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THE NATURE AND EXPLOITATION OF NARROW TIN-BEARING VEINS: A CASE STUDY FROM SOUTH CROFTY MINE, CORNWALL, UK.

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SYNOPSIS

Narrow veins represent an important resource of valuable metals throughout the world, however they are generally technically challenging to exploit because of their geologically complex nature. The tin-bearing veins of south-west England are classic examples of complex narrow veins that have been economically exploited for many years. Their detailed geological understanding is crucial for effective evaluation and exploitation. The more complex the vein then there is a greater need for strong geological control and thus the utilization of overhand shrinkage stoping as an extraction method. The less complex veins are more applicable to mining by longhole open stoping with less, but still effective geological control. The Camborne-Redruth mining district, where South Crofty is located, contains a series of east-north-east-trending and steeply-dipping veins hosted in larger lode zones. The veins generally display a complex structure and paragenesis, which is a consequence of the superimposition of a succession of hydrothermal events involving separate stages of wallrock alteration, mineral deposition, dilation and brecciation. The mineralizing fluids entered the veins as a series of chronologically and structurally discrete pulses, with the lateral and vertical distribution of minerals reflecting this. The distribution of cassiterite within the veins is complex due to the fact that only two stages of the paragenesis contain cassiterite.

INTRODUCTION

A "*fracture*" is a crack or opening within rock that represents a line of discontinuity. The term "*vein*" refers to a mineralized or infilled fracture which is considered narrow when it has a width of less than three metres (Figure 1a; Plate 1).[1] The term narrow vein is however not rigorously defined and some consider veins up to six metres wide as narrow. Wider veins such as the copper-bearing Anaconda Vein (Butte, Montana) display an average width of 8-10 metres with localized maxima of 30 metres.[2] "*Lode*" is a commonly used term and refers to a vein and its associated zone of wallrock alteration which may or may not contain ore minerals (Figure 1b). The terms lode and vein have similar meanings and are often used synonymously, the authors however prefer use of the terms as defined here. The term "*lode zone*" is also used and describes a linear belt of sub-parallel fracturing which contains both veins and wallrock alteration and whose extremities may only be marked by microfractures (fractures <15 microns in width; Figure 2).[3] The lode zone term is particularly relevant where the width of a lode is substantially increased because of the inclusion of large body(s) of host rock into the vein (e.g. horses) or because of a highly anastomosing vein system. An "*orebody*" is that part of a vein, lode or lode zone which contains economically viable quantities of mineral (Figure 1c). The orebody may

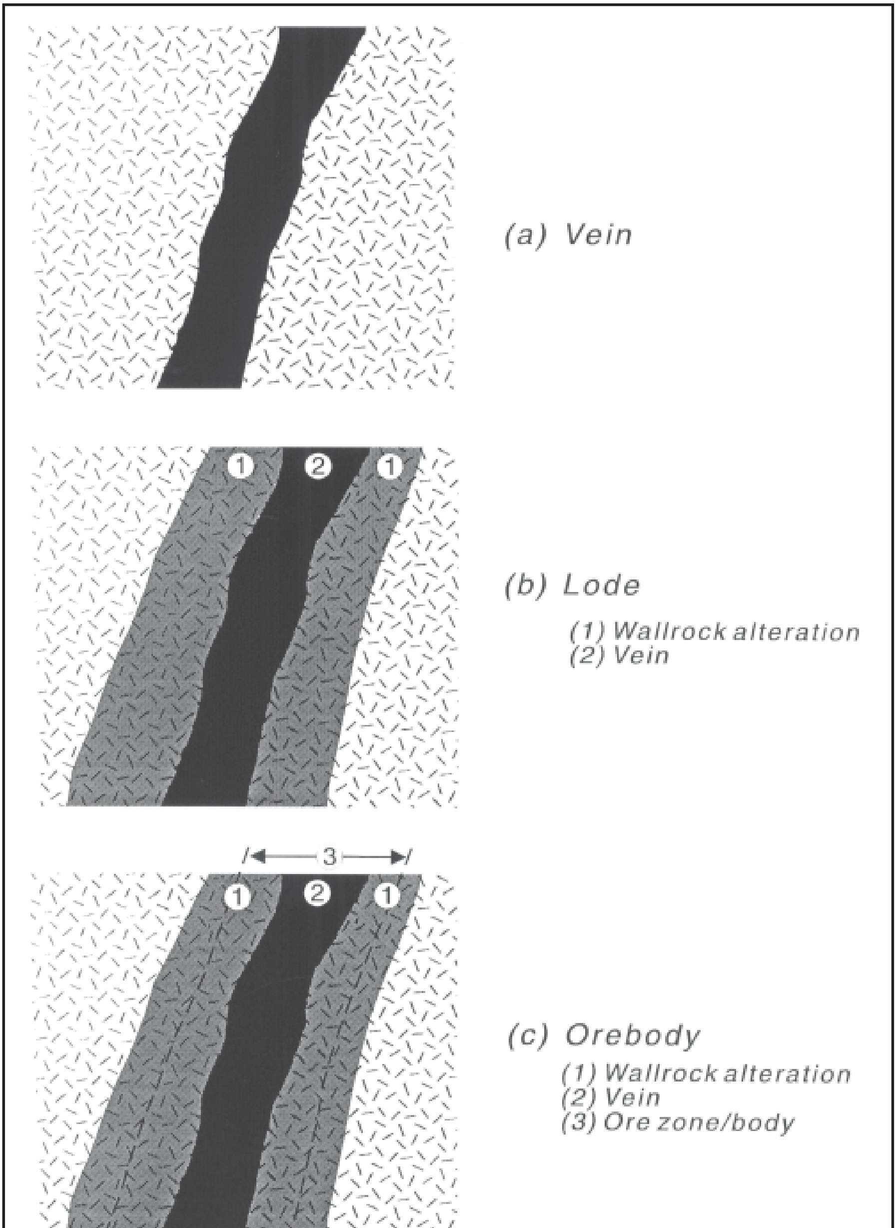


Fig.1. Mineralized fracture terminology.

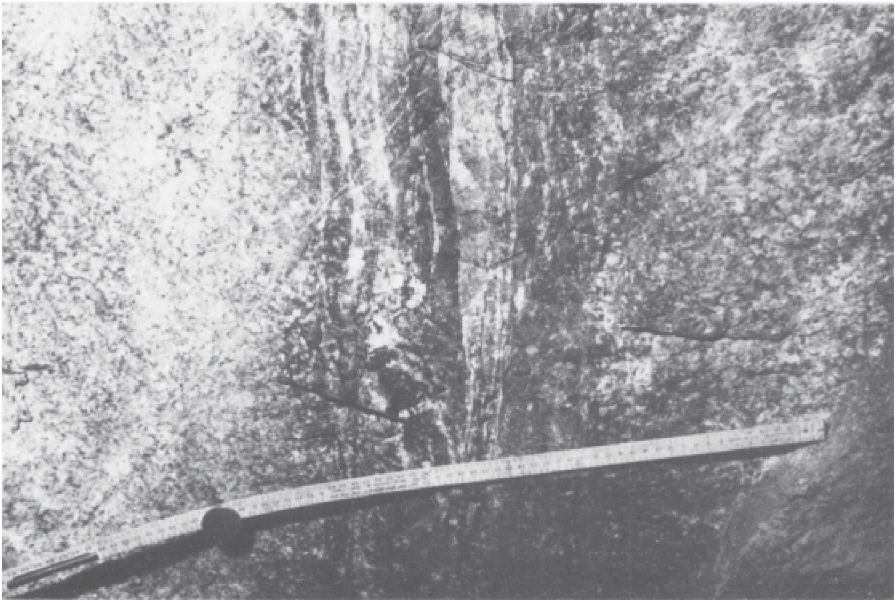


PLATE 1. Narrow (0.25 m), composite tourmaline peach vein running through granite with only minimal wallrock alteration. Tin grades are distributed through the blue peach. Roskear B Lode, 410 sub-level. (S.C. Dominy, July 1992)

include only the vein, and/or wallrock alteration if they contain economic quantities of mineral. Orebodies display differing degrees of geometric complexity with three main groups identifiable: (1) those with regular boundaries and/or inclination, relatively simple type; (2) those with irregular boundaries and/or inclination; and (3) those that have undergone strong faulting and/or folding and show extreme strike, dip and width variations, the most complex type.[4]

Initial vein formation often results in the development of a sinuous and variable width fracture network which develops into a wider composite vein by structural overlap during a multistage history. Ore mineral deposition is often restricted to a particular stage of this history, resulting in sections of the vein system which are economically barren. The economic grade of a vein is not always correlated to width, however recent studies on gold-bearing veins in Spain have shown some link, explained by the higher persistence and inter-vein connectivity by wider structures.[5] The prediction of the geometry, location and persistence of veins is of importance to the mine geologist and engineer. Each mine- and, indeed mining district- has its own unique structural and paragenetic characteristics, which require a thorough understanding by the geologist undertaking evaluation and exploitation activities.[6]

Narrow vein systems represent an important resource of valuable minerals such as tin and gold, but how can they be effectively evaluated and exploited? Spatial variations in the veins make it difficult to estimate their geometry and resources from drill data. Drilling is used to determine vein position, continuity, structure and mineralogical characteristics, though is not generally a representative measure of grade.[3,7] The need for exploratory underground development is strong to assess the nature of the vein and its grade. Thus geological interpretation is the key, so ultimately not only must ore grade be good and the values distributed throughout the vein with some degree of uniformity and/or predictability, but a sound geological model must be devised.[4] The ultimate challenge of narrow vein mining is to guide the operation so as to produce ore with as little dilution as possible, at the least cost commensurate with the needs for safety etc.[8] In narrow vein operations, mining costs often represent more than 65% of the total operating costs. Many have stated that the full extent and nature of an orebody is not known until it has been mined out. Certainly for narrow vein-hosted gold deposits which show highly erratic distribution this is the case (e.g. Dolgellau Gold-Belt, North Wales).[9,10,11] On the wider scale this old adage is true because of the combinations of variables which determine what portions of the mineral

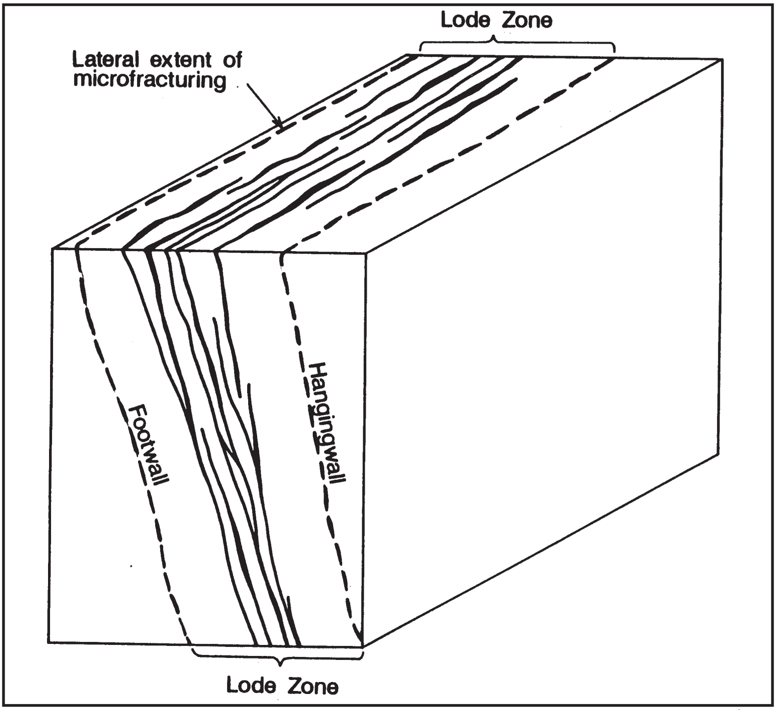


Fig.2. Conceptual view of a lode zone.
(Reproduced courtesy of the Institution of Mining and Metallurgy)

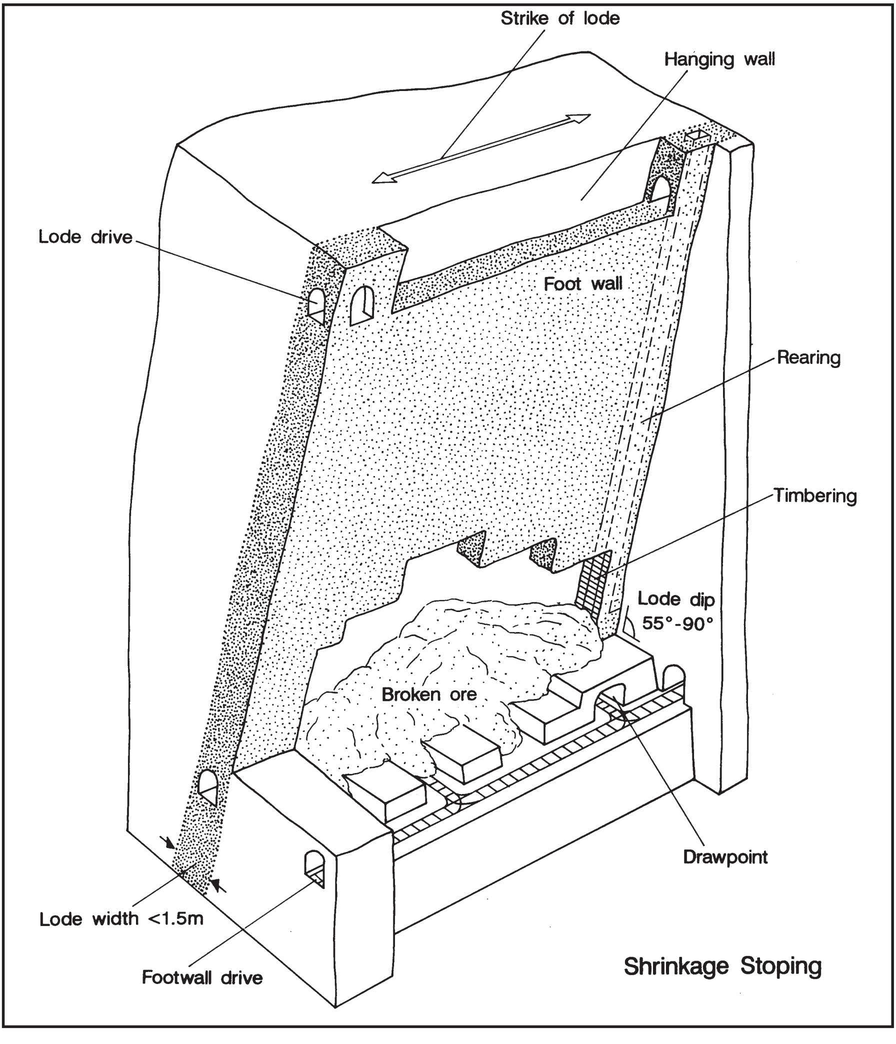


Fig.3a. Key features of the overhand shrinkage stoping method.

deposit can be mined at a profit at any given time during the life of the mine. Today the mine operator/owner has more control on the price of the commodity with increased use of forward selling and price hedging. Many base metal producers will often have long-term contracts agreed for bulk sales, though those selling directly onto the spot market still face problems. Political factors are less easy to predict and can strongly affect the economic viability of a deposit. There are a number of uncertainties which place a strong pressure on the geologist undertaking reserve evaluation to arrive at grades and tonnages which are as close to the truth as possible and to guide the mining operation efficiently.

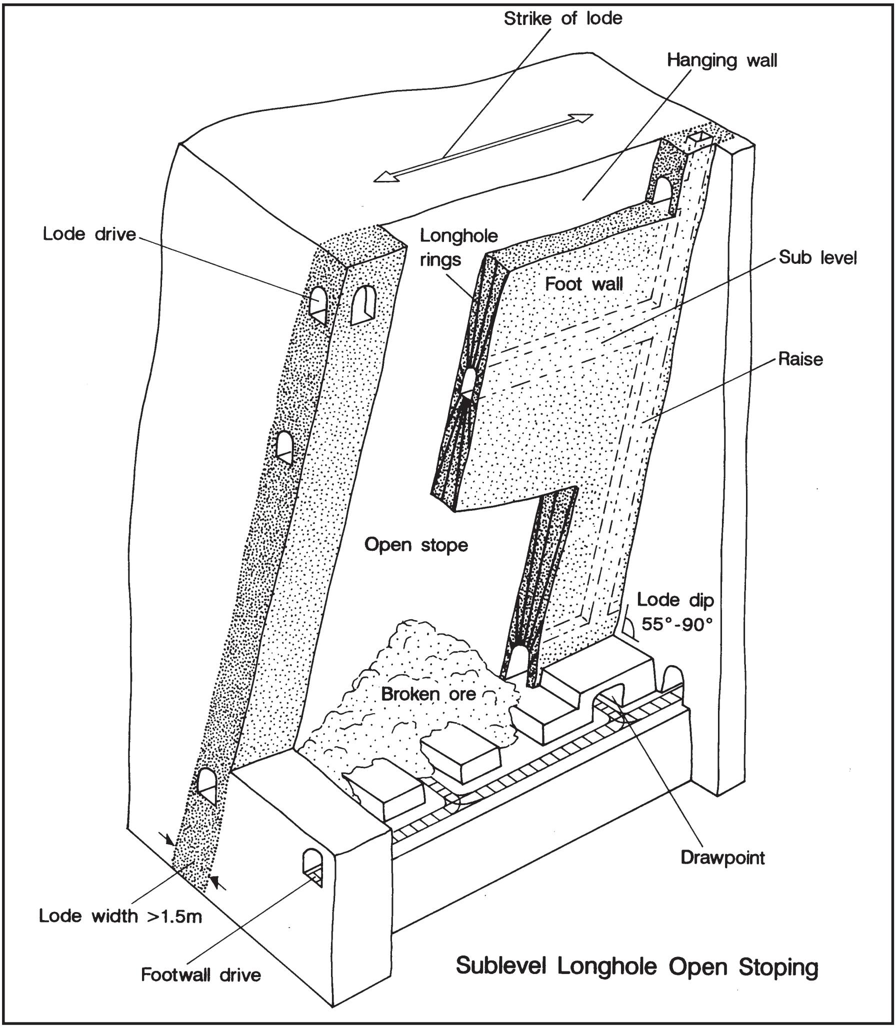


Fig.3b. Key features of the longhole open stoping method.

MINERALIZATION IN SOUTHWEST ENGLAND

Vein systems with varying spatial, temporal, alteration, mineralogical and structural complexities are a ubiquitous feature of the south-west England orefield and have been recognised for many years.[13-23] The veins are typically steeply-dipping systems and may occur in swarms; over 35 sub-parallel veins were observed in the Camborne-Redruth area.[24] They are generally located near porphyry dykes and along the long axis (north-east south-west) of the granite batholith although some are found at the batholith margins (i.e. on the granite/metasediment contact). The simplest structural type occupies a single in-filled fracture but complex multi-stage systems are more common.[14-25]

Most of the veins strike about east-west and dip steeply with values in excess of 70°, although variations may occur both laterally and vertically. Widths of the individual veins vary from a few centimetres to about 3-4 metres, with overall lode widths (ie. including wallrock alteration) up to 12-15 metres (e.g. Dolcoath, Main Lode, 12 metres wide).[24] One of the widest lode on record was the Main Lode of Dolcoath Mine on the 550 Fathom Level where it reached approximately 30 metres.[24] Henwood reported an average vein (lode?) width for the region at 3 feet 2 inches (about one metre), however this is likely to be below the real value.[14] The lateral extent of the veins is highly variable, but some are traceable for over 3000 metres along strike (e.g. Pryces-Tincroft Lode). In many cases the tin (and copper) mineralization are discontinuous, with barren zones leading into ore-bearing zones and veins branching and bifurcating along strike. Their vertical extent is variable, the Dolcoath Main Lode has been worked for some 1000 metres in depth.[24]

Three principal mineralizing stages are recognised within the orefield, as follows:-[17] (1) a pre-batholith stage of minor strata-bound and syn-sedimentary mineralization (Fe-Mn-Cu); (2) a syn-batholith stage (or main-stage) characterised by early Sn-W stockwork mineralization followed by Sn-Cu vein/lode mineralization; and (3) a post-batholith stage of epithermal (or crosscourse) activity which displays barren to Zn-Pb-Ag mineralization.[18,20,21,26,27] Pervasive kaolinization of granite which resulting in the formation of economic china clay deposits (e.g. St. Austell) was also related to this stage.[28]

NARROW VEIN EXPLOITATION

Underground mining of a narrow vein deposit is inevitably associated with ore dilution. Dilution is understood to be waste rock (or low grade ore) added to the mined ore, thus resulting in a final run-of-mine tonnage greater than planned and with an overall lower grade. Dilution is always unwanted, and is either a) planned; waste taken within the planned stoping limits or b) additional; waste coming from beyond planned stope limits.[29] The sum of the planned and additional dilution values constitute the overall final dilution. The geologist must work closely with the mine engineer to choose the right mining method which will produce the minimum amount of dilution.

The selection of the appropriate mining method depends upon vein geometry and physical characteristics. For narrow systems the chosen method must adapt to irregular ore limits and allow for good ore recovery with minimal dilution, in principal a method is selected which is safe and profitable. Particular consideration must be given to: (1) ore and wallrock strength, (2) vein strike and dip; (3) consistency of orebody width (regularity of ore/waste boundary), (4) the dimensions and regularity of pay-zones within the orebody (e.g. areas above the cut-off grade), and (5) overall grade of mineralization. Worldwide two methods are commonly used to extract ore from narrow vein systems. These are: (1) overhand shrinkage stoping, and (2) longhole open stoping. On the mine-scale the choice of their use is based on a number of factors as above, but often that of width.

In South Crofty lodes of less than 1.5 metres width are shrinkage stoped (Figure 3a), while for those of 1.5 m and over longhole stoping is used (Figure 3b). Some 75% of current production is gained from longhole stopes, 10% from shrink stopes and 15% from development drives and raises.[30]

Before stoping starts, the vein system must be evaluated and mining blocks defined. A block represents a volume of known rock tonnage to which a specific grade has been assigned, the block may be ore or waste. During the definition of mining blocks the amount of planned dilution is accounted for, and the geological reserve adjusted suitably. The mining blocks in South Crofty are divided into three categories based on the level of development and evaluation, and thus confidence. They are (1) measured; (2) indicated; and (3) inferred.[31] The highest confidence measured blocks have full lode exposure over two levels or sublevels and raises with three metre sample spacings. Within a measured block grade distribution and the spatial nature of the vein system will be well understood and any likely dilution problems will hopefully be realised. Indicated blocks have exposure between two levels or a maximum 20 metre down-dip extension below one level. Inferred blocks are defined upon level of exposure, proximity to higher confidence blocks and extrapolation of known data. As more geological and sample information is acquired about a specific block, it moves into a higher confidence category. Exploration on vertical and lateral extensions of known vein systems continues to add to the reserves/resources of the mine. Block evaluation and reserve estimation at South Crofty are detailed further in Gribble.[32]

Overhand shrinkage stoping or one of its variants was the main mining technique employed in the Cornish tin and copper mines (Figure 3a).[33-35] The miners drill up into the lode from a base level, blast and then return to drill standing on the broken ore. In this way they work progressively up dip filling the stope with broken ore and using it as a drilling platform. This method has many advantages, it allows the geologist constant access to the lode as work progresses and the flexibility to leave behind low grade ore or to extract irregular richer areas of the lode not previously known from sampling records. In most cases final dilution is controllable and kept to 10% or below. The disadvantages of this method are that up to 60% of the ore is “locked up” until work in the stope is completed which may take several weeks and it is expensive in comparison to longhole stoping in terms of manpower, resources, time and safety considerations. The effectiveness of shrink stoping is also controlled by the skill and experience of the miners.

More recently in South Crofty, a longhole open stoping method has been applied to larger lodes over 1.5 metres in width (Figure 3b). Longhole stoping requires the establishment of sublevels between the main levels. Drilling crews are then positioned within these levels and fans (each one called a “ring”) of drill holes above and/or below the level on one metre spacings are drilled to a specifically designed pattern for that location. This pattern is based on the geological section at that position and the firing requirement. Crews pre-drill a series of these rings which are later charged and fired. Each ring may have a dip length of 20 metres or more and release over 75 tonnes of ore. In this way large areas of ground can be stoped out very rapidly. Similarly, if areas of waste are mined, they can be selectively mucked-out and dumped. This method of mining is capable of delivering large volumes of ore very quickly, which is of great benefit in terms of cash flow and resources. The main disadvantage is that rapid changes in lode width or payability may not be seen, with the consequent risks of high dilution, though generally only in the range 15-25%, or of leaving ore behind. Also long holes may wander off lode if the ground conditions change.

Clearly, for both methods, precise and accurate geological data is essential to maximise the efficiency of these stopes, thus maximising recovery and minimising dilution. This is collected by the mine geological team who sample and map all stope and drive faces regularly, expanding the geological knowledge-base and enabling a close control on geological variations and complexities.[32]

SOUTH CROFTY TIN MINE

South Crofty Mine is located between the towns of Redruth and Camborne (Figure 4) and is an amalgamation of at least 12 mines including East Pool, Roskear, Agar, Dolcoath and Cooks Kitchen mines. Its detailed history is reported in Dines[24], Buckley[36] and Brock[37], and a collection of recent

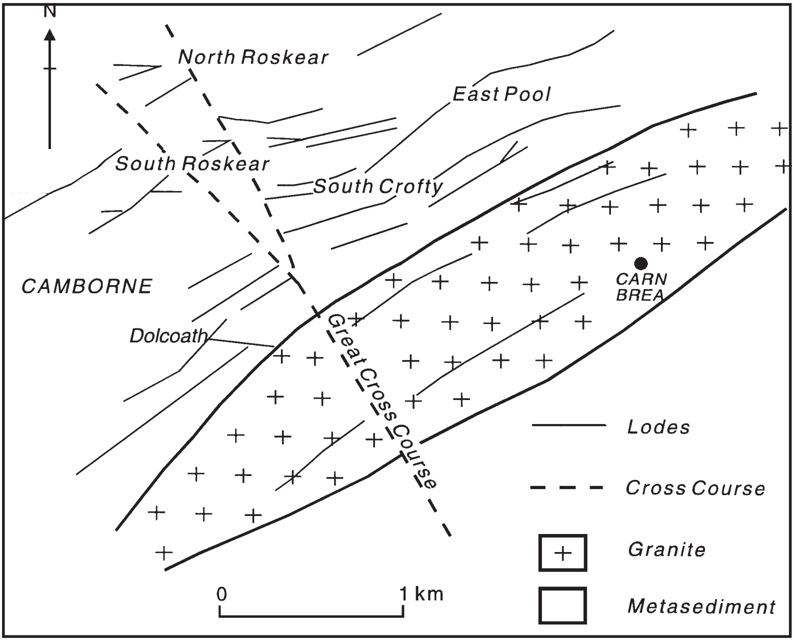


Fig.4. Diagram showing the location of South Crofty Mine.

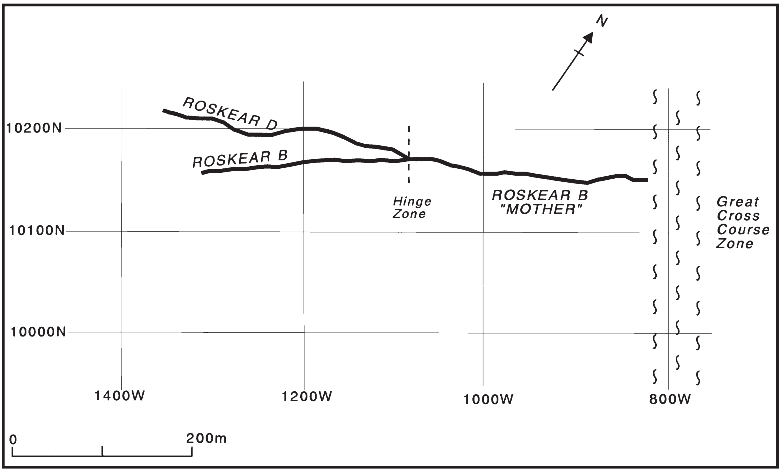


Fig.5. Schematic plan of the South Crofty 420 fathom level.

underground photographs are given in Deakin et al.[38] It is the only working tin mine in Cornwall, producing some 177,082 tonnes of tin ore at a grade of 1.25 % in 1994.[30] In January 1995 the mine contained a total identified reserve of 3,230,000 tonnes at a grade of 1.49% Sn and a hypothetical resource (maximum) of 8.5 million tonnes at a grade of 1.00-1.50% Sn.[30] The steeply-dipping, discontinuous tin-bearing veins are hosted by east-north-east-trending lode zones. The veins formed by episodic fracture re-opening and fluid flow, which resulted in the deposition of cassiterite associated with tourmaline and chlorite gangue minerals. The mineralization at South Crofty has previously been reported by Gillett[39], Taylor[40-43] and Clark[44] and more recently by Scrivener et al.[27], Farmer et al.[46], Farmer and Halls[18] and Dominy et al.[3,26]. Four types of mineralization are recognised as follows: (1) sub-horizontal quartz floors, and steeply dipping lode zone-hosted; (2) cassiterite-tourmaline and (3) chlorite veins; and (4) steeply dipping quartz and chalcedony crosscourse veins which cut the lode zones.

The main tin mineralization is found within lodes which vary in width from between 0.5 to 10 metres, though individual veins may vary from 0.1 to 3 metres in width. The lode zone may reach 40-50 metres in width and possesses a hangingwall and footwall which forms the limit of brittle deformation, between these a high density of variably mineralized macro- and micro-fractures are found (Figure 2; Plate 1).[18]

At South Crofty, the width of the fracture sets containing each stage of the mineralization is depth related. At depth the lodes are dominated by sulphide-poor assemblages, whereas at higher levels sulphide-rich assemblages dominate. Observation of the Roskear A Lode (400 fathom level) shows sulphide-poor veins generally <0.5 metre, whereas the same lode on the 360 fathom level similar veins are nearer two metres wide and carry sulphides.

The Dolcoath South Lode (290 fathom level) rarely exceeds one metre in width, whereas the No.8 Lode (400 fathom level) reaches three metres in width. These features result in the classic tin and copper zonation in the Dolcoath Main Lode where chalcopyrite-fluorite mineralization was dominant above the 190 fathom level and absent below.[21] Such zonation is explained, in part, by variations in mineralizing fluid chemistry and vertical changes in pressure.[19]

The tourmaline stage of mineralization is characterised by the deposition of black and blue tourmaline-bearing veins. The black tourmaline veins, up to five millimetres wide, are hosted in fractures which show three strike orientations of 050°, 060° and 090° forming spatially variable networks associated with pervasive wallrock tourmalinization. The formation of these vein networks, areas of localised brecciation and concomitant micro-fracturing resulted in regions of weakness within the host granite. This marked the initial development of the lode zone.

The main tin deposition occurred between 287 and 284 million years ago (Ma) and was associated with lode zone reactivation and the formation of blue tourmaline- and cassiterite-bearing veins known locally as *"peach veins"* (Plate 1).[47-49] The veins show two strike orientations which formed simultaneously during lode zone reactivation: one set lies parallel to the strike of the lode zone (060-065°) and the other at an angle of approximately 12-15° anticlockwise (045-050°). Vein textures show overprinted generations of tourmaline-cassiterite-quartz mineralization and multiple events of lode zone reactivation. Detailed studies of cassiterite and tourmaline mineralogy have shown that the minerals are co-genetic, and that variations in mineral chemistry and form are attributable to a complex interplay of fluid composition and structural regime.[18,46,50] High grade zones are often marked by the formation of breccias in which blue tourmaline vein fragments are cemented by coarse cassiterite as observed in sections of Roskear B Lode. Cassiterite mineralization is hosted in either (1) the matrices of hydraulic fractures or (2) discrete veins formed by reactivation of pre-existing fractures.

Further reactivation of the lode zones lead to the deposition of chlorite-bearing veins which were believed to have formed between 273 and 252 Ma.[47,48] Their attitude was quite distinct from those of the blue tourmaline veins which they cut. The veins show two principal strike orientations, 060° to 070° and 080° to 090°. The first vein set corresponds to the main lode zones and the latter to the east-west-trend of the "caunter or contra" lodes of the Camborne-Redruth mining area.[24] Chlorite vein formation was accompanied by the right-lateral displacement of the earlier blue tourmaline veins. The earlier part of the chlorite mineralization was cassiterite-bearing, but later stages were apparently cassiterite deficient and were associated with the deposition of vuggy and crustiform quartz veins within the chlorite veins.

The most recent style of mineralization is represented by the crosscourse veins which are hosted in sub-vertical, north-north-west- to north-trending

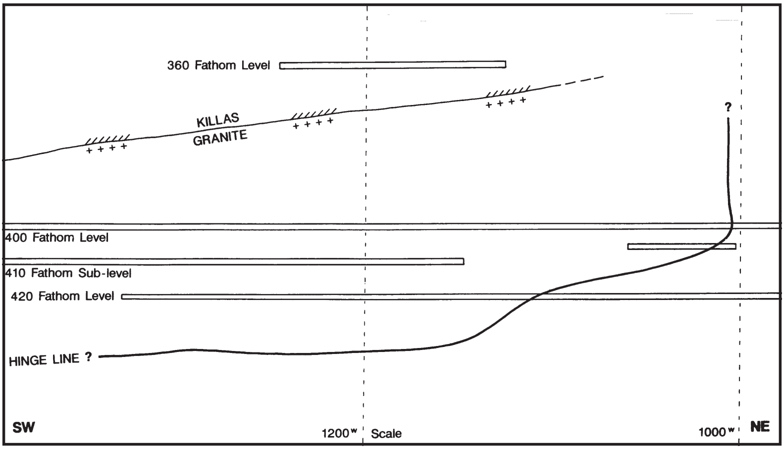


Fig.6. Longitudinal section of the Roskear B Lode showing the nature of the split hinge zone.

strike-slip faults that are seen to displace laterally the main lodes by few centimetres and up to 100 metres.[26] No dates for South Crofty crosscourses are available, but recent work of Scrivener et al. has demonstrated a 236 Ma age for similar structures observed in the Tamar Valley region.[27] Two scales of structure are seen 1) broad zones of ramifying fractures and argillic alteration and 2) discrete quartz/chalcedony-filled extensional veins with variable amounts of fluorite, hematite, chlorite, pyrite and mineral pitch. These veins contain no economic mineralization.

STRUCTURE OF THE ROSKEAR LODES

The Roskear B-D Lode system represents a substantial lode zone probably containing in excess of one million tonnes of mineralized rock. The Roskear workings are situated between the 800W and 1400W lines of the mine grid, in the western section of the mine area (Figure 5). The lode system strikes east-north-east except for off-set segments of Roskear D which strike almost east-west corresponding to the caunter lodes and dip generally towards the south-east. The lodes are part of one structure which splits into two sections (Figure 5). The Roskear B Lode is considered to be the Mother Lode and splits at approximately 1000W on the 400 fathom level into two sections, the northern Roskear D Lode and the southern Roskear B Lode (Figure 5). Roskear D Lode is the continuation of the Mother Roskear B Lode and was named prior to a full understanding of the structure. For the purposes of this work the structure will divided up into three parts; Roskear B Mother Lode, Roskear B Lode and Roskear D Lode and the 400 fathom level will be used as a reference horizon (Figure 5). The hinge of the split plunges to the south-west and varies in dip from sub-vertical between the 360 to 400 fathom levels (1000W), to about 45° on the 420 fathom level (1100W) and flattens towards the 445 fathom level (1200W; Figure 6). The overall three-

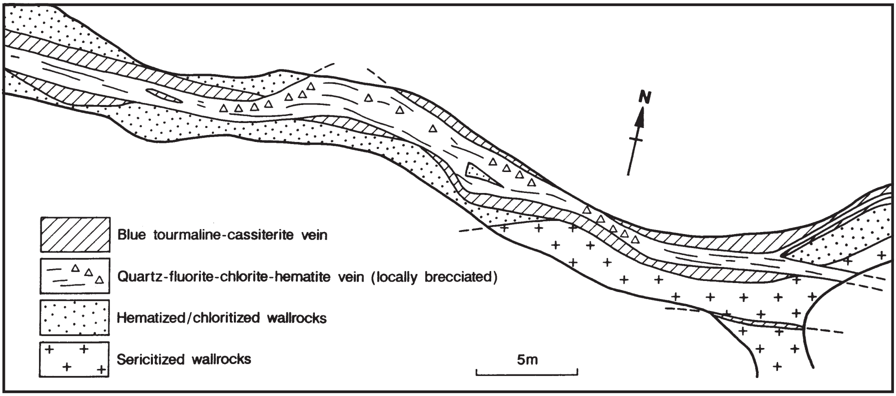


Fig.7. Plan view of part of the mapped back of the Roskear D Lode on the 410 fathom sub-level showing an offset zone (mapped by S.C. Dominy in 1993).

dimensional shape of the structure is believed to be in the form of a modified horse which closes above the 445 fathom level and below the 340 fathom level. Drilling and development on the 445 and 470 fathom levels has shown a blue tourmaline dominated vein which is considered to be the downward extension of the Roskear B Mother Lode.[51]

The lodes contain evidence of early vein networks of black tourmaline and pervasive wallrock tourmalinization which have been strongly overprinted by the main cassiterite-bearing blue tourmaline veins (Figures 7 & 8; Plate 2). Some sections of the Roskear D Lode are dominated by zones of pervasive, variably cassiterite-mineralized tourmalinization with very little blue tourmaline veining. The off-set segments of the Roskear D Lode have been reactivated and filled with massive chlorite-fluorite assemblages associated with pyrite/marcasite and veins of banded and vuggy quartz and kaolinitic clay (Figure 7). Petrographic studies reveal that cassiterite may be intimately intergrown with chlorite and hematite. Open/vuggy textures are common with chlorite forming small rosettes associated with quartz and fluorite. This later mineralization is associated with pervasive chloritic and hematitic wallrock and vein alteration which overprints all the previous stages.

MODEL FOR LODE ZONE DEVELOPMENT

The economically viable veins at South Crofty, exemplified by the Roskear B-D system, are hosted within a large-scale lode zone. The lode zone is approximately 30-40 metres wide and at least 600 metres in length. The model for its development is characterised by five principal stages which individually show multi-stage activity, and overall display the overprinting of different structural and depositional regimes (Figure 9).

Stage 1: The precursor stage to mineral deposition was the formation of a dominant east-north-east-trending joint set within the host granite as a result of regional stresses imposed during granite cooling.

PLATE 2. Narrow (0.07 m), tourmaline peach vein running through granite. Net vein system on vein wall overprints early black tourmaline veins. Central white quartz and red hematite vein within peach vein represent late-stage reactivation. (S.C. Dominy, July 1992)

Stage 2: The earliest stage of mineralization was characterised by the deposition of black tourmaline veinlets, up to five millimetres wide, within reactivated joints. These tourmaline-filled fractures define the east-north-east-trend of the lode zone which was to act as a zone of weakness and high fluid flow. The tourmaline veins have varying dips, many sub-vertical and show two main strike orientations of 050-060° and 090° which give rise to anastomosing vein networks. This stage was dominated by oblique shearing which resulted in the right-lateral displacement of markers by up to about five metres.

Stage 3: The blue tourmaline veins were deposited in fractures that were sub-parallel to the main lode zone with orientations of 045-050° and 060-065° during lode zone reactivation. The pre-existing east-west trending black tourmaline veins acted as bridging structures which were reopened allowing blue tourmaline vein deposition.[52] This has given rise to the offset pattern of the B Mother and D Lode segments (Figure 5). During this stage the lode split developed which again was controlled by the pre-existing east-west-trending black tourmaline vein sets. The blue tourmaline veins contain cassiterite intergrown with microcrystalline aggregates of schorl and show textures indicative of rapid crystallization. These textures were the result of tectonically controlled pressure changes during lode zone reactivation. This stage was dominated by oblique shearing which resulted in the left-

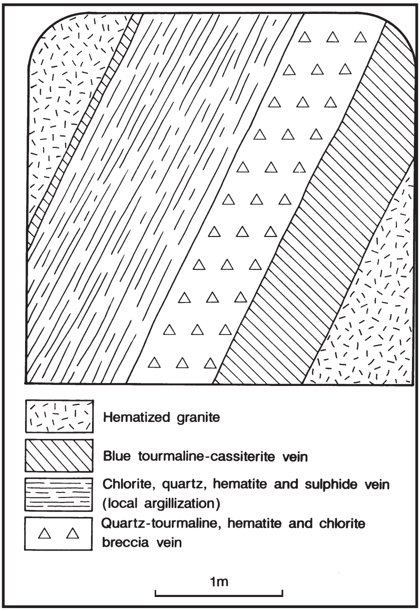


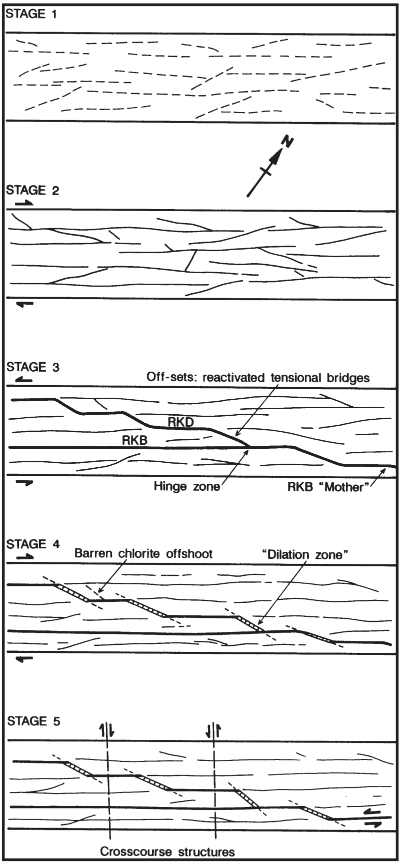
Fig.8. Section of a typical quartz-tourmaline and chlorite-fluorite lode on the Roskear B-D Lode South Crofty Mine.

lateral displacement of markers and the development of 45° south-west plunging slickensides. Peach vein widths vary from narrow stringers up to two metres and grade values vary from <0.1% Sn to over 15% Sn.

Stage 4: The tourmaline stage was followed by the deposition of chlorite in fractures of two main orientations; 065° and 090°. These were formed as a result of dextral shear reactivation of the lode zone and the re-opening of parts of the earlier black and blue tourmaline veins. Early chlorite mineralization along the lode system was accompanied by localized cassiterite deposition and wallrock chloritization and hematization. Later reactivation of the lode zone led to the dilation the east-west vein offsets resulting in the deposition of a variable chlorite, fluorite, sulphide, hematite and kaolinitic clay assemblage. This stage resulted in the dilation of the earlier blue tourmaline veins and the formation of wide chlorite-fluorite breccias containing blue tourmaline vein fragments. Crustiform and vuggy quartz veining was also associated with this stage and is evidence to suggest deposition within an active fault regime.

Stage 5: The final stage of development is marked by the deposition of north-west-trending locally brecciated, banded, crustiform quartz, chalcedony, chlorite and hematite-filled veins which laterally displace the main lodes by up to 0.4 metre. Further lode zone reactivation is characterised by oblique intra-lode shearing, evidence of this was preserved within a shrink stope on Roskear D Lode (420 fathom level; N. LeBoutillier, pers. comm.) as hematite filled structures between the hanging and footwalls. The shears are irregular and impersistent, but a single plane was seen to run the full length of the

Fig.9. Schematic diagram showing the stages of the development of the Roskear B-D Lode system.



stope. A net right-lateral displacement is indicated by slickensides and offsetting of the crosscourse veins by up to 0.3 metre.[26]

DISCUSSION

The Roskear B-D Lode system is a classic example of a granite-hosted complex vein system. The fracture-controlled development of the lode zone containing the economic narrow veins defines their spatial form, thus a clear geological understanding is required during evaluation and exploitation activities. The veins formed as a result of multi-stage fracturing and fluid flow, which resulted in the deposition of cassiterite associated with tourmaline and chlorite gangue minerals.[17] Grade distribution within the lodes is complex and erratic due to the fact that several stages of the paragenesis contain cassiterite. Most high grade mineralization is observed within three structural styles:

1) in the blue tourmaline peach veins where fractures are parallel to the lode zone and where they attain maximum widths (>1 m),

2) in coarse cassiterite-blue tourmaline peach breccias and
3) in well defined chlorite veins where virtually no structural reactivation has occurred.

Steeply plunging ellipsoid zones of high grade ore-shoots have been identified which are explained in terms of intersecting fracture sets related to lode zone reactivation.[18,52] The intersection of different fracture sets commonly provides preferential sites for mineral deposition as a result of high fracture connectivity and density, and fluid flow.[5]

Variations in geology are important factors in controlling the mining operation, a number of notable features are discussed below:

1) Variation in wallrock alteration is important since wallrocks may contain substantial amounts of cassiterite either disseminated or as veinlets. In cases where large widths of mineralized wallrock are present the overall width of the orebody will generally be >1.5 m so longhole open stoping would be the more applicable extraction method.

2) The presence of cassiterite and chlorite together can create problems during the grinding part of the processing circuit. The chlorite can form coatings on the cassiterite ("chat" formation) and lead to inefficient grinding and thus cassiterite loss.[53] Similarly the presence of hematite and/or fluorite in the vein can cause reduction in cassiterite recovery during processing.[53] Other than total avoidance at the mining stage, this problem is virtually impossible to overcome and should be addressed during processing.

3) Late-stage crosscourse-style reactivation is particularly relevant to mining, since wallrock alteration, clay vein development and on-lode faults effect rock stability and fragmentation characteristics. Pervasive hematitic, chloritic and sometimes kaolinitic wallrock alteration lead to soft and unstable stope walls, which may cause high dilution if not controlled. In general terms veins with such characteristics will probably be mined by shrink stoping, thus maintaining maximum control over dilution. If longhole stoping were used then there would be a tendency for large amounts of dilution.

4) Dilation and comminution of the cassiterite-bearing peach veins within off-set sections by late faulting/quartz-clay veining leads to the in-situ dilution of tin grades and thus barren/low grade zones within the orebody. Extreme comminution of cassiterite-rich veins leads to a marked lowering of grain size and thus difficulties in recovery during processing. Either mining method could be used in such circumstances, however where large tonnages are involved longhole stoping would allow the removal and dumping of the

waste away from ore. Shrink stoping would mix waste with ore, which would then be accounted for as planned dilution.

5) Isolated, but continuous hematitic fault planes within the wallrocks can lead to stope instability and thus ore dilution. Shrink stoping would be best used in such conditions as it would allow for better geological and mining control.

6) Localized variations in strike are linked to the off-set segments and are thus problematic. Variations in dip are less problematic but require careful control, in both cases shrink stoping would be the most appropriate extraction method.

Generally speaking, the more complex the vein/orebody, the greater the need for careful geological control and, thus, the application of overhand shrink stoping as an extraction method. The less complex vein/orebody is more applicable to mining by longhole open stoping with less, but still strong geological control.

In conclusion it is clear that narrow composite veins are complex structures which formed as a result of a multi-stage history of fracture dilation and infill. Cassiterite deposition is related to two stages of the model, and is thus not observed ubiquitously throughout the entire system. This is a typical feature of vein-tin deposits in Cornwall and elsewhere where only 30-40% of the vein system may be economic.[54] Narrow veins often constitute viable mineral resources, but their successful exploitation is fraught with technical problems. In most mines, including South Crofty, run-of-mine ore comes from several lodes, each with different structural histories and parageneses. These complex geologic features are also likely to change within individual lodes. Under these conditions, it is difficult for the geologist to make any but the most general predictions. With careful study and experience, however, educated predictions can be made. The application of geological study can be supported by use of 3D computer modelling software which will assist the mine geologist and engineer in their quest for an efficient and economic operation, a technique already well proven at South Crofty.[32]

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