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CONTROLS ON ORE LOCALIZATION IN TIN-BEARING VEINS: A REVIEW

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Controls on ore localization can be investigated through field observation, and historical and current production records. Integrated, these data can yield an important insight into the processes of mineralization, orebody geometry and fracture genesis. South-west England is a classic tin province with steeply-dipping, endo- and exo-granitic veins, which display diverse structure, paragenesis and ore distribution. Payable grades within veins are often restricted to discrete oreshoots which contain between a few thousand to millions of tonnes of mineralized rock. Mineralization is typified by cassiterite with a gangue of chlorite, quartz, fluorite, tourmaline and sulphides. Ore localization is determined by a number of controls: (1) host fracture geometry; (2) lithology; and (3) physio-chemical conditions. One or more controls are usually operative in any one shoot. The shapes of fractures influence deposition by determining the width of openings and the surface area for fluid/rock interaction. Variations in strike and dip, and the intersection and branching of veins are common sites for localization. Strike and dip variations result in dilatent zones along strike (strike-slip faults) or up dip (dip-slip faults). The hinge zones of vein intersections and branches are often regions for grade and width enhancement. Lithology controls mechanical properties which affect fracture shape, density and chemical reactivity. Contacts between different rock-types act as zones for vein break-up/deflection and are sometimes related to ore localization. Physio-chemical conditions relate to temperature and pressure, fluid chemistry and wallrock reactivity. The prediction of the geometry, location and persistence of veins and oreshoots is of importance during the modelling of mineral deposits for both genetic and economic evaluations.

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INTRODUCTION

Tin-bearing vein systems with varying spatial, temporal, mineralogical and structural features are a ubiquitous feature of south-west England (Figure 1). They have been recognised for many years (Carew, 1602; Borlase, 1758; Henwood, 1843; Cronshaw, 1921; Hosking, 1988; Willis-Richards and Jackson, 1989; Alderton, 1993). Three principal mineralizing stages are recognised within the orefield (Jackson *et al*., 1989). A prebatholith stage of minor strata-bound and syn-sedimentary mineralization (Fe-Mn-Cu) and a syn-batholith stage characterised by early Sn-W stockwork mineralization followed by the economic Sn-(Sn-Cu) vein mineralization. The post-batholith stage of crosscourse activity bears Zn-Pb-Ag-Fe-Ba-F vein mineralization. In this paper we address the main-stage Sn vein mineralization.

The knowledge of ore localization in vein deposits is fundamental to the understanding of fluid transport and depositional processes. It is also of significant importance during the evaluation and exploitation of this style of mineralization (Dominy *et al*., 1997). This paper reports localization controls in south-west England and provides the most comprehensive review since Collins (1912). The work is based on field studies by the authors at Wheals Concord, Jane and Pendarves and South Crofty and a county-wide investigation of historical mine data.

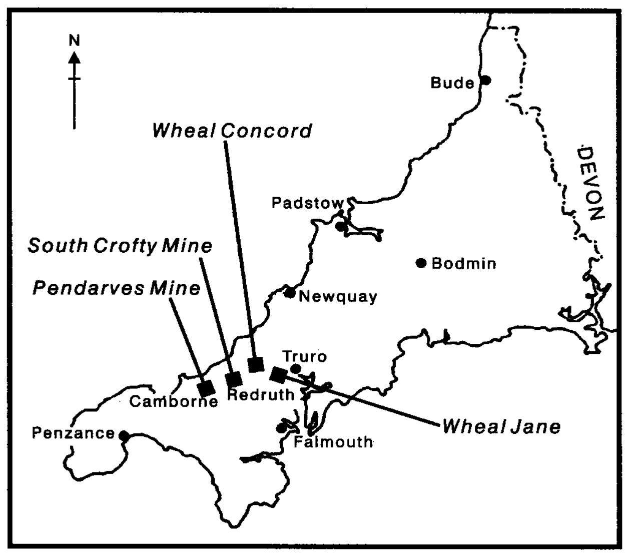

Figure 1: Map showing the location of the case study examples.

NATURE OF VEINS

Isolated veins are rare with swarms more common. Over 35 sub-parallel veins are seen in the Camborne-Redruth area (Dines, 1956). The simplest structural type occupies a single in-filled fracture, but composite systems are more typical (Henwood, 1843, Farmer and Halls, 1992). In most cases veins can be described as lodes, since associated wallrock alteration is also mineralized and is often part of the orebody (Figure 2). Lode/vein dip is generally steep, in excess of 70°, though dips of less than 45° do exist (e.g. Great Flat Lode; Dines, 1956). Vein widths vary from a few centimetres to about 2-3 m, though lodes may reach 30 m. The extent of individual veins is variable, with some traceable for up to 800 m along strike and a few 100 m down-dip.

Many of the endogranitic systems can be described as lode zones which often contain multiple, inter-related veins rather than a single continuous vein structure (Figures 2 and 3; Dominy *et al*., 1996a; Dominy and Camm, 1996). A lode zone can range from 1-50 m in width, have a strike length of up to 6,000 m (e.g. Pryces-Tincroft Lode, South Crofty mine) and a down-dip extent of up to 1,000 m (e.g. Main Lode, Dolcoath mine). They are characterized by a core region of vein(s), which display variable lateral and vertical continuity. This is surrounded by variably altered wallrocks containing

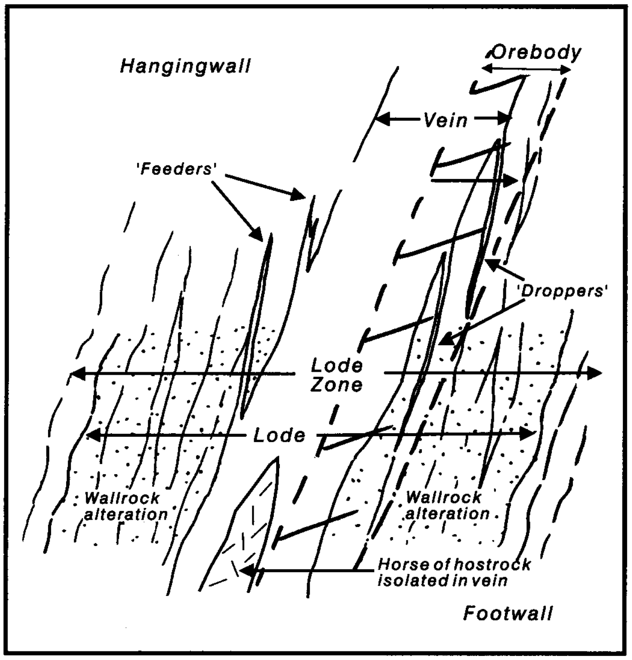

Figure 2: Schematic showing the features of a vein and its relationship to the terms lode, lode zone and orebody. Stippled region shows wallrock alteration either side of the vein and marks the extent of the "true" lode. Vein parallel stringers/microfractures mark the full extent of the wider lode zone. The orebody in this case is marked by a region including the footwall of the vein, droppers and wallrock alteration.

abundant microfractures which become less abundant outwards from the core region. Veins within the lode zone display diverse structural variations which affect their overall geometry. Minor veins or stringers emanating from the vein walls are common, typified by "feeders or uppers" from the hangingwall, and "droppers" from the footwall (Figure 2). Vein stringer networks, sometimes termed "hanging- or foot-wall stockworks" are also common. Exogranitic systems are more laterally restricted, though their complexity and composite form often match the criteria for a lode zone, and display the geometric features seen in the endogranitic veins.

Tin Distribution and Payability

Vein deposits, particularly tin, display an uneven distribution of mineral/metal across and within the plane of the vein. Wallrock disseminations (e.g. alteration) and stringers result in orebody margins being defined as assay cut-offs rather than along geologic contacts. It is possible that over 60% of an orebody may be distributed within the wallrocks rather than within the vein (Dominy, 1994). Potentially economic mineralization is generally restricted to a particular stage of a vein's paragenesis, and to specific zones or oreshoots along its strike.

An oreshoot is part of a deposit (e.g. vein) in which the valuable minerals are more richly concentrated (Amstutz, 1971). They are characterized by height (up to 350 m), plunge lengths (up to 1,000 m) and widths of up to 30 m (typically 1-3 m). Their geometry is variable ranging from highly irregular masses through to horizontally or vertically elongate tabular bodies. Contained ore may range from a few thousand to over a million tonnes. In south-west England the largest tin-bearing structure was undoubtedly the endogranitic Dolcoath Main Lode, which the authors estimate contained at least 10 million tonnes of rock. It produced some 2.5-3 million tonnes of ore at a grade of about 1.6% Sn (40,000 tonnes Sn metal), implying a payability of about 25%. A study of the mine longitudinal section shows that stoped areas account for 35% of the total. Dolcoath Main Lode contained of a series of oreshoots along its lateral and vertical extent.

Outside the oreshoots cassiterite deposition is sporadic producing low grade and/or barren zones. Even within the oreshoots, deposition is not uniform and low grade areas may be present. These features are compounded by structural complexities and make reserve estimation and exploitation difficult (Dominy *et al.,* 1997). The erratic nature of tin grade distribution is well known and sample populations generally display a log-normal form (Garnett, 1967; Kuscevic *et al.,* 1972). Clark and Garnett (1974) note that datasets are not always log-normal and that more than one population may exist. This is explained by the overprinting of two or more paragenetic stages- a feature they report in Simms Lode of Geevor mine. Geostatistical studies of sample populations are sparse for the south-west, generally because of the inherent problems of applying the method to veins. Clark (1978) constructed semi-variograms for data from Geevor mine which revealed the presence of two ranges (10 m and 45 m; the hole effect) and are consistent with high grade oreshoots surrounded by low grade/barren regions. Gribble (1992) noted a similar relationship from the South Crofty No. 8 Lode. Both workers report a low degree of grade variability (e.g. low nugget variance) which is a surprising result and may be related to local geology. Tin veins typically display large grade range from <0.1% to in excess of 40% Sn. The high-grade outliers give the sample population a high standard deviation and represent less than 5% of it. During reserve evaluation high-grade values are usually cut to a pre-determined lower level to reduce their influence. Cut values are variable, at Wheal Jane 3% Sn and South Crofty between 4-10% Sn dependent upon lode were used.

NATURE OF ORE LOCALIZATION

Previous Work

Early studies world-wide recognised variations in strike and dip, and vein intersections as sites for ore enrichment (Newhouse, 1942; McKinstry, 1948). The mineralization in south-west England has been the subject of research over past years (Carne, 1822; Moissenet, 1877; Collins, 1912; Taylor, 1965, 1966; Garnett, 1961, 1962, 1966a/b, 1967; Hosking, 1950, 1964; Rayment *et al.,* 1971; Jackson *et al.,* 1989). Several important factors have been recognised controlling localization, including (1) host lithology, (2) geometry of host fractures and (3) physio-chemical conditions. The most exhaustive work by Collins (1912) reports controls related to steeper parts of veins, lithological contact zones, variations in dip/strike and vein/fracture intersections. The studies of Garnett (1961, 1962, 1966a/b, 1967) at Geevor mine revealed that oreshoots were related to high-angle intersections of veins and pre-mineralization crosscourses and variations in dip. In South Crofty mine Taylor (1965, 1966) confirmed the importance of vein dip controls. More recently specific

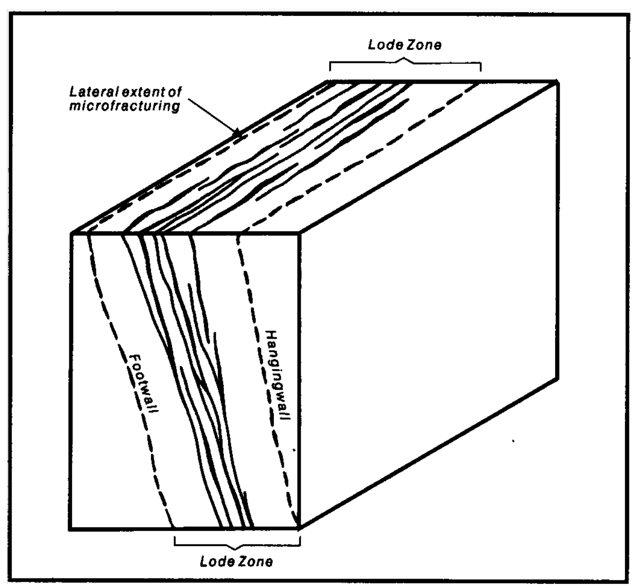

Figure 3: Conceptual view of a lode zone (From Dominy et al. 1996a).

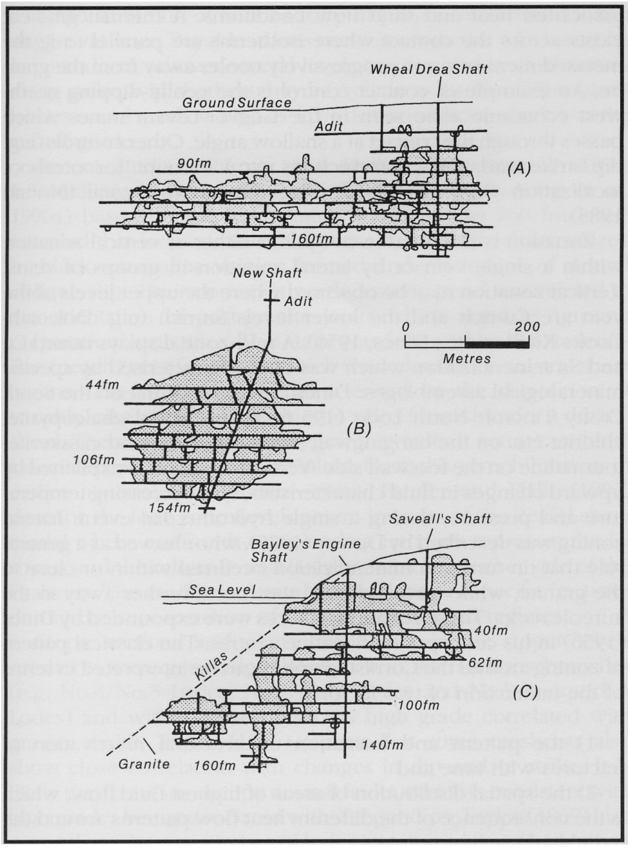

Figure 4: Longitudinal section through workings showing form of worked oreshoots.
(A) Wheal Drea; horizontal elongation suggesting control by dip variation, (B) Pryer Lode, Wheal Kitty; vertical elongation and ovoid form suggesting control by strike variation, and
(C) Savealls Lode, St.Just United Mines; narrow elongate oreshoot between 62-100 Fm Levels reflects control by intersecting veins (Modified after Taylor, 1978).

structural domains and intersecting fracture sets within a shear zone model at South Crofty mine have been recognised (Farmer and Halls, 1992; Dominy and Camm, 1996).

Methods of Study and Sources of Information

Field investigation should be a component of any study into the controls on ore localization. Work may include detailed surface and underground geological mapping and must be integrated with production sampling and drilling data if available. This is however not always possible particularly in areas where workings are long since closed and inaccessible. Abandoned mine data provide an invaluable source of information often as longitudinal- or cross-sections and plans. Whilst useful, they should be approached with care as inaccuracies of survey pickup and/or data recording are often present. Longitudinal sections showing stoping extent give only an approximate shape of the oreshoot and unless assay data are available do not imply 100% payability. In many mining areas works published during the period of operation provide an insight into the nature of the oreshoots.

Raw data can be managed in a number of ways including the production by hand or computer of plans and sections. Detailed examination by Garnett (1966a) of the grade variations at Geevor mine provided a number of methods for analysing this variability and predicting grades. He used contours of grade and accumulation (grade x width) to deduce controls on payability by comparing with contours of thickness, dip and distance of the vein from a fixed reference plane (Connolly diagrams). The Connolly technique is a contouring method based on the projection of data onto a nominal reference plane drawn at a fixed distance parallel to the vein (Connolly, 1936). Recent advances in computer technology have lead to powerful three dimensional modelling software into which modern and/or historical data can be input. Throughout any study there must be an emphasis on data cross-checking and re-interpretation to ensure that conclusions are valid.

Controls on Localization- Oreshoots

The location of oreshoots within a vein system is determined by a number of interrelated controls, these are outlined below.

1) Host Fracture Geometry

The shapes of fractures influence mineralization deposition by determining the width of openings and the surface area for fluid/rock interaction. Openings provide loci for fluid flow and hydraulic mechanisms produce wallrock spalling and brecciation. Variations in strike and dip may result in fracture dilation and provide zones for preferential mineralization and grade enhancement (Table 1).

Table 1

DIP-SLIP FAULTING		**STRIKE-SLIP FAULTING**	
NORMAL	*REVERSE*	*DEXTRAL*	*SINISTRAL*
Deposition on steep parts	*Deposition on flat parts*	*Deposition on right deflection*	*Deposition on left deflection*

Localization at dip variations is a common feature and has been noted in numerous mines. In strike-slip regimes strike variations are also important. In a description of Dolcoath mine Thomas (1882) reported the importance of strike changes, a feature noted elsewhere. In most cases fracture movement is related to a hybrid of both regimes, which may be oblique slip or sequential dip-slip then strike-slip (or vice versa).

While vein width is governed by fracture dilation, there is not always a strong correlation between vein width and high grades. In section, dip-related oreshoots are laterally elongate (Figure 4a), whereas strike-related oreshoots are vertically elongated in form (Figure 4b).

Vein intersections and branches are important locations for oreshoot development. A vein intersection is defined as a X-shape in which both veins continue beyond it, in some cases the later vein will displace the earlier one. The angle of intersection may vary from <5 to 90° and the fractures which host the veins may have formed at the same time or in two stages, in which case the vein infill processes may be independent of, or related to, one another. As a general rule, veins with small intersection angles are more likely to be genetically near-synchronous than those with large intersection angles. In restricted cases intersecting fracture sets have given rise to pipe-like "carbona" bodies typified by strong wallrock alteration/mineralization (Dominy *et al*., 1996b). A branch is observed as a Y-shape where the mother vein divides into two or more daughters either along strike or down dip. In some cases a minor branch splits off either the foot- or hanging-wall of the mother vein and may be termed foot- or hanging-wall branch veins.

In three dimensions oreshoots related to down-clip intersections/branches usually display high vertical and low lateral continuity (Figure 4c) and along strike vice versa. Intersections of a series of steeply dipping veins with the low dip (40-45°) Great Flat Lode resulted in finger-like oreshoots. Grade enhancement within this style of oreshoot is associated with any number of the following features:

(1) no change in vein width,
(2) an increase in vein width,
(3) wallrock alteration/disseminated mineralization and/or
(4) wallrock vein/stringer development.

Vein branching at Rosevale (Dominy *et al.,* 1995) resulted in no changes in the vein except grade enrichment. In Dolcoath Main lode vein widening and extreme alteration/grade enrichment occurred within the block of ground between the two branches.

Blanchard (1931) investigated 140 examples world-wide of vein intersections and found that 74% were richer, 12% similar, 9% poorer and 5% were barren with respect to the grade of rest of the vein. Our studies of thirty-five county-wide abandoned mine plans revealed that 70% of vein intersections and 66% of vein splits were substantially sloped out, thus implying payable grades.

2) Lithology

Host rocks control the development of vein mineralization in three principal ways: a) mechanical properties which affect fracture shape and density, b) chemical reactivity which affects fluid/rock interaction and c) pre-existing weaknesses.

Contrasts in rock strength produce varying features from reduction in vein width and payability to vein horse-tailing with strong mineralization. This is related to the mechanical nature of granite and its ability to form well-defined structures. The most common scenario in the region is where a vein cuts the granite/

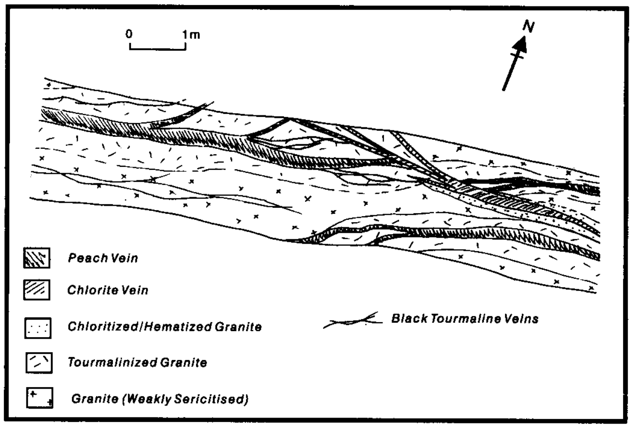

Figure 5. Plan of the mapped back of the South Crofty Dolcoath North Lode (380 Fm Level) showing the composite nature of the structure and the effect of late chlorite mineralization on the earlier peach vein (Mapped by S.C. Dominy).

metasediment contact, but ore mineralization is restricted to the granite (e.g. Tresavean mine). The reverse however, is observed at Wheal Vor (Main Lode) where the metasediment-hosted vein reduces to stringers in the granite (Dines, 1956). The mechanical contrast between the granite and hornfels contact rocks is markedly less than that between the hornfelses and the killas country rocks. This feature has not been widely reported, though Mount (1985) notes that some veins become thin and impoverished away from the granite and out of the contact hornfels at Geevor mine.

Pre-existing lines of weakness such as bedding and cleavage within the exogranitic environment are important. Camm and Dominy (1997) discuss the formation of bedded ore in the Indian Queens area which was controlled by both bedding and cleavage. High pressure mineralizing fluids were able to prise apart these weak planes, resulting in cassiterite-rich open space in-fill. At Wheal Vor, Dines (1956) notes the presence of cassiterite veinlets in the wallrocks where the cleavage was sub-vertical. Within the endogranitic environment lines of weakness are less common, though the role of joint reactivation has been noted (e.g. South Crofty). The localization of the Great Flat Lode has long been attributed to the presence and reactivation of a pre-granite Variscan thrust plane (Dines, 1956).

3) Physiochemical Controls

These controls are related to temperature-pressure conditions, fluid chemistry and wallrock reactivity. The dominant factor is that of temperature which is related to the cooling batholith and associated heat and fluid flow conditions. A thermal gradient exists across the contact where isotherms are parallel to it; the metasediment become progressively cooler away from the granite. An example of contact control is the gently-dipping northwest economic zone seen in the Geevor-Levant mines which passes through the contact at a shallow angle. Other controls (e.g. dip/strike variations, intersections etc.) account for oreshoot localization within this larger "local" economic zone (Mount, 1985).

Zonation is observed in two forms either as vertical zonation within a single vein or by lateral zonation in groups of veins. Vertical zonation may be observed where the upper levels of the vein are Cu-rich and the lower levels Sn-rich (e.g. Dolcoath, Cooks Kitchen etc.; Dines, 1956). A mid-zone displays mixed Cu and Sn mineralization which was often characterised by specific mineralogical assemblages. Dines (1956) reporting on the South Crofty Tincroft North Lode (195 fm level) noted chalcopyrite-chlorite etc. on the hangingwall side of the vein and cassiterite-tourmaline on the footwall side. Vertical zonation is explained by upward changes in fluid characteristics, and decreasing temperature and pressure, during a single hydrothermal event. Lateral zoning was described by Dewey (1925), who showed as a general rule that tin-tungsten mineralization occurred within or close to the granite, while lead and zinc was found further away in the aureole rocks. These zonation features were expounded by Dines (1956) in his concept of emanative centres. The classical pattern of zoning around the Cornish granites can be interpreted in terms of the interaction of two factors:

1) the pattern and formation of structural reactivation of fractures with time and

2) the spatial distribution of areas of highest fluid flow, which is the consequence of the different heat flow patterns around the individual cooling granites.

Recent studies have shown that most of the veins are the product of a number of complex superimposed hydrothermal events (Farmer and Halls, 1992). Polyascendent (or overprinted) zoning and telescoping are far more common (Hocking, 1965) and reflect the multi-stage nature of the mineralization.

Chemical reactivity is an important factor and is evidenced by the diverse alteration assemblages observed (e.g. tourmalinitic, chloritic, sericitic, hematitic, potassic and argillic). Wallrock alteration is particularly well developed in endogranitic veins, though alteration halos in some exogranitic veins (e.g. Wheal Jane-Mount Wellington mines) are extensive and have been used as exploration guides (Rayment *et al.,* 1971). Cassiterite deposition is related to reactions involving the conversion of granite feldspar to muscovite (sericitization). Hydrogen metasomatism leads to the reduction of pH, thus Sn complex destabilization and cassiterite deposition within open spaces.

CASE STUDIES

The following case studies report the broad controls on ore localization in a number of mines, based on the experiences of the authors and published data.

South Croft, Mine, Camborne

South Crotty (Figure 1) annually produced 190,000 tonnes of ore at a grade of 1.2% Sn, it closed in March 1998. The mine worked a number of endogranitic, sub-parallel lode zones which are characterised by quartz-tourmaline-cassiterite-bearing veins overprinted by a variable chlorite-cassiterite and/or fluorite assemblage (Figure 5). For evaluation purposes the lodes were divided into two types based on mineral composition and observed tin distribution. Those composed principally of tourmalinitic mineralization were considered Type I lodes, while those showing hematization, quartz-fluorite enrichment and intra-vein shearing were defined as Type II lodes. Vein widths vary from <0.1 to 3 m, lode widths up to 10-15 m with dips from 70° to vertical.

Tin distribution at South Crofty displays a moderate to high nugget variance. Payable values occur in oreshoots which may be large and extend over several levels and for hundreds of metres along strike, whilst others may be as little as 20-30 m^2. Ore block grades could reach as high as 4.5% down to 1% Sn which was the cut-off grade.

Recent studies (Farmer and Halls, 1992; Dominy, 1994; LeBoutillier, 1996; Dominy and Camm, 1996; Dominy *et al.,* 1996a) based on the lower mine levels (below 260 fm level) revealed that lode zone development was initially characterized by black tourmaline veining formed under a regime of dextral oblique-slip. Their dominant north-easterly trend was related to the orientation of post-granite joints which acted as "ground preparation" structures. This stage was followed by blue tourmaline (peach) vein formation which was related to a sinistral shear regime. The final stage is characterised by the deposition of variably cassiterite-bearing chlorite veins formed under a dextral shear. There is evidence to suggest that at least some cassiterite associated with this stage resulted from the remobilization of earlier material (LeBoutillier, 1996). Farmer and Halls (1992) describe the lode zone development in terms of the Reidel shear model where east-north-east-trending fractures represent the D-shears and the others R- and P-shears which lie either side of the D-shears. This model accounts for the dilation of specific fractures during the superposition of dextral and sinistral regimes.

Stope sections and plans reveal that in the upper levels oreshoots were generally related to vein intersections/branches (e.g. No.4/No.5 Lodes, No.1/Main Lodes and No.9/Prospect A Lodes) and within those oreshoots high grade correlated with greater width. Taylor (1966) reports that some oreshoots also show close correlation with changes in dip and/or strike. It is likely that the veins occupy normal faults, which is consistent with high grades being associated with steeper dips. Taylor (1969) also noted that where a number of lodes intersected quartz-porphyry dykes they became impersistent and of low grade, elsewhere he found the reverse to be true. The intersection of the Nos. 2 and 3 sub-vertical lodes with a zone of sub-horizontal quartz-floors resulted in a 10-15 m wide belt of high grade stringers known as the 3ABC zone. In the North Pool Zone pervasive granite replacement resulted in irregular orebodies located at the intersection of main-stage lodes with quartz floor zones (Dominy, 1994). Within these zones mineralization is characterized by numerous sub-parallel tourmaline-cassiterite veins and pervasive granite tourmalinization with disseminated cassiterite.

Inspection of stoping patterns shows that the distribution of oreshoots are not sub-vertically oriented as previously considered. It was also observed that stopes commencing in a zone of high grade rapidly become low grade or barren with height. Gribble (1992) explains this observation in terms of ellipsoidal oreshoots plunging at 40-45°. The Type I lodes showed ellipsoids which plunged to the south-west, whilst Type II lodes showed a south-easterly direction. These zones correspond to the line of intersection between Riedel fractures generated during lode zone reactivation.

Most high grade mineralization appears to be associated with the blue tourmaline stage and observed in two styles; (1) where the blue tourmaline vein is parallel to the main lode zone trend (e.g. sections of Roskear A Lode); and (2) in well developed quartz-cassiterite breccias which are related to changes in vein strike (e.g. sections of Dolcoath South Lode). These features are related to the formation of the blue tourmaline veins during sinistral lode zone reactivation, in the first case D-shear formation and in the second to fracture dilation. Strong cassiterite mineralization within the later chlorite veins is usually related to open space filling and typified by a lack of post-deposition reactivation. Early work noted the importance of dip-slip (normal) movement, whereas recent studies stress the role of strike-slip faulting during vein formation. This difference may be explained by the fact that the veins studied by Taylor were at higher levels (above 260 fm level) than recent work (below 260 fm level). The veins were dominated by the fluorite-chlorite assemblage as opposed to the tourmalinitic assemblage, a feature also noted by Dines (1956). The two sets of observations represent distinctly different stages of the paragenesis which formed under contrasting structural regimes. In reality the structural complexity of the veins testify to their prolonged, multi-stage development under differing stress regimes.

Within South Crofty it is noticeable that the width of the fracture sets containing each stage of the paragenesis is related to depth. The tourmaline vein on the Dolcoath South Lode 290 fm level is less than 1 m wide, whereas 200 m below a similar vein in the No. 8 Lode 400 fm level is sometimes over 3 m wide. The deepest stoped horizon near South Crofty, and in the region, was on the 550 fm level of Dolcoath Main Lode (Dines, 1956). At this level the tourmalinitic lode varied in width from 5 to 30 m. Some spectacularly high grade oreshoots were encountered, but were both small and few in number.

The sulphide-rich chlorite veins are generally found at higher levels in the mine. On the 360 fm level the Roskear A Lode chloritic vein is over 2 m wide, whereas 70 m below the same vein is less than 0.5 m wide on the 400 fm level. These observations account for the upper "copper-chlorite zone" and the lower "tin-tourmaline zone" in the Dolcoath Main Lode (Dines, 1956). This zoning is attributed to pressure-temperature regimes along the granite/killas contact, and is supported by fluid inclusion data which demonstrate that the deeper tin zone is related to generally higher temperature fluids (Scrivener *et al.,* 1986).

Wheal Concord Blackwater

Wheal Concord (Figure 1) produced some 10,000 tonnes (1.4% Sn) of ore during an 18 month period (1981-83), closing finally in 1987. It worked a single exogranitic vein; Chynoweth Lode, though five others were intersected. The Chynoweth Lode is a complex east-north-east-trending, north dipping structure (30-

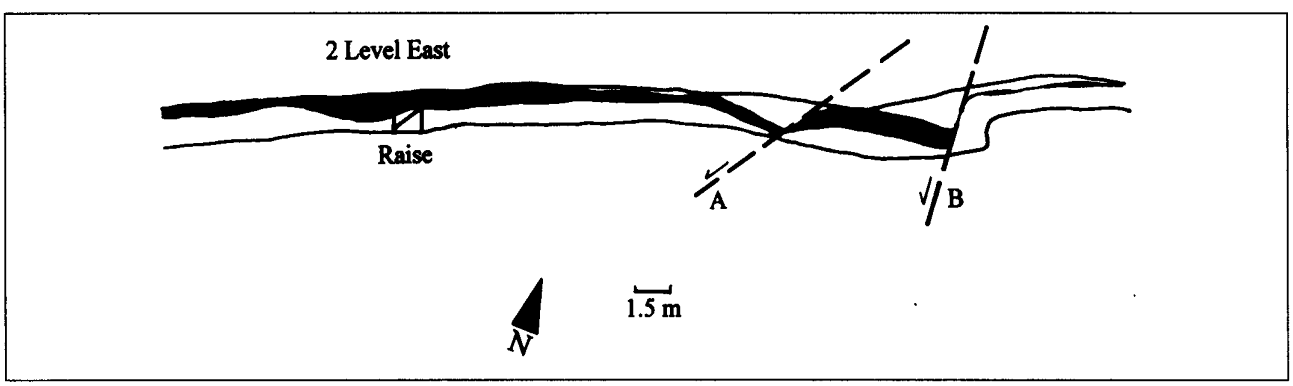

Figure 6: Plan of Wheal Concord Chynoweth Lode (2 Level East) showing "centre stope block raise "position and the pinch and swell nature of the vein. At the eastern end the vein is attenuated and changes direction around two faults (A and B), beyond the second fault (B) the vein became narrow and barren (Mapped by F. Rottenbury).

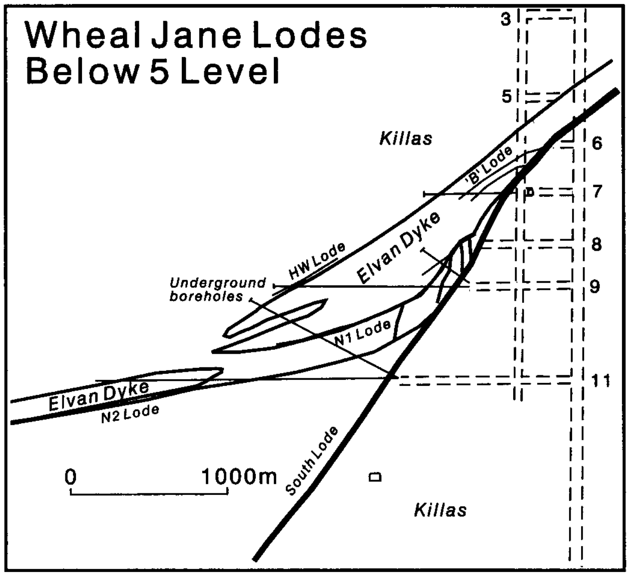

Figure 7: Cross-section through Wheal Jane from 5-11 Levels showing the relationship between elvans and vein structures.

45°) hosted within a 30 m wide pre- and syn-mineralization shear zone. Mineralization varies from pervasively tourmalinized metasediment to a tourmaline-rich vein with well defined walls. Veins comprise a breccia of tourmalinized metasediment with cement of quartz, chlorite, cassiterite and sulphides. Cross-cutting relationships testify that the tourmaline-cassiterite assemblage was of an earlier stage of vein development than the sulphide mineralization.

Along 2 level east a strong vein was followed for 75-80 m prior to intersecting two south-west-north-east-trending vertical pre-vein fractures (A and B, Figure 6). At fracture A the vein shows minor variation in strike and width. However, at B the vein narrows markedly, follows the pre-vein fracture for about, 1.5 m and then regains its previous strike. East of this intersection the vein is narrow (<0.5 m) and shows a gradual change in strike until it cuts a major clay-filled fault zone. Within the fault zone the vein forms a number of narrow en-echelon veinlets.

The 80 m section along 2 level east contained strong tin values along its entirety, the highest reported being 15% Sn over 2 m. This section was chosen for stoping which was preceded by the development of a raise in the centre of the block. The raise followed the vein up-dip for 30 m until it met the "Concord" fault which displaced the vein 8 m to the south. The raise continued on-vein further up-dip beyond the fault to the adit level above, however the grades in this section were patchy and the dip steeper (50°). The raise revealed that the vein pinches and swells up-dip prior to being cut by the fault. During stoping the high grades were encountered throughout the initial 30 m zone. The wider sections of the vein and associated foot- and hanging-wall stringers were found to be cassiterite-rich, overall the stope yielded a 1.4% Sn grade.

Elsewhere in the mine the complex nature of the mineralization is typified by strong but laterally and vertically impersistent veins, veins grading into narrow zones of alteration and/or vein networks and the displacement by faulting. The controls on ore localization are complex within the Chynoweth Lode, but a number of points become clear. High grades were related to a strong vein (e.g. >1 m wide), shallow dip (30°), east-north-east strike and where droppers and feeders were well developed. The dominant fault direction was reverse which accounts for ore localization on shallow dip sections. An interesting fact is that mineralization was often accomplished in one stage of brecciation, revealed by the presence of coarse cassiterite crystals encrusting host rock clasts. In these areas grades of 5-15% Sn were not uncommon. Despite localized high grades, the high discontinuity of the system compounded the closure of the mine.

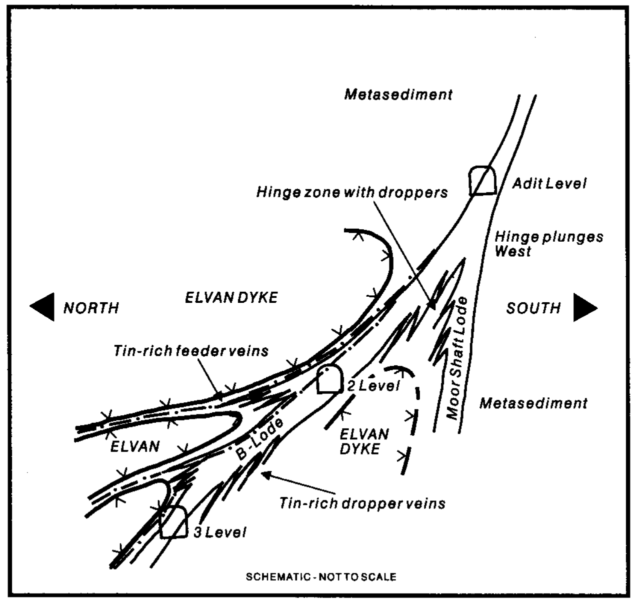

Figure 8: Schematic section of the Wheal Pane B-Lode between Adit and 3 Level showing the hinge of the B and Moor Lodes and the development of cassiterite-bearing droppers and feeders between 2 and 3 Levels. The footwall of the elvan dyke shows a faulted and irregular surface (Mapped by G.S. Camm).

Wheal Jane, Baldhu

Annual production at Wheal Jane amounted to about 190,000 tonnes at a grade of 0.8% Sn and 2.5% Zn prior to closure in 1991 (Figure 1). The mine worked a series of exogranitic veins associated to the footwall zone of a complex quartz-porphyry (elvan) dyke system (Figure 7). Within Wheal Jane two distinct vein systems are identified and were related to separate mineralizing events. The gently dipping North 1 and 2 Lodes were formed in normal shear and acted as centres for early greisen-style mineralization (quartz-cassiterite-muscovite-arsenopyrite) related to primary granite magmatism. They later acted as guiding structures for the emplacement of the elvan dykes. The steeper dipping post-elvan South Lode (including B and Moor Shaft Lodes) formed as a result of combined tensile and shear stresses contemporaneously with the intrusion of a later granite. The South Lode-type veins are characterized by altered and brecciated metasediments with cement of cassiterite and variable amounts of sulphides.

B Lode is a zone of brecciated slate and vein quartz mineralized by cassiterite and tourmaline with regions of massive pyrite and sphalerite. Breccia clasts are generally tourmalinized and wallrocks sericitized and weakly tourmalinized. A number of different ore types were reported, but the main tin mineralization was restricted to: (1) tourmalinized slate breccias; (2) quartz veined slate; and (3) highly pyritic slate breccias. The tourmalinized slate breccias, so-called A-zone ore, were the most productive, being 90% payable and with grades up to 8% Sn. A region of particularly strong mineralization is located where a flexure occurs in the footwall of the elvan and which hosts the hinge of the B and Moor Lodes (Figure 8). Within this zone mineralization to a thickness of 3-4 m occurs with the immediate elvan footwall contact marked by a 1 m thick sulphide horizon. Moor Lode dips 65° north-west below B Lode, attains an average thickness of 1.8 m and contains grades up to 1% Sn. The B/Moor hinge zone plunges west and appears to repeatedly flatten and steepen. The flatter zones were associated with dropper zone formation and contain payable grades, the hinge zone was approximately 45% payable (Figure 8). Between 2 and 3 Levels on B Lode, high grade mineralization was associated with chloritic shears as a series of dropper veins which carried 3-4% Sn (Figure 8). These features were almost certainly related to normal movement along the lode footwall.

South Lode commences just below 7 level, forming the ultimate footwall, where the B/M Lode splits into the South and North (1 and 2) Lode sections (Figure 7). These can be traced to the bottom of the workings 240 m vertically below. Between 7 and 9 levels the split hinge-zone shows an increase in thickness of up to 400% (2.5 to 10 m) and localized grade enrichment. The lode is hosted within slates, dips at 55° below the elvan dyke, strikes 055° and can be traced along strike for 1,300 m. Complex overprinting of minerals is present, though a broad progression from tourmalinization, to massive sulphide deposition and quartz-sphalerite veining is observed. Individual veins are steeper dipping, and terminate against the lode zone margins suggesting that mineralization developed as a series of en-echelon fractures within a normal shear zone. Below 9 level a medium-high grade oreshoot with low lateral and high vertical continuity plunges steeply down-dip. Some 75% of the oreshoot contained a grade of above 0.6% Sn and 45% above 1% Sn. The oreshoot is likely to represent the central region of the en-echelon vein zone and the lower grade region the tip of these veins.

The pre-elvan North 1 and 2 Lodes lie above South Lode from which they split on 8 level at a dip of about 45° (Figure 7). Within the complex hinge zone wider mineralization is observed with some increase in grade. The North 1 Lode lies below the elvan dyke footwall at a dip of 20° and below North 2 Lode continues at a similar dip in the slates. Both structures are less well mineralized than South Lode and are characterised by massive greisen mineralization overprinted with chlorite and cassiterite and minor sulphides. Tin grades in both lodes are restricted to steeply-plunging oreshoots which are related to wider zones and localized strike/dip variations. Overall both lodes were less payable than South Lode.

Early deformation related to the Variscan Orogeny resulted in the formation of north-west dipping low-angle fractures. These acted as "ground preparation structures" in which the North Lodes were deposited and later reactivated during elvan dyke emplacement. The elvan dyke system has been an important control in ore localization at Wheal Jane as it acted as a rigid barrier during later shear zone development of the South, B and Moor Lodes (Rayment *et al.,* 1971). Localized geometric variations in the footwall of the elvan resulted in orezone development during fault activity. Elsewhere the split of B/Moor and North 1 and 2/ B Lodes resulted in wider fracture zones and higher grade mineralization. The major South Lode displays a remarkably uniform distribution of tin values in its centre (75% above 0.6% Sn) which is attributed to mechanical re-mobilization (Holl, 1990). The North 1 and 2 Lodes display more restricted mineralization and poorer grades, and is explained by narrower fractures and the dominance of greisen-style mineralization.

Wheal Pendarves, Camborne

Prior to closure in 1987 Wheal Pendarves had an annual production of about 40,000 tonnes at a grade of about 0.6% Sn (Figure 1). Veins locally contained higher grades than 0.6% Sn, however the stopes were prone to high additional dilution during mining. Production was based on two granite-hosted lode zones; Harriet and Tryphena Lodes.

The north-east-trending Tryphena lode zone dips steeply south-east and is composed of a number of separate sub-parallel veins (Dominy *et al.,* 1996a). The lode zone is dominated by the No. 1 vein, which was the principal economic structure associated with the smaller, less continuous Nos. 3, 5 and 6 veins. Mineralization is characterised quartz-tourmaline-cassiterite vein fill and pervasive wallrock tourmalinization, chloritization and hematization. Strong tin grades are often contained within the wallrocks related to either disseminated or veinlet bound cassiterite. The No. 1 vein is traceable for up to 800 m and varies in width from a few mm to about 3 m. Observation reveals that the No. 1 vein, along strike, is flatter in the central portion and steeper to the east and west, though local variations are common. The vein is inferred to be a normal fault since it displays steeply dipping swells connected by flatter narrower zones. In a raise linking 5 and 6 level west drives (vertical distance of 32 m) the vein commences at 80°, flattens to about 60° and thins (<0.25 m), and then steepens (75°) and thickens (1 m) before reaching 5 level above. Elsewhere, the vein flattens to 60° below 4 level west and steepens to 75° before reaching 3 level west some 45 m above. On the 4 and 5 levels east the vein divides into two separate structures with a series of en-echelon linkages running between the two. This region maintains strong grades principally because of the high density of mineralized fractures between to two veins.

In the western section of the mine on and above 3 level west a westerly dipping oreshoot is related to the granite contact. Stoping above 2 level west encountered the contact 10 m above the level, at which point the vein dip changed from 70°S to 45°N, narrowed and became barren. However, after further up-dip development the vein was found to strengthen, increase in dip and contain high grade values away from the contact zone. On the western drives the Tryphena Lode intersects a north-northeast-trending, 20-30 m wide quartz-porphyry elvan dyke. On entering the dyke the structure maintains its overall width, but develops into a network of thinner veins, shows a small change in strike and contains strong cassiterite mineralization within wallrocks (e.g. dyke) and veins.

The north-east-trending Harriet Lode is a 50-60° south dipping structure up to 2 m in width traceable for about 600 m. Mineralization is characterised by a series of narrow veins in-filled with a cassiterite-chlorite-tourmaline assemblage. A number of strike changes are observed along the structure (e.g. 5 level east), the resulting short north-north-east-trending sections are characterised by vein thinning (<0.5 m) and impoverished tin grades. Elsewhere the lode intersects a number of 1-3 m wide, shallow, south dipping (20°) elvans but maintains its course and structure.

The strongest veins at Pendarves are observed within the granite, as the contact is approached the veins break up and eventually thin and die out within the killas. Local effects of elvan dykes range from minimal to extreme break up. The major oreshoot control in Tryphena Lode appears to be the dip of the vein, where steeper regions correlate with high grades and widths, in accordance with normal fault movement. Variations in strike along Harriet Lode result in vein and grade reduction. The north-east lode zone parallel fractures are stronger in terms of both width and grade. Branching of Tryphena Lode results in the localized widening of the overall structure by the development of higher density well mineralized fractures. The granite/contact exerts some control in the western section of the mine where a west plunging oreshoot is observed in Tryphena Lode.

SUMMARY

Controls on ore localization are complex and related to the many stages of structural reactivation that are present within a vein. The work presented demonstrates localization involves a number of variables including host fracture geometry, lithology and physio-chemical conditions of wallrocks and fluids. The most effective way to study these controls is through careful field observation, however this is not always possible particularly where workings are inaccessible. Historical production data including mine plans, longitudinal- and cross-sections provide particularly valuable information.

The endogranitic systems typified by South Crofty and Wheal Pendarves represent lode zones in which mineralized fractures are associated with pervasive wallrock alteration. Within South Crofty localization is related to spatial changes in strike and wide sections of the vein that are oriented parallel to the lode zone trend. The lode zone parallel sections represent specific structural domains which were activated at different times within a shear regime. Moderately plunging oreshoots correspond to the line of intersection between Reidel fractures generated during vein reactivation. At Wheal Pendarves variations in dip related to normal faulting exert a strong control where steeper/wider sections of the vein are most productive. Similarly localized changes in strike resulted in vein and grade diminution. Vein branches within the lode zone gave rise to some orezones because of a higher density of mineralized fractures.

The exogranitic systems typified by Wheals Jane and Concord are related to a proximal granite source from which ore fluids were expelled. Ore localization at Wheal Jane is complex and in part controlled by the development of an elvan dyke system. This dyke post-dated the early greisen-style mineralization but exerted control on later mineralization along its footwall. Local controls are related to vein branching and variations in strike and dip. At Wheal Concord vein formation was related to a series of syn- and post-mineralization faulting events which resulted in oreshoots with limited lateral and vertical extent. The dominant control on localization was reverse faulting where high grades were restricted to shallow dipping wider zones.

The concept of ground preparation, local changes which will later favour ore deposition, is uncommon in south-west England. Examples include alteration phenomena, faulting/fracturing and bedding and/or cleavage. In the south-west ground preparation phenomena are noted in both exo- and endo-granitic systems. Within South Crofty the lodes zones were related to the reactivation of post-granite joint sets and in Wheal Jane the low angle lodes (e.g. North 1 and North 2 Lodes) were hosted by pre-granite Variscan structures. Exogranitic mineralization in mid-Cornwall (e.g. Parka and Gaverigan) and Wheal Vor was in at least part controlled by bedding and/or cleavage planes.

Geological understanding is essential in the exploration, evaluation and development of any vein mine (Dominy *et al.,* 1997; Dominy *et al.,* 1999). The controls defined in south-west England are applicable to vein-type deposits world-wide. Research by the authors note similar localization phenomena in gold and lead-zinc veins of Scotland and Wales (e.g. Dominy *et al.,* 1996c).

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