1876, the modern corer takes the form of core tubes of lengths of 10 to 30 feet and a diameter of a few inches. Weights are fitted to the corer and it is dropped vertically through the water so that upon impact with the sea-bed a sample of the sediment is forced into the tube. The corer is then brought to the surface and the sediment core retrieved. By this means cores of lengths of up to 17 feet have been obtained. To obtain a greater penetration of the sea-floor use may be made of water pressure and explosives. In this manner cores of 70 feet have been taken. Corers have been adapted for any depth of water and are chiefly designed to provide samples of the sediments, but cores and samples can also be obtained from the bed-rock if it is sufficiently soft. The method fails when the hardness of the bed-rock prevents the entry of the cutting edge of the corer.

Dredging of sediment and bed-rock samples is possible from all depths. Extremely strong equipment is necessary and by measuring the pull exerted upon the dredge winch it is possible to predict the nature of the sea-bed ; whether there is rock outcrop or sand. By dislodging pieces of rock from outjutting ledges, the dredge obtains a sample of the bed-rock and by a series of traverses the operator may determine the boundaries of a sea-bed outcrop. During work conducted by the writer in Cornwall the same principle was applied by trailing a small grappling iron behind the diving boat. By the use of the above techniques sea-bed samples were dredged from a depth of 19,900 feet in as early as 1901. The deepest bottom samples so far obtained are from a depth 34,000 feet in the Phillipine Deep.

Closely allied with bottom sampling are techniques of underwater photography. The first underwater photographs were obtained in 1893 and since that date it has become possible to take sea-floor photographs by remote control. The camera may be lowered to the sea-bed upon a device by which it is triggered off at a certain distance from the bottom, depending upon the expected underwater visibility. The apparatus may include artificial lighting, a compass, and a current direction recorder. 25,000 feet is the maximum depth from which a photograph of the sea-bed has so far been obtained. Underwater television is now a practical proposition and was used with success when locating the wreck of the Comet airliner off Elba and in searching for the submarine *Affray* in 1951. It is capable of being used in several hundreds of feet of water and appears to have a better definition than the human eye.

THE USE OF DIVERS

During a voyage of the research ship *Calypso* in 1954 the corer was dropped in 40 feet of water in order to obtain a sample of the bed-rock. When the line was hoisted aboard the corer was missing. It happened that the boat was equipped with divers who decided to retrieve the corer from the sea-floor. A dive was accordingly made and it was found that the corer was bent into a Z-shape. To discover the reason the divers dug into the shallow covering of sand and found that the bed-rock was composed of granite. They returned to the surface and dived again fully equipped with hammers and chisels, and it was not long before samples of the rock were handed to the geologist on board the boat. This simple story illustrates the weakness of all corers and the way in which diving geologists may be integrated into a programme of off-shore geological exploration.

The oil companies rapidly appreciated the possibilities afforded by this new sampling technique and in the Persian Gulf an extensive geological survey of the sea-bed was carried out with a ten-man diving team in combination with a marine gravimeter, samples of the bed-rock being taken from the floor in water depths of 200 feet. The Humble Oil Company established a diving team for underwater geological work off Texas.

All the methods employing geophysics, drilling, coring and dredging are remote-controlled means of obtaining information and samples. In any science the direct method of observation is always desirable where there is no danger of injury to the observer. Apart from sinking and cross-cutting out to an area beneath the sea the geologist has no method of direct observation of the petrology and structures. The sea-bed, however, is accessible to man in the form of divers, but the latter have only very rarely been employed in the past owing to their extremely limited mobility under water and the art of diving has been very much confined to professionals. Since the development of the aqua-lung in 1943 by J. Y. Cousteau, the diver is no longer dependent upon the surface for his air supply and also possesses complete mobility when in the water since his natural positive buoyancy is neutralised by the use of suitable weights. The aqua-lung provides the equipment which enables man to make a safe examination of the sea-bed, provided that there is a complete understanding of the possible dangers involved. The limit to which a dive may be made with an aqua-lung is 300 feet and a geologist can be quickly-trained in its use to a workable depth of 150 feet.

This means that where the sea conditions permit, a geologist

may make a series of dives and conduct a complete study of the sea-bed *in situ*. It is now possible to collect samples of sediment by auger, sample the bed-rock where exposed or covered by only a thin mantle of sediment, and make any necessary observations upon the minor geological structures exposed.

Already several extensive surveys have been completed by diving geologists. During 1953 diving teams mapped 2 square miles of the sea-bed of part of the continental shelf on the north side of San Nicolas Island, California. With the geologists diving in pairs it was found possible to obtain all the necessary information and samples from a depth of 50 feet with a dive of an average duration of 14 minutes. In France, a geological survey of the sea-bed of the Bay of Mont-Saint-Michel was completed during 1955. The work was undertaken to supply information for future harbour constructions and a team of divers was employed. The method may also be applied to inland waters and part of the bed of Lake Norra Dellen in Sweden has been mapped by a diving geologist and the information gained correlated with mapping already conducted on the surrounding land. Depths of 60 feet were exceeded in this work.

Meanwhile work has continued in the U.S.A. and geologists are now diving to study sediment formation, the mechanism of underwater erosion, and to carry out extensive underwater mapping. Dugan refers to the existence of the Geological Diving Consultants Inc., who, by 1956, had made approximately 5,000 dives with the specific purpose of obtaining geological information. Records show that the average duration of a dive is 15 minutes to a mean depth of 55 feet. The team of divers, which consists of three geologists, makes an average of nine dives a day.

In the United Kingdom the aqua-lung's usefulness was quickly appreciated by the marine scientists and it is now regularly used for the study of marine biology and related subjects. The aqua-lung was first used for geological purposes in the English Channel, but the work suffered from the fact that personnel, untrained in geology, were employed. During 1959 an expedition from Imperial College, London, spent two months in the Azores Islands and the writer, as a member of this expedition, devoted the time to developing a technique of underwater geological mapping with an aqua-lung in conjunction with echo-sounding and surveying methods. This work was continued in Cornwall during 1960 when the writer was assisted by five divers in making a survey of the geology of the sea-bed for an area of 2 square miles off the coast between St. Agnes and Perranporth.

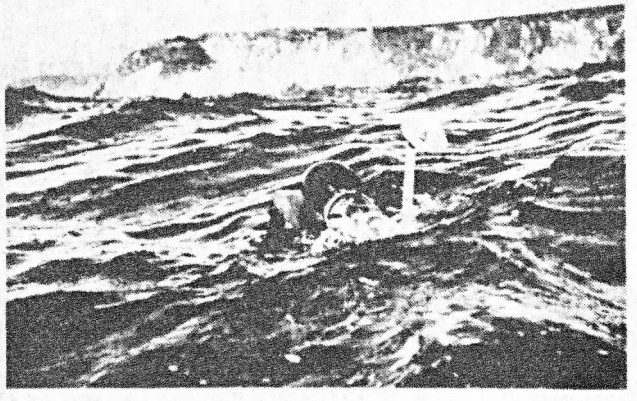
The same principles apply to geological mapping underwater as to mapping on the land surface, but the technique varies according to the prevailing conditions. With good underwater visibility the geologist may swim along the exposed rock contacts or the boundaries of the sea-bed outcrop with the diving boat following his movements. In the conditions usually existing in the United Kingdom the visibility is the limiting factor in all the work and it is possible for the diver to make only a series of spot dives. The underwater geological map is therefore compiled by interpolation from a large number of spot samples and observations of the structure. The diver is also limited in his work by physiological factors. Owing to his susceptibility to pressure the maximum depth to which he may dive is 300 feet using present equipment. This means that a rock sample may be obtained by a geologist from a maximum depth of 300 feet but a more realistic figure of 150 feet should be regarded as the maximum routine working depth.

In areas of good underwater visibility it is advantageous to provide the diver with a means of rapid preliminary exploration of the sea-bed. This is best undertaken with an aqua-plane which can also satisfy the further requirements of precise position control and communication between the diver and the diving boat. Towed by the diving boat, the aqua-plane is simply a small underwater glider upon which the diver lies full-length. The general depth and direction of movement are decided by the speed and course of the diving boat, but a lesser amount of control is also possible by the diver. For physiological reasons the maximum gliding depth for long durations is limited to 30 feet. Several unsatisfactory attempts have been made by amateurs to develop a successful aqua-plane, but it requires a professional engineer, possibly a specialist in aeronautics, to solve the serious design problems.

In common with other branches of geology, it is essential to record immediately the vast amount of observed detail, for observations concerning a studied and sampled outcrop are easily erased from the diver's mind during his ascent to the surface. It has therefore been found advisable to supply the diver with an underwater writing pad and this method works successfully. However, there are times when physical discomforts or dangers distract the diver from the laborious recording of all the detail. In such cases some form of simple throat microphone adapted for underwater use could be employed to advantage. The diver would be able to register immediately through a tape-recorder all the observed details. Such an aid would also reduce the effect of the dangers to human life that may be encountered during diving.

Where the bed-rock is covered by sediment it is frequently impossible for the geologist to obtain a rock sample by digging through the sediment. The development of a small drill which could be lowered to the sea-bed from the diving boat and be controlled by the diver would provide a great advance in the efficiency of sampling. The drill should be capable of penetrating the sediments and of obtaining a short core of the bed-rock. A further application of an underwater drill would be in the sampling of economic sediments, since the present estimation of the grade of sea-bed sediments is very liable to errors.

Although the aqua-lung diver is at present limited to a maximum depth of 300 feet a large proportion of the continental shelf may be explored by this means. Further experiments on gaseous breathing mixtures and increased knowledge of the long-term physiological effects of diving may in future extend the range.



A diver surfaces following the completion of the sampling operation. The cliffs of Cligga Head are shown in the background

UNDERWATER MAPPING IN CORNWALL

In July, 1960, a team of divers devoted three weeks to underwater geological mapping in the south-west of England. The method of mapping by means of the aqua-lung was perfected and, under the direction of the writer, a detailed geological examination of part of the sea-bed was completed. A total of six divers operated from a small boat and mapped 2 square miles between St. Agnes Head and Cligga Head. The divers worked on the sea-bed in pairs, obtaining a sample and a photograph of each outcrop located. The detection of areas of possible outcrop was effected by interpretation of an Admiralty bathymetric chart illustrating the " topography of the sea-bed." Greater detail was obtained by traversing with a small portable echo-sounder. An aquá-plane was also used and a diver was towed underwater for distances of up to half-a-mile noting the occurrence of sea-bed outcrops.

Where samples of the sea-bed and photographs were to be obtained two geologists always dived together. With a mean diving depth of 55 feet it required an average of only 10½ minutes underwater to complete all the necessary work.

The bed-rock was found to outcrop over approximately 40 per cent. of the sea-bed examined. This figure varied and was influenced by the weather conditions. The coastline was bordered by a belt one-quarter of a mile wide in which all the bed-rock was covered with sand. Nevertheless, the overall frequency of outcrops in the prospected area was greater than that on land. Apart from the cliff section, very few exposures exist inland.

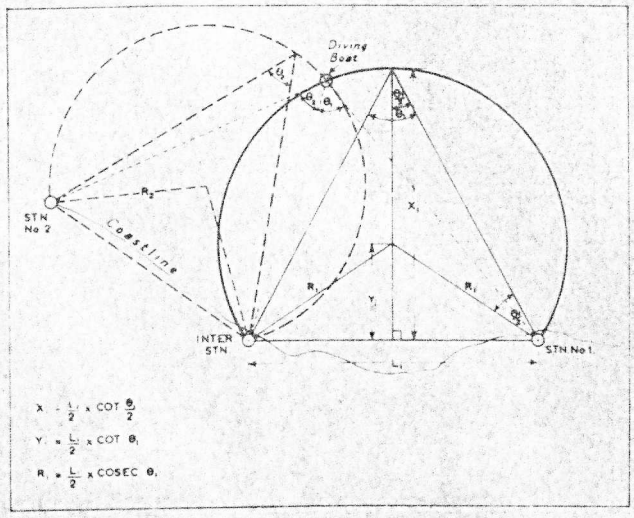
All the outcrops located on the sea-bed were of schists or " killas " as it is commonly referred to in the south-west of England. Variations were detected in the degree of alteration of the " killas " and the aureole of metamorphism, as mapped on the land, was successfully traced out to sea for a distance of 1 mile.

SURVEYING TECHNIQUES

When the boat from which operations are being conducted is within sight of land its position may be fixed by intersection from survey stations upon the coast. Although accurate, this method suffers from the disadvantages that at least two observers are required upon the land, and the engineers on the boat, unless equipped with radio, are ignorant of their exact positions until they return to their shore base. A less accurate method which eliminates these difficulties consists of taking bearings to survey stations on the coast and plotting the position of the boat on board by graphical methods.

In all off-shore work, the geologist must know the position of the boat as accurately and as quickly as possible. Where the land features can be seen clearly the best method is the use of sextant charts. These are based on the principle that any point on a circle passing through two other points subtends a constant angle θ at those points which may represent survey stations erected upon the coast. A series of circles of varying diameter representing different values of θ are constructed through the two survey stations. From the diving boat, the observed angle θ_1 is measured by a sextant and the position of the boat is then known to be somewhere on a given circle passing through the two survey stations. In the same manner the angle θ_2 to two further stations, one of which may be common to the first pair, is measured. The position of the boat is therefore fixed by the intersection of the two circles.

In practice, mutually and easily visible coastal survey stations are first erected. For pairs of selected stations sets of circles corresponding to varying values of θ are plotted on a plan. This constitutes the sextant chart from which the position of the boat may be determined in any part of the exploration area. At any position a minimum of two pairs of survey stations must be visible from the boat. On board the boat readings are taken of θ_1 and θ_2 with the sextant and the position of the boat is immediately determined by the intersection of the corresponding circles or by interpolation between them when necessary.



The principle of the sextant chart

For the exploration work in Cornwall during 1960 such a sextant chart was constructed. To cover the total diving area of 2 square miles seven survey stations were established by triangulation and resection from the existing ordnance survey stations. From the seven stations eight sets of circles were constructed for variations in θ of 1-degree between 30-degrees and 150-degrees. The maximum distance between any two survey stations from which a set of circles was constructed was approximately one mile.

At the limit of the diving area, one mile from the shore, the distance between the circles represented 150 feet. At any point in the area a minimum of three sets of circles could be utilised for the position fixing. A distance of one mile from the shore was the greatest distance at which the position of the boat could be determined with sufficient accuracy. This limit was imposed by the prevailing visibility and sea conditions which prevented a reliable reading of θ. The effects of the sea swell upon the 14-foot boat which was used throughout the work were found to be considerable. With a larger diving boat the limit of 1 mile could be extended.

For off-shore exploration when easily visible points on the coast may be fixed, the sextant chart technique is recommended. It may be adapted for rapid work by determining θ from compass bearings to the survey stations, but more accurate fixes will be obtained by using a sextant. The sextant chart method is now used for harbour construction work where there is land-locked water. Although it can be employed on a straight coastline it is more applicable to use on water surrounded on two or three sides by the land, such as an estuary. The method is widely employed by the Admiralty.

When the boat is out of the sight of land the difficulties encountered in fixing the position of the boat become more numerous and less easily overcome. The methods employed include dead reckoning, astronomical fixes, radar, and Decca. In the past a large amount of scientific work has been completed without accurate positioning. This work is of little value without an accurate and readily available positioning

technique. Recently the situation has improved with the development of many electronic devices now in use for maritime navigation.

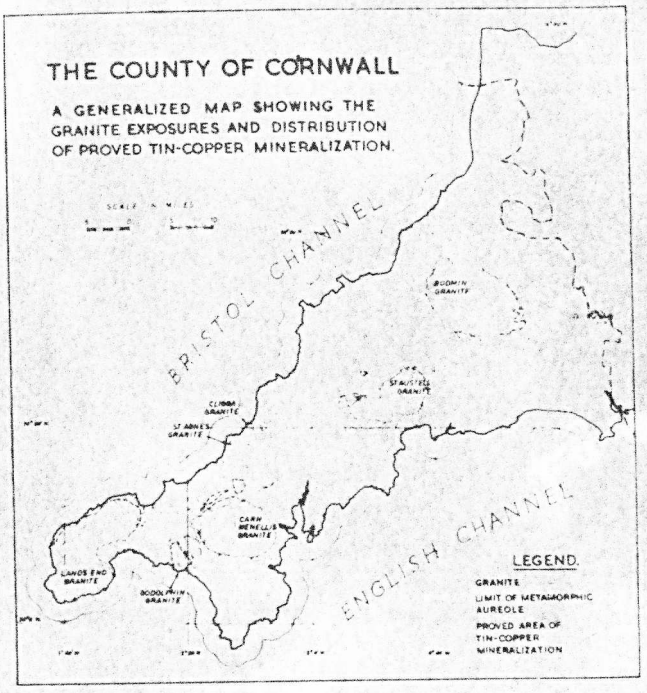
The above methods supply the operator with the position of only the boat, and it is then the responsibility of the surveyor to determine the position of the diver relative to the latter. The importance of the positioning of the diver depends upon the accuracy with which the position of the boat is being determined at the time and upon the area of the sea-bed covered by the geologist in a single dive from the anchored boat. During the work conducted in Cornwall the position of the boat was fixed to the nearest 100 feet. Owing to poor underwater visibility of less than 10 feet and the dangerous sea conditions the geologist descended down either the anchor line or a vertical shot-line beneath the boat. When a descent was made down the anchor line the surveyor knew the length of the anchor line in use and the depth of the water was measured with the echo-sounder. The bearing along the anchor line was taken with a compass and an estimate of its inclination was provided by the diver as a check. The surveyor was therefore able to calculate the position of the diver relative to the boat provided the former did not leave the immediate vicinity of the bottom of the line. With improved underwater visibility the writer has employed a further method. Sea-bed sampling points at distances of up to 50 feet from the line have been fixed by taping from it and reading the bearing to the line with an underwater compass. This method is important in underwater archaeological investigations where extreme accuracy is necessary. One may imagine in the future, under conditions of suitable underwater visibility, adaptations of standard surface surveying techniques in the form of underwater plane-tabling, chaining and offsetting.

When the diving conditions are sufficiently favourable to allow the diver to be completely independent of the diving boat, as opposed to making use of a safety line, full use cannot be made of the diver in geological mapping, for no device has yet been developed which accurately tracks the diver underwater from the diving boat. The ideal method would provide a continuous record of the diver's position combined with the automatic recording of all his observations by an underwater microphone and would greatly increase his efficiency.

EXPLORATION IN THE UNITED KINGDOM

The writer is particularly concerned with the exploitation of tin-copper mineralisation in the south-west of England. For centuries deposits have been worked from the land in this region and to a very limited extent from beneath the sea during the 18th and 19th centuries. The mineralisation is closely related to the intruded granite and in plan shows a marked association with the land exposures of the granite. The land surface and the ground beneath has been extensively explored with the result that many hundreds of mines have been opened. At one time Cornwall was the world's major producer of both tin and copper. Exploration has never extended beyond the low water mark and the mines that have been worked beyond this limit, such as Botallack and Levant, have been developed by underground exploration in the direction of the sea from already active mines on the land. Workings in the remainder of the mining areas in this region of England have ceased abruptly below the low water mark. This was a result of the limitations of the mining methods in use during the times when the mines were in production. It is most unlikely that mining areas which have yielded large tonnages during the 19th century when worked beneath the land should suddenly become uneconomic below the coastline. Bearing in mind all the factors influencing the formation of such mineral deposits, it may be assumed that areas of economic mineralisation as proved from the land will continue in area and in depth irrespective of the existence of the sea. They may be expected to continue in the same manner as their counterparts, the boundaries of which have been determined as existing entirely beneath the land surface.

The limit to which divers may be employed for off-shore geological exploration around the Cornish coasts can be represented by a line drawn around the coast at a distance of about 2 miles from the low water mark. The area of Cornwall is approximately 1,390 square miles and the additional area included by the 2-mile limit is 440 square miles, increasing the total area of Cornwall by 32 per cent. Only part of this area is worthy of mineral exploration since the majority is well outside the present known area of mineralisation. The area to the west of a line drawn through Newquay and Truro and extended to the south coast must be considered as worthy of off-shore investigation. The area of the land surface to the west of this line, excluding the Scilly Isles, is approximately 440 square miles. Enclosed between the low-water mark and the 2-mile line is a total area of 240 square miles. Thus, by including the off-shore areas the total prospecting ground in West Cornwall is increased by 55 per cent.



The increase in prospecting ground in Cornwall produced by the inclusion of the off-shore areas to a distance of 2 miles

The aim of preliminary exploration in the south-west of England is to determine the configurations of the granite batholith at depth ; a factor which is important in the localisation of mineralisation. Geophysical surveys will be necessary, supported by detailed geological mapping of the sea-bed, to determine the petrology, minor structures, and degree of metamorphism of the country rocks into which the granite has been intruded. This combination necessitates a survey boat capable of being fitted with the required geophysical equipment and of carrying a geological diving

team. The boat would operate within the 2-mile limit but would venture further out to sea as required.

The selection of suitable areas is only one of the problems confronting any mining company wishing to prospect in this country. Companies are deterred from exploring or opening new mines by both the capital risks and the system of taxation of metalliferous mines which can be unfavourable compared with taxation in other countries. Nevertheless, efforts must be made by those concerned in all branches of the industry to develop further the methods of off-shore mineral exploration not only for application in the United Kingdom but for use in all countries with an interest in the future of their mining industries.

ACKNOWLEDGEMENTS

The work on underwater geological exploration employing aqua-lung divers has been made possible by the financial support of the Imperial College Exploration Board under the Chairmanship of Professor H. H. Read.

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Divers Investigate the Levant Mine

A successful attempt to locate the point of ingress of sea-water is described

R. H. T. Garnett, B.Sc., A.R.S.M., D.I.C.

Abstract.—Divers were employed in a successful examination of the sea-bed above the undersea workings of the Levant Mine, Cornwall. The point was located at which the sea had flooded into the abandoned mine.

Introduction

The Levant mine is situated on the north-western flank of the Land's End Granite in the mining district of St. Just, Cornwall. One of the most famous mines in this region, it has been worked for tin, copper, and arsenic since the beginning of the 18th Century. The abandoned mine workings extend for a total distance of 7,000 ft. in both country rock and granite, the lodes having been followed for 5,000 ft. out to sea and to a depth of approximately 2,000 ft. below sea-level.

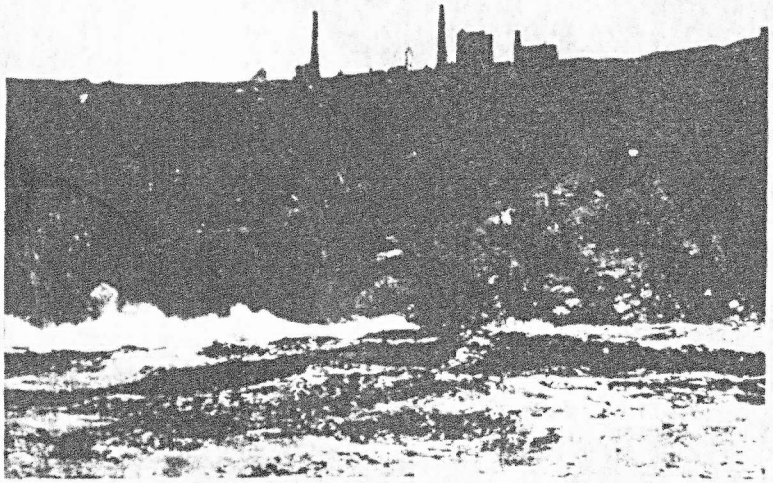
The bottom levels of the Levant mine, from which the majority of the production was being won, became inaccessible in 1919 after the failure of the man engine and the consequent disaster. Mining of the upper levels continued until 1930 when the mine finally closed. The mine development prior to 1919 was directed in depth and in a seawards direction. If production from this region had not been brought to a standstill by the disaster and the flooding of the lower levels there is a distinct possibility that continued development in depth and exploration along the granite contact would have proved further areas of mineralization.

Some recent underground development in the adjoining Geevor mine has been in the direction of the abandoned workings of the Levant sett. For this reason it was essential to know the exact source of the water with which the Levant mine is flooded. The possibility existed that the water was the result of either rainfall or the entry of the sea into the workings. Even when the mine was in production it was considered by some engineers that part of the levels close to the sea-bed, known as the "40 Backs," were dangerous and doubt had existed as to whether or not the sea had broken through to the workings at this point since the mine's abandonment.

The first mention of the "40 Backs" is made in 1818 by Hawkins (1) [1] who states that—

"The first level of the mine is 17 fathoms below the high-water mark and is extended 40 fathoms.

[1] References are given at the end of the article.



Levant from the Sea.

As the shore declines very rapidly there can scarcely be more than 10 fathoms between the end of the level and the sea. In one part of it workmen, tempted by a bunch of copper, followed it to the height of 5 fathoms above the level but feared to proceed further. Not only the roaring of the sea in stormy weather but the ordinary breaking of the waves on the beach is distinctly heard by the miners. The water is salt but there is so little of it that, although the depth is 42 fathoms, the whole is drawn to the adit in a bucket by the labour of two men."

By June, 1869 (2) some concern was felt about the safety of this level and an independent referee was engaged to report upon the ground in question. The referee, Captain J. Vivian, reported as follows (3) :

" In conformity to your request I have carefully examined the 40 level under the sea and the backs worked over the same. I consider the workings perfectly secure and, had I the supervision of the property as Manager of the Mine, or Lords Agent, I think it quite unnecessary to take any further precautions to render the mine safe from the sea. I should not, however, stope any more ground in the back of the 40 nor drive the level further."

Memoirs and first-hand verbal witnesses (4 and 5) report that the " 40 Backs " caused considerable concern to the management during the years immediately prior to the final closure of the mine and the various statements are summarized in correspondence between Major B. Llewellyn and Mr. J. H. Trounson (6). The latter writes :

" It is at this place (the " 40 Backs ") that the greater part of the water making in the mine enters through the lode at a place where it was unwisely stoped too near to the ocean floor many years ago. The lode here is apparently of a somewhat friable and soft nature, and it has always been regarded as somewhat of a danger area. To make matters worse the worked out stopes or ' gunnies ' at this point are unusually wide for Levant. A few years before, this area collapsed and an effort was then made to fill the gunnies by stoping adjacent country rock. This, however, failed by reason of the large volume of the old stopes that it was necessary to fill, and subsequently heavy timbers were put in to support the danger area.

According to my information, however, this precautionary work was never satisfactorily completed and it would seem to be a matter of considerable urgency that if ever the mine were re-opened this relatively small yet dangerous area in the back of the 40 fathom level stopes should be reinforced by cementation and, possibly, by means of a masonry arch or some other form of support more permanent than timber."

By examination of the underground plans of the Levant mine it was discovered that the " 40 Backs " area is directly connected with the entire remaining levels of the mine. Therefore if access was to be gained by unwatering to any part of the mine workings below sea-level it was necessary to determine whether or not the sea had gained entry to the mine through the sea-bed in the region of the " 40 Backs " or in any other part.

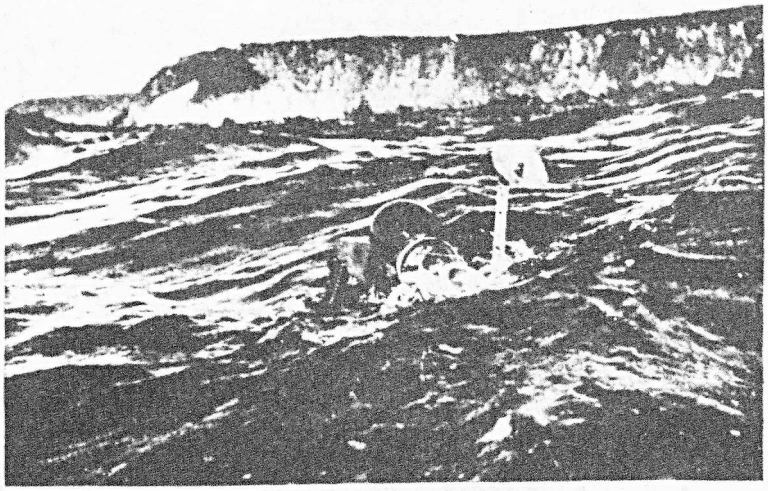
Preliminary Investigation

During the early part of 1960 the use of fluoresceine was suggested for the detection of any breach between the Levant workings and the sea. Already widely used in air-sea rescue and spelaeology, this chemical is said to be capable of being detected when as little as one part of fluoresceine is present in 40,000,000 parts of water—a quality attributable to the brilliant green fluorescence of its alkaline solution.

The adit above high-water mark which connected to the Levant skip shaft had previously been cleared during 1959. Observations on the water level in the latter showed that there existed a variation in the water level which could be correlated with the rise and fall of the tides. A plan was devised whereby a quantity of fluoresceine was introduced into the workings through this adit during March, 1960, imparting to the water in the mine an intense green coloration. Two days later during an ebb tide there could be observed a patch of water well beyond the low-water mark possessing a distinct green appearance in contrast to the remainder of the sea.

This was due to the fluoresceine which was again visible at the same spot on the following day. Taking advantage of the excellent sea conditions a boat put out from Sennen Cove and the fisherman, after sailing directly over the area, reported that he had seen " a funnel-shaped mass of green water bubbling up from the sea-bed at a depth of about 5 fathoms below the boat." In addition, the position of the green coloration was calculated from theodolite intersections and plotted in relation to the known Levant mine workings. The fixed position agreed to within 10 ft. with the most probable position of the " 40 Backs." This, together with the fisherman's evidence, appeared to prove beyond reasonable doubt that the sea had gained entry to the workings of the mine in the region of the " 40 Backs."

The use of the fluoresceine gave no indication as to the exact nature and extent of the breach. In order to supply this necessary information the writer proposed the employment of self-contained aqua-lung divers who would be capable of exploring the sea-bed



Diver over the Sea Lodes.

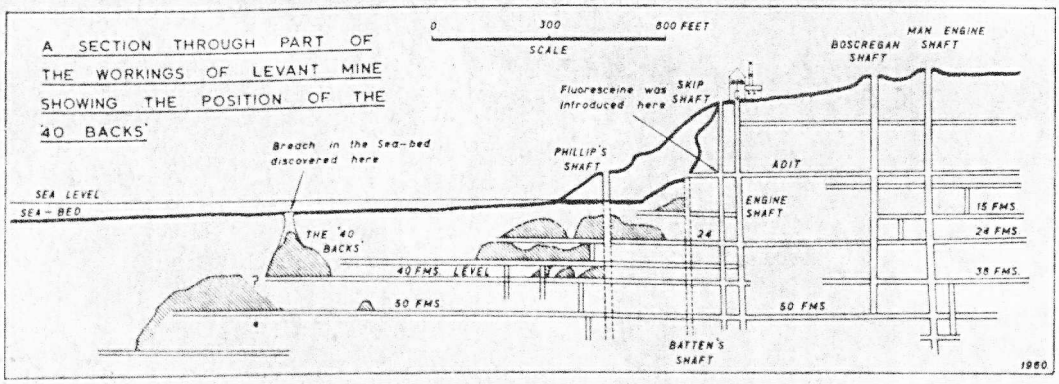
in detail and observing the flow of fluorescein-charged water from the flooded mine at the point of the breach.

Use of Divers

A team of divers from the Imperial College, London, under the direction of the writer, were engaged in a programme of underwater geological exploration in the St. Agnes area (7) during July and it was agreed with the manager of Geevor mine that upon the arrival of suitable weather and sea conditions the Levant mine water would be charged with fluorescein. The divers would then make an examination of the sea-bed upon the appearance of the coloration which was calculated to be approximately two days after the introduction of the chemical into the mine.

Unfortunately a long period of inclement weather followed. The divers were available for only a limited time and it became necessary to start the investigation before the arrival of suitably calm weather. A further quantity of fluorescein was introduced into the shaft on the morning of July 26. On July 28, when the first signs of its appearance in the sea were to be expected, diving was impossible owing to the heavy swell running against the base of the cliffs. On the morning of July 29, the last day on which the divers were available, the sea was again very rough, but the captain of the 28-ft. motor-powered boat, from which the dives were to be made was persuaded to put out from Sennen Cove.

Owing to the high seas the fluorescein was not visible from the shore and the boat had to be manoeuvred into position by the



Sketch Elevation, Levant.

captain, taking his instructions from two observers who, equipped with theodolites on the overlooking cliffs, signalled with the use of flags. The heavy swell allowed the boat to anchor only at a known position relative to the "40 Backs" and not directly over the breach. Despite the adverse conditions two divers entered the water at 2.5 p.m. With the boat anchored securely in 45 ft. of water the descent was made down a shot-line from the boat.

The divers were roped together by a life-line, the other end of which was tended by a person in the boat. With the extra precaution of a safety-line connected to the base of the shot-line, they proceeded to swim in a south-easterly direction, guided by underwater compasses. The sea-bed was composed of greenstone outcrops and the breach, with the green-coloured water issuing from it, was located immediately at a distance of about 75 ft. from the boat and in visibility of 5 ft. Upon their return to the surface at 2.35 p.m. all information was recorded and a further solo dive was commenced at 2.40 p.m. in an attempt to gain a sample of the fluorescein-charged water for laboratory as well as visual confirmation. This proved to be impossible since the heavy swell experienced underwater prevented the diver from employing both his hands for the sampling operation and he surfaced at 2.55 p.m. The boat weighed anchor and returned to Sennen Cove.

The diving equipment consisted of standard twin aqua-lungs with dry- and wet-suits, as described in a previous paper (8).

Conclusions

The fluoresceine was found to be issuing from an area of the sea-bed measuring 2 ft. by 2 ft. in one corner of a large trench filled with coarse sand. With a length of 20 ft. and a width of 10 ft. the trench appeared to be a continuation of the Levant Zawn. This is a feature of the cliff erosion along a mineralized fracture and the Levant skip shaft is situated at one end of the Zawn. The trench was surrounded on three sides by rocks reaching a height of 5 ft. above the sand level, the fourth side being bounded by low rocks of a maximum height of 1 ft. The fluoresceine flowed strongly from the trench but was quickly dispersed by the swell, which also caused the flow to be intermittent. The rise and fall of the tides was later found to control the appearance of the fluoresceine since the water flowed from the mine workings only when the tide was falling.

From the dimensions of the trench on the sea-bed and the rate of flow of the water it would appear that the stope in the "40 Backs" has been broken into by the sea. This has been caused by the continual fritting away of the lode material, aided by its lubrication by percolating sea water, and by the constant pressure difference existing between the mine workings and the sea-bed prior to flooding.

The investigation of the Levant mine provides yet another example of the usefulness of the aqua-lung diver in the field of engineering and exploration. Work in the south-west of England during 1960 has shown that any programme of off-shore mineral exploration in this region must include a diving team in conjunction with the established prospecting techniques.

Acknowledgments.—The two divers, J. D. Woods and G. Wheeler, were members of a team financed by the Imperial College Exploration Board. Assistance in the work was provided by the management of the Geevor mine, and especially the Chief Surveyor, Mr. A. Bennetts.

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(6) Correspondence between Mr. J. H. Trounson and Major B. Llewellyn, October 8, 1944.

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Carnelloe Mine, Zennor

It has been announced that a Local Inquiry into proposed mining development at the Carnelloe mine, near Zennor, is to be held in Penzance on May 10. Worked in the 1870's as Carnellow Consols, a small tonnage of black tin was produced. The working was abandoned in 1876.

Appendix II

Exploration and Development in the Geevor Mine Area

> "And here I must express the regret which I feel, in common with so many others, that no records are preserved of all those natural phenomena which occur to the notice of our miners in the progress of their operations. I regret it not only on account of the loss which the science of geology sustains by its omission, but because I believe it has materially affected the stability of our whole mining system; for if it be true, that old mines are often re-opened, in reliance of some vague traditional reports of their former productiveness, which generally prove fallacious; how desirable it would be to prevent all this waste of capital, and to preserve it for less hazardous speculations ....."
>
> ..... J. Hawkins (1818).

As Dr. K.F.G. Hosking has said recently, such sayings as "Tin is where you find it" and "Where it is, there it is," have done the utmost harm to the mining industry. This investigation into the geology and mineralization of Geevor Mine has led to a better realization of the complexity of the structural controls of mineralization. Although it is not suggested that the conclusions apply equally to other mining districts of Cornwall their possible structural complexity is demonstrated.

The most important aspect is the practical application; a subject in itself, which unfortunately cannot be discussed in this thesis. The work at Geevor Mine has indicated the necessity of maintaining detailed day-to-day geological records which should be comparable in importance with the underground surveying. Every aspect of exploration and development on all

scales should be based upon geological reasoning which in turn should be aided by experience and the study of past records.

The above statements do not apply only to Geevor Mine, but have been repeated with respect to every mining field. They will continue to be repeated until it is eventually realized by the mining industry as a whole that geology is the very core of the mining operation, especially in the exploitation of a metal such as tin. It is not a luxury, specialist service to be called in if the company financies allow and usually just before the mine is closed.

The shortcomings of this approach were first realized in Cornwall, as evidenced by the remarks of Hawkins (1818) above. Until there is a major change in the whole mining industry past errors will be continually repeated and properties will close unnecessarily, especially in the event of a revival of the Cornish mining industry.

Fig.(H)

The plan of the mine workings in the Pendeen-Botallack area included as Fig.(H) in Volume III was originally compiled by H.G. Dines and J.A. Robbie to a scale of 25"/mile. The present writer has added certain details such as the surface geology, and the workings of Geevor Mine have been brought up to date (1960).

An application was made on 11th August for permission to reproduce the plan in this thesis. The reply to this application is presented overleaf. Acknowledgements to the two officers of the Geological Survey has nevertheless been given since it is not the intention of the present writer to imply that the work has been entirely his own.

GEOLOGICAL SURVEY AND MUSEUM
Exhibition Road, South Kensington, LONDON S.W.7
Telephone: KENsington 9441/5

Please address any reply to
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and quote: 104/2/4J
Your reference:

16th August, 1961

Dear Sir,

Thank you for your letter of 11th August. We have no knowledge of the plan you mention which is said to have been produced by H. G. Dines and J. A. Robbie. It is certainly not an official plan and we do not take responsibility for it. No mention of H.M. Geological Survey should be made in relation to the presentation of this plan.

The Geological Survey's mining work in Cornwall is published in 'The Metalliferous Mining Region of South-West England', and this, together with the six-inch and one-inch sheets and explanatory sheet memoirs,* available in our Library are the only official Geological Survey publications to which references attributed to the Geological Survey may be made.

* and also memoirs which are Reports of the Mineral Resources of Great Britain.

Yours faithfully,

F. M. Trotter

(F. M. Trotter)
Assistant Director

R. H. T. Garnett, Esq.,
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EMP/EL

Structural Control of Mineralization in South-West England

R. H. T. Garnett, A.R.S.M., B.Sc., D.I.C.

The author stresses the important influence of the cross-courses

With the present high level of the price of tin, and the favourable long-term prospects, interest is being revived in south-west England, particularly in Cornwall, as a potentially more important tin-producing area. Several exploration programmes are being commenced both in the neighbourhood of abandoned mines and in districts which have been relatively unexplored in the past.

Cornwall is one of the major mineralized fields of the world, possessing a very high concentration of tin and copper lodes within a relatively small area, but there is a surprising lack of knowledge concerning the economic geology of the deposits. For detailed information on the majority of the mines and districts it is necessary to rely upon local hearsay, old plans and sections, and private reports. The *Memoirs* of the Geological Survey and a number of other publications during the 20th Century, including that of Dines (1956), are very dependent for any details of the economic geology upon the work of 19th-Century geologists—such as, Henwood (1843) and the publications dealing with individual mines in the *Transactions* of the Royal Geological Society of Cornwall.

A regional control of mineralization in the area by structure, temperature, and stratigraphy has always been recognized. The effect of a localized structural control, which is of paramount importance, has not always been established, however, although many writers have observed that the tin and copper content of the lodes was affected by changes in their dip and strike.

Approximately normal to the tin-copper lodes, the majority of which strike between E.–W. and N.E.–S.W., is a series of apparently less frequent N.–S. fissures. When infilled with quartz they are known as cross-courses and were often referred to in old reports as "cross-bars," "cross-gossans," "cross-lodes," and "cross-veins." Alternatively the terms "trawns" and "gossans," the latter not to be confused with a lode outcrop, were employed to denote a quartz-filled cross-course in the St. Ives and St. Agnes districts, respectively. In the St. Just area the lodes trend, with a wide variation, N.W.–S.E. Numerous steeply-inclined faults strike between N.–S. and N.E.–S.W. and when infilled with quartz are known as "guides." Clay-filled fractures, or faults, are termed "flucans" and are not to be confused with "slides," which are generally parallel in strike to the lodes.

Hosking (1949) outlined the more important theories concerning the origin of the lode fissures. They were considered by the majority of the writers on the area to have been formed by the enlargement of a pre-existing regional fracture system which enveloped both the granite and the country rocks of "killas" and "greenstone" and the formation of new fractures with an orientation controlled by the earlier set. Similarly the origin of the cross-courses has been considered in conjunction with a regional set of roughly N.–S. fractures. On the evidence of their quartz and mesothermal mineral infilling and the fact that they fault the lodes, cross-courses have been regarded as having been formed after the lodes. Hill and MacAlister (1906) and Dines (1956) considered that they were Tertiary and stratigraphic evidence in east Cornwall and Devon supports this view. However, a major fracture is easily propagated in overlying strata as a continuation in strike of a pre-existing fracture at depth. Such evidence dates the age of enlargement and infilling of the fracture and not its age of original formation in older rocks in the vicinity of mineralization.

Especially in eastern Cornwall and Devon, major cross-courses sometimes provided an economic source of lead, zinc, and iron. Otherwise they aroused little interest and by deflecting the lodes they were more of a hindrance to underground development. Tabulated observations on the distance

through which they faulted a lode were provided by Henwood, who demonstrated that the differing horizontal components of movement of the lodes and dykes could not be accounted for by simple normal and reverse faulting. He considered that only the acceptance of oblique, and in some cases rotational, faulting could adequately explain some of his observations. The maximum horizontal component of movement of one cross-course has been recorded to exceed 400 ft., although an average value is of the order of a few fathoms. Many of the cross-courses extended for several miles, whilst others apparently ceased to exist between adjacent lodes.

Because of the undisputed view that the cross-courses post-dated the lodes it was assumed that they could not have exerted any structural influence upon the extent and degree of mineralization within the lodes. However, despite the lack of an explanation many of the early writers noted that some of the cross-courses appeared to influence the tin and copper values. Variations were observed in the lodes as they converged with a cross-course and Henwood recorded that the Malkin lode in Ding Dong mine changed in structure and mineralogy upon approaching a " trawn."

Many lodes proved to be enriched along the line of their junction with a cross-course. According to Carne (1822) there were two instances in Botallack and Parknoweth mines where " very rich courses of tin have been the result of such intersections." Henwood remarked that " not a few of the larger and richer bunches, both of tin and copper ores, have occurred in the immediate vicinity of cross-courses and flucans." Despite these increases in value at intersections the miners were frequently unable, despite widespread trials, to locate the faulted extension of the lode under development. If the extension was found it was often with disappointing results for, as Henwood stated, " frequently has the produce been exclusively found on one side of these intersections, whilst on the opposite side the same lode has been entirely worthless." Notable examples were provided by Wheal Friendship, Wheal Jewel, and Wheal Vor, near Woolf's cross-course.

When contemplating the examination of an old property which has most probably been closed for more than 50 years it is unlikely that any first-hand information may be available. The possible reasons for the cessation of operations and abandonment of the mine and the factors outlined by Trounson (1959) must be considered in detail.

Geophysical and geochemical methods may on occasions in Cornwall be employed to advantage to guide later work, but diamond drillings, from either the surface or underground after unwatering, is the most important exploration technique in Cornwall. Even drilling, as a result of the low core recovery that is obtained in penetrating many of the lodes and the very sporadic distribution of tin values throughout them, provides no basis on which to determine the grade and value of a lode. Under ideal circumstances diamond drilling will indicate no more than a lode's presence and any possible further conclusions may be based only upon geological evidence extracted from the core.

When investigating an old property diamond drilling may be employed to examine proved lodes in depth, to locate their possible extensions, or to search for adjacent parallel lodes. Available plans and sections often indicate that development on a lode worthy of investigation terminated in the vicinity of a cross-course, the stoped-out ground extending up to the feature but not beyond. An obvious attraction to the exploration engineer is to drill on the other side of the cross-course for the lode extension which may be expected to carry economic values. By employing examples from Geevor mine in the St. Just district the writer stresses that such a procedure should be attempted with caution, since a lode cannot always be expected to exist on both sides of a cross-course.

At Geevor mine the lodes and cross-courses (guides) occupy regional fractures which were originally formed before the first phase of tin-copper mineralization. Infilling of the lode fissures and cross-course fissures was completed in several stages, each accompanied and separated by periods of stress change which resulted in movement along and enlargement of the pre-existing fissures. Complete infilling of the lode fissures was usually completed before the commencement of the infilling of the cross-course fissures. In the following discussion a fissure, which when infilled qualifies for the term lode, is a potential lode prior to infilling and is therefore termed a lode fissure. The same form of nomenclature is applied to the cross-courses.

Between successive pairs of steeply-inclined cross-course fissures which extended throughout the granite and country rocks blocks of ground moved alternately up and down relative to one another. Individual

blocks possessed a width, defined by the spacing of the cross-course fissures, varying between 1,000 ft. and 5,000 ft., the longer horizontal axes of the blocks coinciding in direction with the strike of the fissures. The oblique movement of the order of 10 ft. to 20 ft. resulted in a horst and graben structure, as shown diagrammatically in Stage 1 of Fig. 1. Cross-course fissures are mainly vertical and were subjected to normal faulting. When steeply inclined in the same direction alternate fissures were subjected to reverse and normal faulting.

Within the uplifted blocks, or horsts, movement took place along the lode fissures through 10 ft. to 20 ft. in the manner shown in Stage 2 (Fig. 1). It was accompanied by mineralization and those lode fissures along which movement took place were infilled to form lodes. When those with the same strike dip in opposite directions normal faulting took place on each. Conjugate lode systems were formed as described by Webb (1947), although sufficient movement to permit mineralization frequently took place on only one set of the system. In Geevor mine the majority of the lodes dip steeply to the south-west and alternate ones were subjected to reverse and normal faulting, enabling the dislocation of wedges of ground to accommodate the maximum stress directed from below.

The direction of movement of the blocks between the cross-course fissures was determined by the same stress distribution as governed the final development of the lode fissures. Those lode fissures—such as, L_2—possessing a line of intersection with the cross-course fissure coinciding with the direction of displacement of the blocks between the cross-course fissures suffered no apparent horizontal displacement. In such a case movement was more easily activated in the graben on the other side of the cross-course fissure and the lode fissure became mineralized in both directions.

The main tin-copper lode mineralization phase did not affect the cross-course fissures during Stage 2 (Fig. 1), since the alignment of the minimum principal stress normal to the lode fissures allowed only the latter to be opened for mineral deposition. Nevertheless mineralization has been observed to extend for a few feet along a cross-course on either side of a lode. Referring again to Fig. 1, there was a tendency for the cross-course fissure C_3 to impound the mineralizing solutions ascending in lodes L_1 and L_3 since the relative

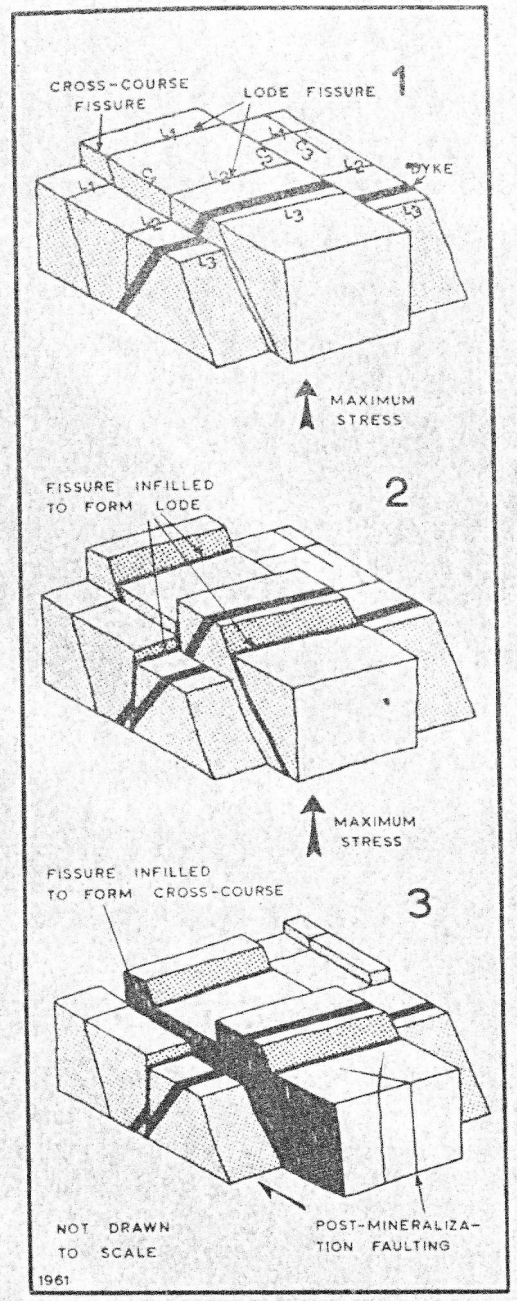


Fig. 1.—Diagrammatic Representation of the Structural History of the Cross-Courses and Tin-Copper Lodes.

movement of the lode fissure walls was terminated against C_3. A narrow zone of high values was sometimes created in a lode at the intersection with a cross-course fissure and to one side only of the latter. In the case of these

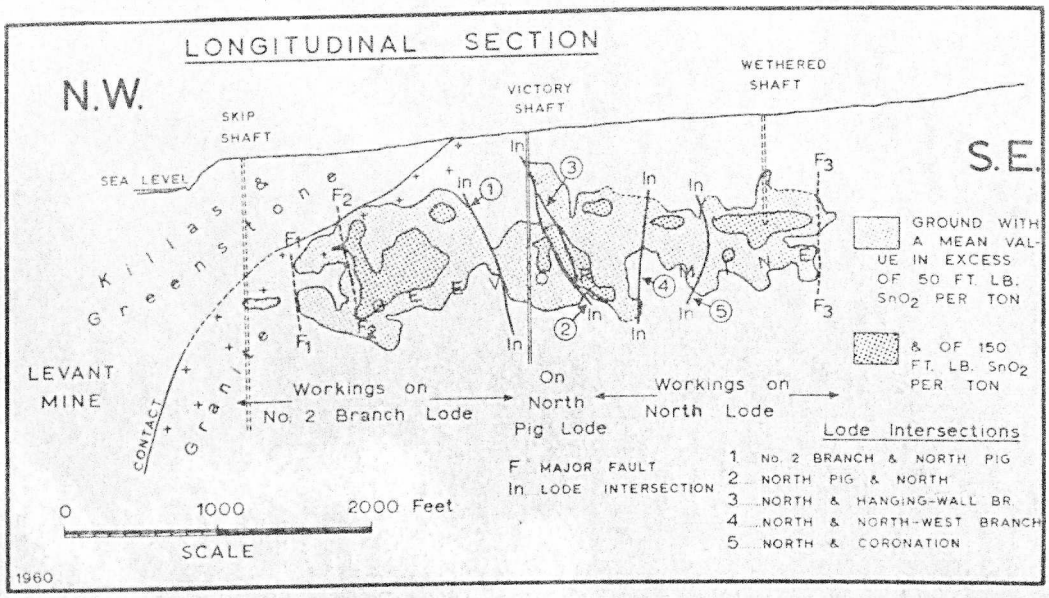


Fig. 2.—Longitudinal Section through the Workings of Geevor Tin Mine.

lodes their line of intersection with the cross-course fissure did not correspond with the direction of movement of the blocks.

Subsequent displacements along both the lodes and cross-course fissures under the same stress distribution resulted in further phases of mineralization. The final phase, consisting of quartz, calcite, and 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 cross-course fissures and post-mineralization conjugate faults along newly-formed fractures as shown in Stage 3 of Fig. 1. Relaxation of the same stress caused infilling of the cross-course 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 cross-courses.

In Geevor mine late horizontal slickensides were superimposed on the lode constituents during the period of formation of the tear faults. In both the lodes and the cross-courses horizontal slickensides tended to erase earlier vertical slickensides originating during Stage 2 (Fig. 1). Even later disturbances, with no associated mineralization, produced movements in the planes of the lodes and cross-courses, which sometimes resulted in the deflection of a cross-course by a lode.

In the St. Just district cross-course fissures were usually not infilled unless their strike varied extensively, like that of the North Levant Lode, from the average. They appear as major faults or fault zones about 10 ft. wide. Mineralization in Geevor mine was terminated between two major faults which now give a first impression of being major post-mineralization tear faults with a horizontal throw up to 10 ft. These denote the limits of the original horst formed during Stage 1 (Fig. 1), when the block now containing the economically-mineralized lodes was uplifted through a height of the order of 10 ft. A longitudinal section through the mine, provided in Fig. 2, illustrates the extent of the workings and the value of the ground blocked out on the No. 2 Branch, North Pig, and North Lodes.

The first phase of tin mineralization in the mine was associated with intense wall-rock alteration, including tourmalinization and reddening of the granite. Deposition of cassiterite was extremely sporadic and occurred throughout the majority of the lodes in the western half of the property. An earlier or simultaneous relative movement of the walls of a lode was not necessary for

deposition to take place and, considered alone, the first phase rarely resulted in economic ground. In some circumstances the first phase of tin mineralization and the early wall-rock alteration took place before any movement between the cross-course fissures. Consequently the located extensions of any lodes in the usually unmineralized graben structures often contain traces of cassiterite and possess substantial wall-rock alteration.

In the western part of the mine the first phase of tin mineralization in the No. 2 branch lode was not impounded by the most westerly of the two faults, F_1, and formed a small patch of values around level 12 and in line with the skip shaft of Levant mine. A second tin mineralization phase, indicated loosely by the 50-ft.lb. contour line, was confined by F_1 as a result of movement having already taken place in the plane of the latter. The 150-ft.lb. contour line indicates a third phase terminated by the fault F_2. The fissure resulting in F_2 was in existence before the commencement of the second phase of mineralization. Movement along it took place after the termination of the second phase, upon which it therefore exerted no structural control, and before the third phase.

Both the second and third phases were subjected to a local control by the granite surface through a combination of temperature and structural effects. Extensive tin and copper mineralization was exploited until 1930 in Levant mine to the west, where the lodes were situated almost entirely in the country rocks of " greenstone " and " killas." The cessation of economic tin mineralization in Geevor mine in the vicinity of the granite contact was due more to the existence of the two major faults, one of which terminated the mineralization on three other parallel lodes, rather than to any direct effect resulting from the situation of the granite contact or the presence of " greenstone " in the adjacent country rocks. A limit of economic tin mineralization in the eastern part of Levant mine is marked by a well-developed cross-course, there being a relatively barren block of ground between the latter and the major fault F_1 of Geevor mine.

In the eastern part of Geevor the first phase of mineralization is not evident, since it was locally developed near the granite contact. Vertical movement took place on the major eastern fault, F_3, before the second tin mineralization phase commenced and both the second and third phases, indicated loosely by the 50-ft.lb. and 150-ft.lb. contour lines respectively, were confined to the west as a result.

With the exception of the first, the main tin mineralization phases were executed for the most part under prevailing conditions of variable compression from all directions and were impounded by the cross-course fissures or faults. During the latter part of Stage 2 the influx of quartz, calcite, and siderite was accompanied by an all-round stress relaxation and the partial subsidence of the uplifted portions of ground between adjacent lodes. In the Geevor mine there are only small variations in the dip of the lodes where adjacent to the cross-course fissures. Since the direction of relative movement of the horsts and graben was in the same direction as the mean line of intersection of the cross-course fissures and the lode fissures there was little apparent horizontal displacement of the latter during Stage 1. Throughout the relaxation phase many of the lode fissures on the relatively unmineralized side of the cross-course fissures which had hitherto been subjected to the first sporadic tin mineralization and early wall-rock alteration only were infilled with the quartz, calcite, and siderite, etc.

In many of the mining districts there is a wide variation in the strike of the lodes. To many the term " caunter lodes " was applied with conflicting estimations of their age relative to those lodes possessing what was regarded as the predominant strike. Examples have been provided by many writers of the faulting of one lode by another and of the mineral infilling of one passing continuously through that of the other. The relative age of infilling of two separate intersecting fractures is not conclusive evidence of their relative age of fracture formation, nor is it indicated conclusively by any deflection imposed upon one by the other. The majority of lodes were subjected to two or more phases of infilling, each accompanied by movement. When two lodes intersected and the periods of mineralization in one were out of phase with those in the other, mutual interference with the extent of mineralization in each took place, especially when the strike differences between the two were large.

The simplest case of two intersecting lodes, each subjected to only one phase of mineralization coincident with movement, can be considered. If mineralization took place in both lodes simultaneously enrichment resulted at the intersection due to increased fracturing and the lodes are continuous on both sides of the junction. If each lode underwent

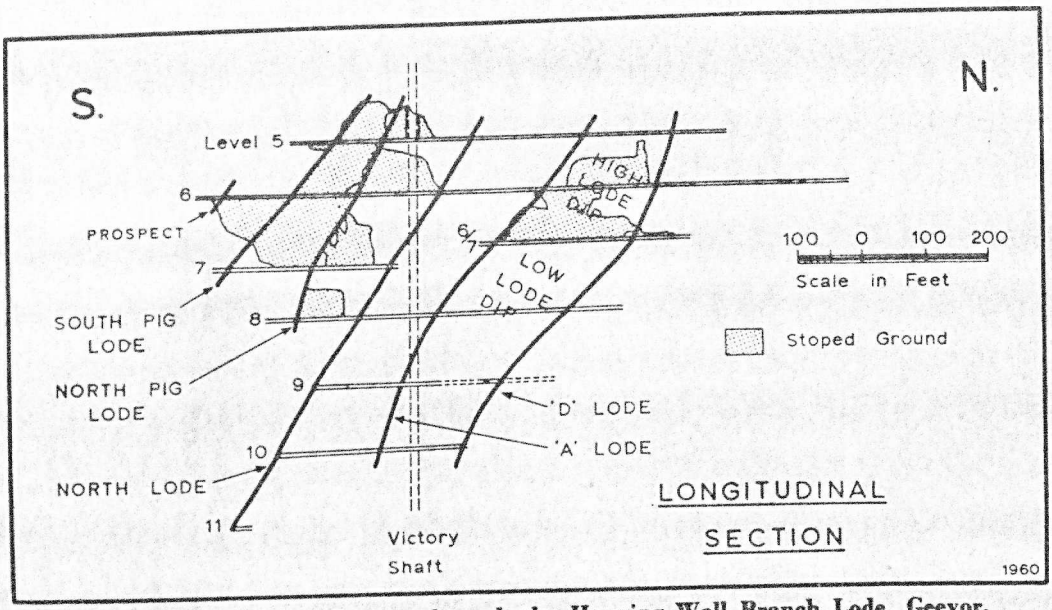


Fig. 3.—Longitudinal Section through the Hanging-Wall Branch Lode, Geevor.

mineralization at different times and on each occasion no influence was exerted by one lode upon the other there will be no appreciable change in the tin values that may be attributed solely to the influence of the intersection. Both lodes would tend to be continuous beyond the intersection on each side. When mineralization occurred on the two intersecting lodes at different times and structural interference took place, more usually only one lode proves to contain economic values on the other side of the intersection. Complications arise through the occurrence of more than one phase of mineralization and movement on each lode.

Some of the effects of mutual interferences at lode intersections in Geevor mine are indicated in Fig. 3, which shows the stoped ground on the easterly-dipping Hanging-wall Branch lode; the latter makes an angle in plan of about 70° with the majority of the lodes. Although it approximates towards the strike of the local cross-courses it does not possess any of the mineral assemblages associated with them and has been locally stoped on the upper levels. Five major south-dipping lodes were intersected by the Hanging-wall Branch lode. The tin mineralization of the " D " lode was impounded by and confined to the west of the Hanging-wall Branch lode. That of the " A " lode and the North lode was enriched in the upper levels. There was no control exerted upon the mineralization of the North Pig lode, while that of the South Pig lode in the Victory section was impounded and stoping confined to the west.

Selective movement on the Hanging-wall Branch lode enabled the controls described to operate. The extent of the mineralization on the latter was influenced by the various lodes and the majority was confined, as indicated by the stoping, between the " D " and " A " lodes and between the South Pig and North lodes. Some effects of temperature zoning are apparent in the stoping pattern. Mineralization of the Hanging-wall Branch lode between the " D " and " A " lodes was associated with a downward relative movement of the hanging-wall for a few feet, which resulted in the highest tin values being confined to the steepest parts of the lode. The values which might be expected between levels 6/7 and 10 are absent, owing to the low lode dip in this region below level 6/7.

The more important aspects of this work are the practical applications. When old plans and sections of abandoned mines indicate that the " blocked out " or stoped portions of a lode terminate at a major cross-course or fault caution should be applied in any scheme to search for what may be thought to be the simple faulted extensions of the economic lodes already exploited on the other side of the cross-course. Resort should not be had completely to exhaustive diamond drilling.

It was not common practice to indicate all the cross-courses and major faults encountered in a mine on the plans and sections of the

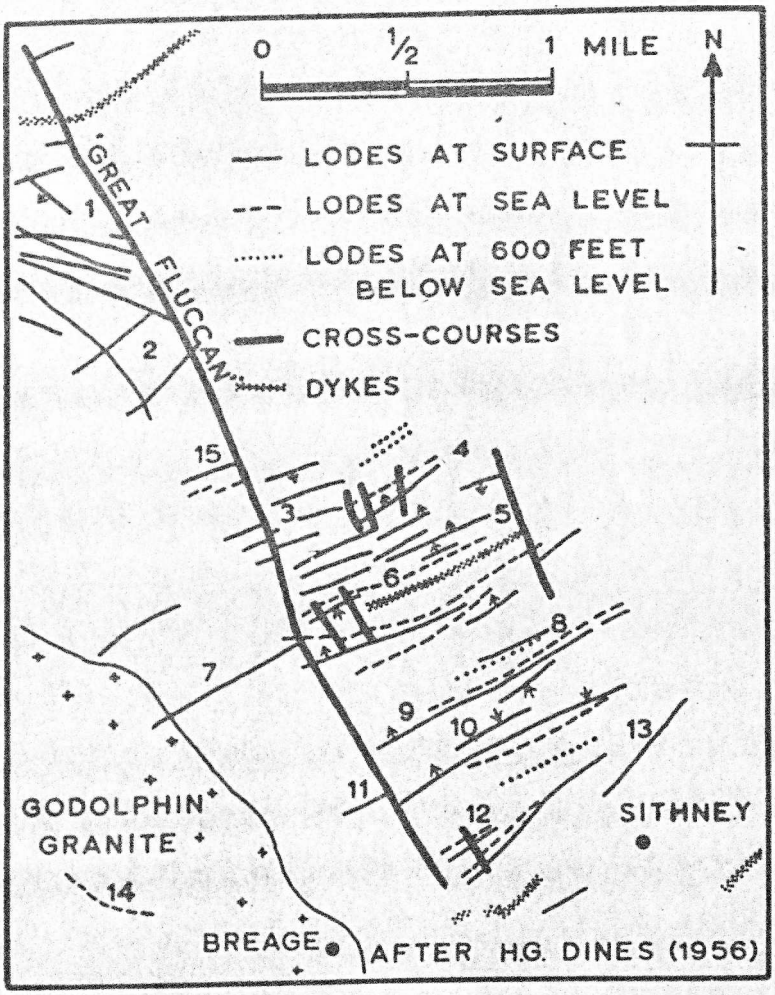


Fig. 4.—Part of the Breage Mining District, Cornwall.

(1) Godolphin; (2) East Great Work; (3) Polladras; (4) Penhale Vor; (5) Gwin and Singer; (6) Vor; (7) Carleen; (8) Sithney Metal; (9) Metal; (10) Carnmeal; (11) Emma; (12) Great Fortune; (13) Sithney Carnmeal; (14) Trevena; (15) Polrose.

underground workings. Since cross-courses provided easier-breaking ground and were usually normal in direction to the average lodes they were frequently employed as a site for cross-cuts. The exact position of a cross-course is often therefore indicated by cross-cuts possessing sinuous outlines in plan. If the presence of a cross-course at the extremity of a lode is proved or indicated by the presence of a cross-cut from one of the development ends it is likely that it has exerted a local structural control upon the extent of mineralization within the lode in question. After an initial investigation by diamond drilling either from the surface or adjacent underground workings the second stage of the exploration should concentrate more thoroughly upon a search for undiscovered parallel lodes, which may also be subjected to a control by the same cross-course.

A majority of Cornish mine plans indicate a profound lack of exploratory cross-cuts and non-outcropping parallel lodes were frequently found only when they existed as branches of those that were being developed.

If a structural control by cross-courses is suspected or confirmed they should always be considered in pairs, each demarcating the limits of successive horsts and graben. If a block of ground is encountered in which strongly-developed sub-economic lode fissures occur a search should be conducted for an adjacent block, indicated by a further cross-course along the strike of the lode fissures in which movement and consequent mineralization has taken place.

A very strongly-developed and long lode fissure often terminated the movement of the blocks between, and along the strike of, cross-course fissures. The movement of blocks on

opposite sides of the lode fissure could take place at different times. A result of this rather complicated process may be appreciated more readily if the reader imagines a chess-board as representing a mineralized area in Cornwall. The lines running N.–S. on the board denote the cross-course fissures and those running E.–W. represent the more numerous lode fissures. As a result of stress distributions before and during the mineralization period, irregular blocks of ground represented by the black squares rose relative to the white squares. In the black squares further movement occurred which initiated the mineralization of the lode fissures to form lodes.

When a cross-course fissure exerted a structural control upon the tin mineralization within an intersecting lode the values do not decrease suddenly. Occasional rich portions are located at the intersections, but more usually the values diminish gradually over a distance of the order of 100 ft. Wall-rock alteration phenomena and late gangue mineral infillings were not always controlled by the cross-course. Therefore the lode, at an intersection with a cross-course, although being subjected to a structural control, may not demonstrate any change in its appearance over a short distance and is often identical in outward character on both sides of the cross-course during an underground examination. Only a detailed mineralogical and structural study, conducted in conjunction with systematic sampling, over a distance of about 100 ft. on each side of the cross-course on one level indicates whether or not the lode is worthy of major development on additional levels. The value and character of a lode at the intersection with a cross-course are no criterion for judging its overall production potential.

If, during development of a productive lode on several levels, a cross-course or major fault is encountered development should proceed beyond the cross-course on only one level—that most likely to disclose high values, judging by those on the already-developed side. If the first phase of mineralization was not impounded by the cross-course fissure then the tin values encountered are usually of a grade sufficient to encourage continued development, but rarely result in stoping ground.

No exploratory cross-cuts or diamond-drill holes should be sited on, or in the immediate vicinity of, cross-courses or major faults when the direction of the contemplated cross-cut or hole is approximately the same as the strike of the cross-course or fault. They should, where possilbe, be sited equidistant between two such features, against the centres of fully-developed lodes or against the richest portions of the lodes; a rule which was applied to advantage in Cornwall before 1850.

Cross-courses and major faults are usually normal to the mean-strike direction of the lodes. When this is not the case the exploration cross-cuts and diamond-drill holes should, within reason, be aligned in the same direction as the cross-courses and major faults and not necessarily normal to the lodes. A rapid scrutiny of mining records produces many examples of districts in which the above principles may be applied with advantage. One such area, illustrated in Fig. 4, is that to the north of Breage, on the north-eastern flank of the Godolphin granite, and in which is situated the celebrated Wheal Vor.

Proof that the controls outlined above have operated in one district should not be regarded as a guarantee that the same effect has occurred throughout the south-west, or even throughout Cornwall. Each mining district possesses individual characteristics of mineralization and structure and should be considered on its own merits. It should also be remembered that any mine plan shows only the lodes that have been discovered and not all those that actually exist. Nevertheless it is anticipated that this brief outline of one of the many forms of local structural control of mineralization in the south-west, the knowledge of which is utilized in all underground exploration at the Geevor tin mine, may be applied profitably at additional properties in the future. Indiscriminate diamond drilling and exploration resulting from the re-opening of old properties will only result in a repetition of past errors. Exploration, which can only be directed by a geologist provided with the necessary appreciation of the mining problems involved, must be conducted with a complete awareness of all the features of localized structural control of the tin-copper mineralization.

Acknowledgment.

The writer wishes to thank Mr. D. J. Shearman, of the Imperial College of Science and Technology, London, for encouraging discussions on the matters discussed in this article and on closely-related topics.

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Appendix III

Vocabulary of Cornish Place Names in the St. Just district

Bal - a mine or place of digging.
Balleswidden - the white mine
Bartinney - the hill of the sacred fires.
Bre or Brea - a hill
Bryn - a hill or cliff, vide: 'Zawn Brinney' a creek in the cliff.
Bollowal - Bos-owel, the house on the cliff.
Bojewyan - the Jew's dwelling.
Bosavern - Busea verran, the old house.
Boscaswell - fortified house.
Bosean - Boshen, summer house.
Bosorne - the earthy house.
Bostraze - opposite house or house beyond.
Bosvargus - house above the wood.
Boswedden - the white house.
Bosworlas - Boswellas, the lower house.
Botallack - or Botalac, the dwelling of the serpent god.
Buscriggen - the house by the water.
Calartha - the wood of the bear.
Carrallack - the rock of the serpent god.
Carn - a heap of rocks.
Carn Bean (Carnyorth) - the rock of the little bear.
Carn Brea - the rocky hill.
Carnglaze - the grey rock.
Carnyorth - the rock of the bear.
Carn Vres - the rock of judgement.
Chycarne - the house by the rock.
Chyrose - the house in the valley.
Chywoore - the house on the common.
Cock - purple, e.g., Wheal Cock.
Dowran - on or near the water.
Gews - Guew, a plain field.
Genver - the river's mouth.
Gurland - the rocky enclosure.
Hal - a moor or down.
Halgalour, Hal-gol-luir, the down of the holy moon.
Hen - old, e.g., Huel Hen Zawn, the creek of the old mine.
Hendra - Hendre, the old town.
Huel - Wheal, a mine.
Innis or Enys - an island.
Joul - the devil, e.g., Stamps and Jowl Zawn.
Keigwin or Chygwin - the white house.
Kelynack - the wood of the serpent
Kenidjack or Kenijack - the ridge or head of the flying serpent.
Kerrow - a plough.

Lidden or Ledan	- Broad, large, e.g., ledenpol - the large pool and Porthledden - the broad entrance or harbour.
Lefrowda	- the place of fun or recreation.
Leswidden	- the white place.
Letcha	- the flat rock.
Nancherrow	- rough or hard valley.
Nanjulian	- stronger fortified valley.
Nanpean	- Nans-pedn - the head of the valley.
Nanquidno	- happy valley.
Numphra	- shady valley.
Owel	- a cliff or hill, e.g., Huel Owels, a mine on the hill.
Parknoweth	- Parc-an-noath, the bare field.
Pendeen	- Pen, the head, and Din, a man, - the head man's place.
Porth	- a harbour or gate.
Portheiras,	- Portheras - a woman porter.
Roscommon	- Ros-crag-gon, a valley of shells.
Spearn	- a thorn.
Tornoon	- hill of the common.
Trease	- Tre, a town, and res, a valley; the town by the valley.
Tregeseal	- Tre, a town, and gass, dirty; dirty town.
Tregiffian	- the town of forgiveness.
Trevedra	- tre and vidren or vyalran; town by a brambly river, or more likely, tre a town, bedh, a grave, and row, rocky; the town of the rocky grave.
Trevegean	- the town of the giant's grave.
Trewellard	- the town, or dwelling, among the mines.
Vean-Vean	- little as Trevean, little town.
Veor-Veor	- great; Treveor - a great town.
Woon Gumpus	- the plain or level downs.
Zawn	- a creek.

For further information on words of celtic origin, the reader is recommended to consult:- "A Guide to Cornish Place Names" by R. Morton Nance, Worden (Printers) Ltd., Marazion, Cornwall.

A glossary of local geological terms is provided in "Geological Terms used in S.W. England", by J. Robson and R. Morton-Nance, T.R.G.S.C., Vol. XIX, Part 1, 1955-56.

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