The application of computer software to orebody modelling and evaluation at South Crofty tin mine, Cornwall

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Abstract: The orebodies at South Crofty take the form of a series of steeply dipping composite fissure-veins/lodes in the classic style of this mining district. Extraction is underground. The tin bearing lodes belong to the ENE-striking series. Cassiterite mineralization is in two main stages characterized by tourmaline and chlorite gangue respectively. The paragenesis and distribution of this mineralization appears related to the structural evolution of a lode, or group of lodes.

There are two main groups based on lode composition. The first contains relatively simple veins whose dominant gangue is blue/black tourmaline, and which have limited wall rock alteration. Cassiterite mineralization is associated with a later quartz brecciation of these veins. The second group has a more obviously complex paragenesis with the development of a series of quartz and quartz-haematite phases. Cassiterite mineralization in this group is associated not only with tourmalinite veining, but also with a chlorite-fluorite event. Wall rock alteration, often haematite dominated, is often extensive.

In structural terms, both groups of lodes appear to have evolved in a similar manner, initially, with the lodes dividing in an en-echelon style. Division is limited to recognizable zones. Intralode shearing and open space mineralization, however, characterizes only the second group, where the tourmaline element of the lode zone may be lost as a result.

The resulting distribution patterns of cassiterite mineralization for these two groups are broadly elliptical when viewed in longitudinal projection.

A differing style of orebody is also present. These are zones comprising a series of relatively small flat lying veins together with replacement mineralization, making up steep 'dipping' sub-cylindrical bodies. Cassiterite belonging to both tourmaline and chloritic phases is present.

These distributions can be successfully modelled by computer. This is essential for grade prediction where information between mined levels is absent. In this example, SURPAC was used, enabling a powerful combination of string modelling techniques, together with a geostatistically produced block model. This last is computed using inverse-distance weighting with ellipsoidal search envelopes.

Within the lodes, variation in the elliptical pattern is accounted for by modelling of differing trends, followed by extraction from each model using string intersection. The results are then combined into one model in longitudinal projection. Block grades are simply calculated by overlaying the block pattern, as string shapes, with resulting grades. Geological or mining reserves can be calculated using the same method.

Further modelling is required for the mineralized zones. This is achieved by using string structures and 3D visualization for sections through the orebody. These are defined from a combination of diamond drilling and interpretation. The use of strings ensures the original data co-ordinates are honoured. A three-dimensional triangulated surface is formed over these cross sections, with interpolation between sections controlled by the geologist. Zones of differing grade within the orebody can be similarly modelled. Volumes are simply calculated. The 3D model may contain proposed or existing underground workings, in addition to the orebody model. The complete model is then sectioned in a chosen orientation. These sections are used to enclose grade data held in a geostatistically calculated block model to complete grade calculations.

Production of both tin and copper from South Crofty dates back to the earliest days of Cornish mining, with underground extraction well under way during the seventeenth century. Dominantly a copper producer until the late 1800s, output from the mine became almost exclusively tin as the mine deepened into the host granite. The mine itself lies in the heart of the Camborne–Redruth mining district, amongst the relics of the famous Dolcoath, Carn Brea, Tincroft and East Pool mines in this most productive region of the Cornubian orefield.

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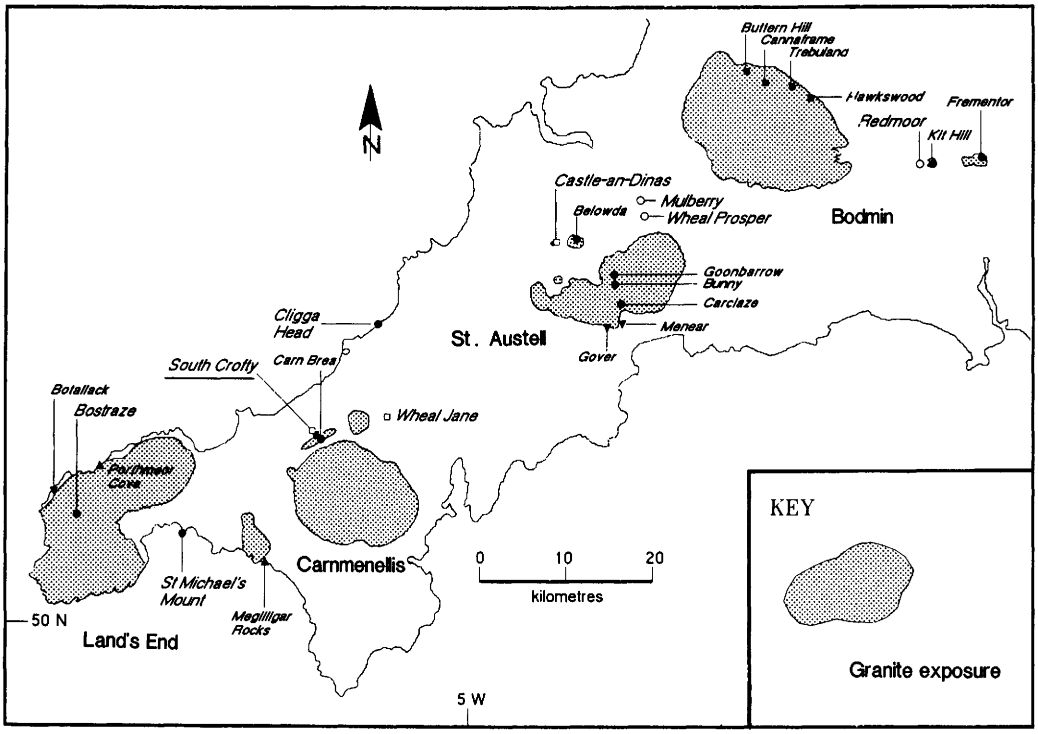

Fig. 1. South Crofty in relation to the granite intrusions and other sites of mineralization.

This practically based study is divided into two parts. The first describes the nature of the cassiterite mineralization at the mine, as applicable to the assessment and interpretation of the orebodies as mineable resources. The second describes the application of the SURPAC mining software system which has been in use at the mine since November 1988, for labour saving functions, resource estimation and orebody modelling and interpretation.

Mine geology

Figure 1 shows the position of the mine in relation to the main granite intrusions, and other sites of significant mineralization directly related to the granites, of the southwest region.

Figure 2, an adaptation from a compilation by Dines (1956), shows details of the main geological structures and associated mine workings on the Carn Brea granite ridge which itself lies on the northern flank of the Carnmenellis granite. The two are known to be connected at depth. The granite intrudes the Devonian Mylor Formation, a series of metamorphosed slates and greenstones collectively known as 'killas', and both are cut by E–W-trending, northerly dipping quartz-feldspar porphyry dykes or 'elvans'.

The earliest stage of mineralization recognized is represented by swarms of quartz veins (or floors) which are locally concentrated in zones. The current mine workings lie on the ENE–WSW-trending, steep-dipping, sub-parallel ore bearing veins or lodes within the granite. It is these lodes which form the dominant subject for this study. Earlier production, particularly that of copper, was derived from workings within the overlying killas, not only from the ENE group of lodes, but also from the so-called 'caunter' veins which have a trend similar to that of the elvans. Both the tin lodes and caunter veins are sub-vertical, dipping to both north and south as depicted in Fig. 3, which also illustrates the northward dipping killas/granite contact. A series of faults, locally known as 'cross-courses', make up the last major geological feature of the area. Again sub-vertical in dip, they lie normal to the lode orientation. The extent of displacement of the lodes by the cross-courses depends on cross-course type, as discussed below.

Mineralization and structural evolution of the Cornish orefield has been excellently described

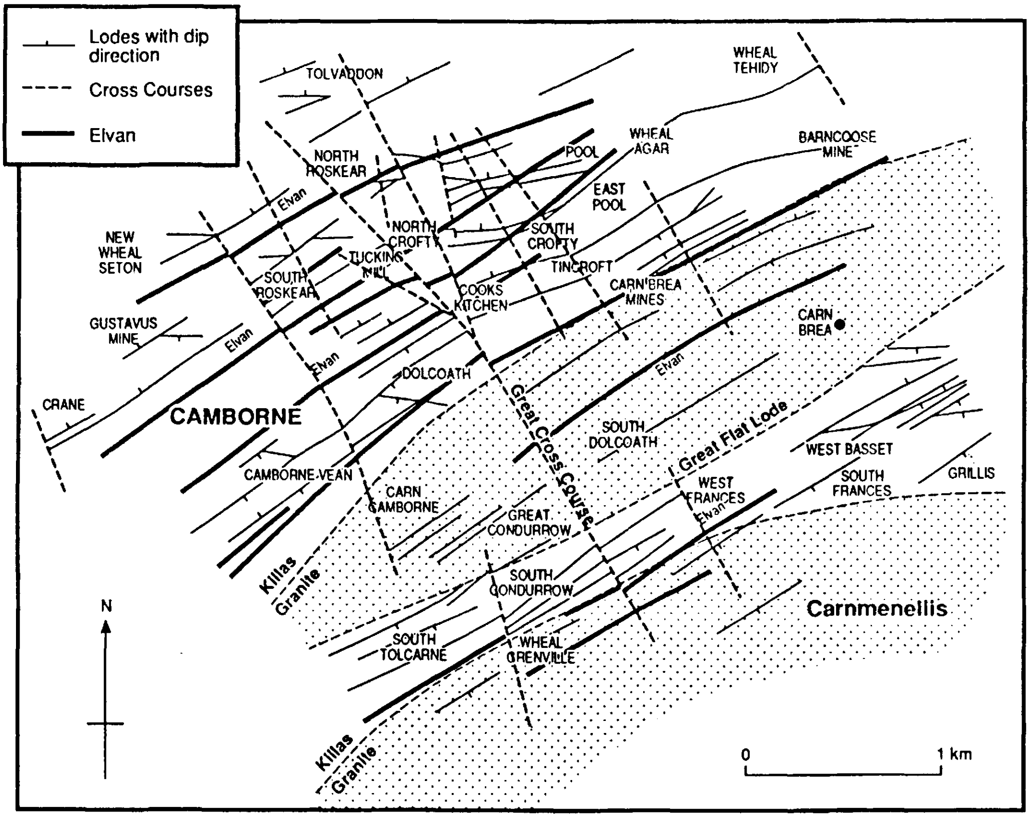

Fig. 2. South Crofty in relation to the main geological features of the locality and historical mine workings.

elsewhere e.g. Bromley (1989), Farmer & Halls (1990), Bromley & Holl (1987), Halls (1987), Allman-Ward *et al.* (1982) and Hosking (1964). The main stages of hydrothermal paragenesis related to metalliferous evolution and grade evaluation at South Crofty can be summarized as follows, based on personal observation and with reference to the above works.

The paragenesis can be attributed to the two distinct phases observed elsewhere in the region (Bromley 1989). The first is the greisen phase which is represented by the quartz floor mineralization. This consists of multi-directional, flat-dipping, veins of limited lateral and vertical extent. Locally they are grouped into zones in which a high concentration of veins exists. These zones are recognizable entities and it can be shown that they are arranged in sub-cylindrical bodies which are steeply 'north dipping'. This phase can be subdivided into three sequential sub-phases based on simple cross-cutting relationships. The first is represented by a pegmatitic assemblage of quartz, K-feldspar and tourmaline with vein widths not exceeding 0.2 m. Relatively few of these veins are observed, and are often indistinct from the granite, with granitic feldspars frequently seen crossing the vein margins. The second phase is represented by quartz and K-feldspar veins which rarely exceed 0.4 m. It is these veins which form the dense 'core zones' where the quartz floors are most concentrated. The third phase consists of veins which typically show a quartz-feldspar, wolframite arsenopyrite/lollingite assemblage, with the wolframite partly altered to scheelite. Chalcopyrite is occasionally present with rare stannite. Cassiterite may be present, although this may be as a result of reactivation, see also discussion below. These veins show further differences in the nature of their distribution. Rather than being present as many minor veins, they form a series or stack of more substantial, laterally persistent veins of shallow, often southward dip, and are up to 1.0 m in width. A number of veins of this composition also show a dip and orientation similar to that of the main tin bearing lodes (although less extensive in strike and dip), e.g. the Quartz Lode in the North Pool

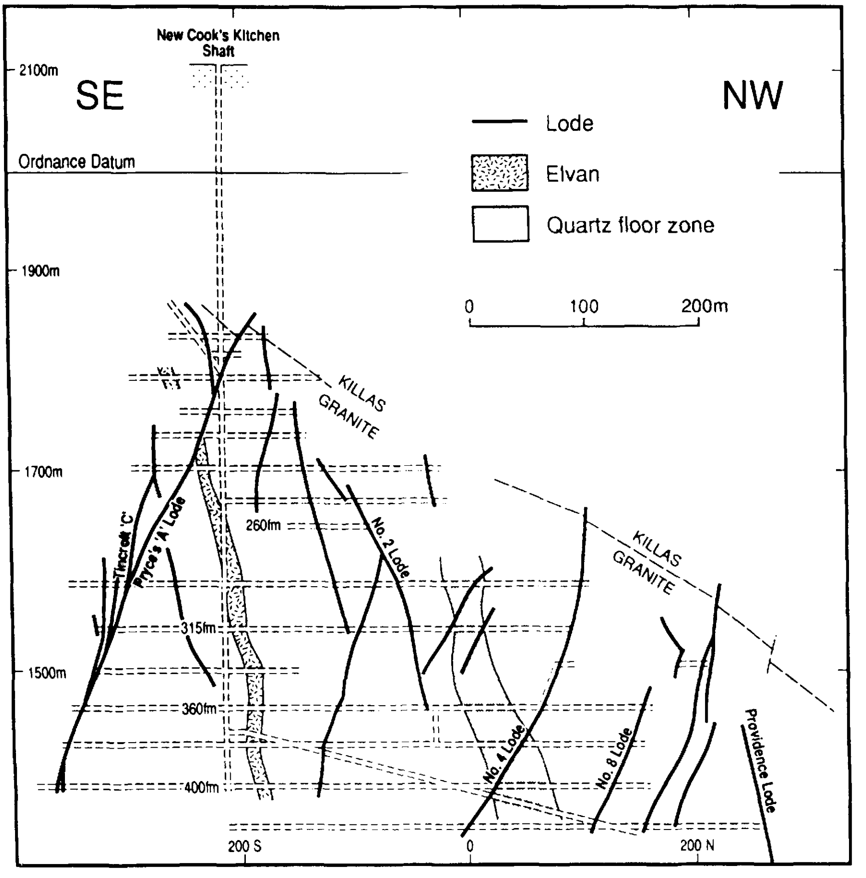

Fig. 3. Vertical section through the mine workings and geology looking west.

area, the Roskear Complex lode in Roskear, and also south of the No. 2 Lode in the Robinsons shaft area, and might be considered as transitional in nature. It should also be noted that a number of veins are recorded as a 'Quartz Lode' in the mine area as a whole, suggesting that a series of these veins are present in the region.

The second major paragenetic phase is that of the tourmalinite breccia mineralization, which contributed most of the cassiterite mineralization and thus the mineral wealth of the mine. This phase itself may be divided further into a tourmaline and then chlorite phase (Bromley & Holl 1987; Farmer & Halls 1990).

Successive pulses of boron-rich fluid propagated through the cooling upper granite in a series of hydraulic events and resulted in the emplacement of a vein, or series of veins, together with pervasive tourmaline replacement of the associated wallrock to form the lode zone. Brecciation within the zone, together with cataclastic textures displayed by the tourmalinite veins, bears witness to the turbulent and rapid nature of formation. Cassiterite is present in association with a quartz brecciation event (or events) of these veins, and occurs as rounded grains or in minor veinlets. Where high grades occur, cassiterite forms a groundmass to tourmalinite clasts.

The chloritic mineralization is generally seen as having been more passive. It is confined to the feeder channel and zones of weakness related to the tourmalinite phase, where the cassiterite occurs as growth zoned crystals indicating a less rapid crystallization than was the case for the tourmalinite phase described above. Fluorite is also associated with this phase. There is some evidence that tourmalinite lodes pass gradationally upwards into chlorite dominated lodes, as demonstrated by the No. 4 Lode and the distribution of mineralization in the North Pool mineralized zones. This suggests that the distribution of chloritic mineralization, as demonstrated elsewhere in the region, may be influenced by proximity to the surface and therefore groundwater mixing. All of the lode zones exhibit both of these paragenetic phases to a greater or lesser extent.

Later additions to the mineralization of the lodes is also present, and dominates the appearance of some lodes. This takes several forms. Firstly hematite replacement, where chloritic replacement of the granite and chlorite vein elements are wholly, or partly, replaced by hematite. Cassiterite is retained, at least in part, together with quartz. Secondly, chalcedonic quartz may be present together with fluorite, marcasite and occasionally chalcopyrite. This last type also occurs as an infill in fissure-fill type of cross-course.

The lode zones thus formed occupy fissures of considerable strike and dip extent exceeding 2.5 km and 0.4 km respectively in some instances.

Whilst the steep-dipping composite lodes form the majority of the resource at the mine, a differing style of orebody is also present where zones of quartz floors (the greisen phase) are invaded by elements of the tourmalinite phase of mineralization. The quartz floors can be seen as playing a 'ground preparation' role in terms of fracturing of the granite host, and orebodies thus formed are of two types. Firstly the '3ABC' complex. In this area, a series of the lodes, notably the No. 2, No. 3 and branches, converge within the core of one of the quartz floor zones. The concentration of lodes, together with anastomosing veinlets dispersed through the quartz floors and granite, combine to form a viable orebody. The second type is represented by the North Pool Zones where quartz floors are invaded by tourmalinite mineralization and where there is also extensive replacement of the granite. The style of mineralization varies with depth in these mineralized zones. At depth, a series of the more massive quartz floors (of the third phase as described above) are extensively invaded by dominantly tourmalinite and cassiterite phases with relatively minor replacement of the granite. At higher levels (i.e. 'up-dip' within the zone) massive quartz veins decrease in importance and tourmalinite and chloritic replacement of the granite, with stringer mineralization, becomes dominant. The downward transition to quartz floors lacking invasion by tourmalinite and cassiterite is, however, rapid. From the above, it follows that the contained cassiterite of the Quartz Lode, also present in the North Pool area (see above), is likely to result from reactivation (rather than belonging to the greisen phase), although little or no tourmaline is present within this lode.

Spatial distribution of structures and structural considerations

Before considering the evaluation of the amount of contained cassiterite within the lodes and orebodies, it is necessary to describe briefly some of their structural features and distribution which may, or may not, affect that evaluation. Further relevant and detailed structural observations at South Crofty have been made by Farmer & Halls (1990).

The first of these features is the cross-faulting, or cross-courses. Figure 4 schematically shows some of the major lode structures either side of the Great Cross-course, which is a series of cross-faults which effectively divides the mine, and mining region, into two halves.

The cross-courses can be divided into two types, both of which are to be found within the Great Cross-course. The first is of the shear type, typically a sub-vertical zone of intense kaolinization within the granite which accompanies narrow shear structures. The shear may have a core section, and where present, has been shown to contain clasts of tourmalinite type vein material complete with cassiterite, as a silica cemented fault breccia. Large displacements may accompany this type. Observation shows an overall lateral lode displacement either side of the Great Cross course of some 60–80 m in the northern part of the mine between the 380 and 420 fathom levels. This assumes correlation of the No. 8 and Roskear A Lodes, and No. 4 and Roskear B Lodes either side of the fault zone. The No. 8 Lode has been shown to exist as short strike length blocks lying between the component faults of the Great Cross-course. The faulting appears to be of a scissor type, with blocks successively downthrown on the western side, with the centre of rotation located at an as yet undefined point south of the current mine workings. Overall downthrow at the northern end is of the order of 120–170 m. The second cross-course type is one of infill, whose mineral content is described above. Displacements on this type of cross-course are minor, rarely amounting to more than a few metres. These observations lead to the conclusion that at least cassiterite resulting from the tourmalinite breccia phase was in place before this phase of faulting, and that, unlike Geevor Mine in west Cornwall (Garnett 1961), the cross-courses had little influence on this phase of tin distribution within the lodes. In summary, grade distribution is only affected by cross-courses with significant throw, and these can be defined and modelled.

The second feature which affects observed grade distribution is the scale of intra-lode,

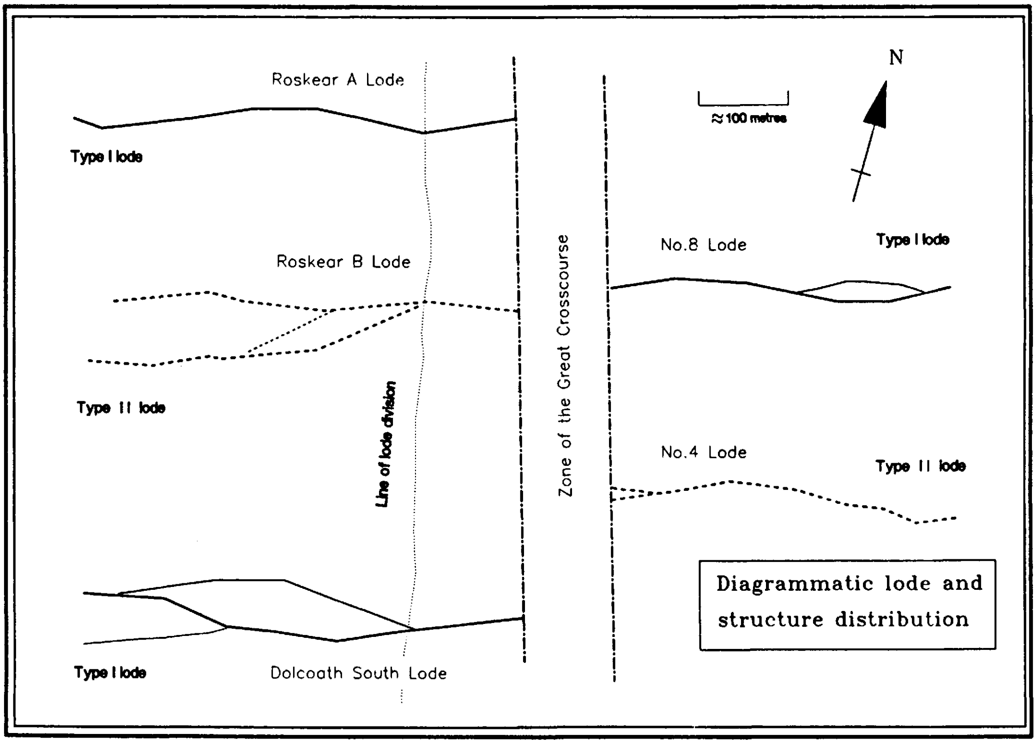

Fig. 4. Features of lode and schematic structural distribution.

strike-slip shearing. Those lodes showing greater proportions of hematite replacement, with perhaps quartz and fluorite infill, generally exhibit a greater degree of intra-lode shear. The dominant effect of this feature is the disruption of, and reduction in width of, the tourmalinite portion of the lode zone, with of course, potential loss of associated cassiterite. The presence of quartz and fluorite further dilutes the potential value of the lode zone. This shearing can be seen to post-date some of the lower temperature mineralization, displacing as it does the infilled cross-courses, which have themselves cross-cut and perhaps displaced the earlier high-temperature mineralization.

A third feature which appears to have little effect on the observed distribution, and is thus taken into account only in terms of vein correlation, is a large-scale zone of lode division (Fig. 4). Here, lodes of both types start dividing westwards along a line which effectively runs parallel to the cross-courses. Division is to a greater or lesser extent dependent on lode type and occurs over a strike length of some 400 m before closing again along a line which runs sub-parallel to the first. This feature seems to have more to do with the development of a lode zone as a structure, with mineralization, in terms of density of veining and/or replacement, developing within the division zone according to lode type. Each lode zone possesses a hangingwall and footwall vein which effectively form the limits of the lode zone, and might be interpreted as limits of a shear zone. These limits may, or may not, be significantly developed as veins. The veining contained within these limits can be seen as tensional gash type veins, arranged in an en-echelon fashion, being effectively vertical and of limited dip and strike extent.

Evaluation of the lode structures

Classification of lode types

For production-oriented evaluation purposes, the lode zones were divided into two types based on mineral composition and observed tin distribution. Thus the lode zones composed mostly of the tourmalinite phase of mineralization are considered to be Type I lodes, while those showing higher proportions of hematite replacement, quartz-fluorite enrichment and shearing are defined as Type II lodes. The latter show greater development of veining and replacement within the division zones as described above. Table 1 shows the classification of each of the lodes.

Table 1. *Classification of orebody types at South Crofty*

Classification	Lode name
Type I lodes	No. 1 Lode
	No. 3 Lode and branches
	No. 6 North Lode
	No. 8 Lode
	Dolcoath South Lode
	North Lode
	Roskear A Lode
	Roskear minor lodes?
Type II lodes	No. 2 Lode
	No. 4 Lode and branches
	No. 6 Lode
	No. 9 Lode
	Dolcoath North Lode
	Pryces–Tincroft Lode and branches
	Roskear B Lode
	Roskear D Lode
	Roskear South Lode
Caunter lodes	No. 7 or Reeves Lode
Mineralized Zones	'3ABC' complex
	'No. 2' complex
	North Pool

Collection of data

In order to assess payability/stopeability and localized strike changes of a given strike length of lode, the development of on-lode drives precedes that for haulages or extraction drives. Thus there is a lack of drivage close enough to development drives to allow drilling between drives on different levels at the density necessary to give representative results for such an assessment. Sample data used in the evaluation of the lodes is, therefore, collected almost exclusively from lode development, either drives or raises. The exposed vein and associated replacement mineralization in the on-lode development is chip sampled across roof and side-walls at 3 m intervals normal to strike. Where the footwall and/or hangingwall mineralization is not exposed over a significant drive strike length, diamond drilling is undertaken. Spacing of these fully cored evaluation holes is typically at 4.5 m centres. Spacings of 3 m did not give significantly more information regarding either grade or the position of contacts.

Initial assessment of lode zones

Once plotted, interpretation of the lode zone is undertaken to delineate the hanging and footwall limits in plan. The interpretation is a combination of the following factors:

(i) continuity of contained, not recoverable, Sn, with a cut-off grade of 1.0% Sn employed on an overall mining or reserve block basis;
(ii) geological contacts, e.g. a defined hangingwall structure with perhaps a known plane of weakness on the contact;
(iii) mining considerations, principally lode continuity i.e. divisions or displacement of structure and minimum mining width.

The latter is dependent on the planned mining method for a given area of a particular lode; the two mining methods employed are overhand shrinkage and longhole open stoping.

The next procedure is the compositing of the sample and drill data to produce a single, length-weighted average of contained cassiterite at approximately 3 m intervals along a given drive, usually coincident with chip sampling locations. The calculation combines chip sample and diamond drill data, in such a way as to take into account the factors outlined above. The horizontal measured width is then converted into true width based on lode dip for the sampled area. For planned shrinkage stoping areas, a minimum mining width, i.e. compositing width, of 1.0 m is applied. Thus a lode or vein of less than this minimum width is diluted accordingly. For longhole open stoping areas, a width of 1.5 m is used for the Type I lodes, and 2.0 m for the Type II lodes where the hangingwall contact is typically less competent.

Grade-cutting is applied to individual chip or core samples and not to the overall composited grade derived at a given sampled location. This is not to smooth data, but rather to reduce the influence of anomalously high sample values in subsequent grade estimation. The ceiling grade used for this exercise is determined by a combination of statistical assessment and geological observation. Statistical assessment is made principally by examination of the frequency distribution of individual values. This is modified by taking into account the lode geology in relation to the observed grade distribution. Thus in areas of known high frequency of higher grades, a higher cut-grade would be applied which is selected on the basis of frequency distribution in a defined zone.

The end result of this process of sample collection, interpretation and compositing is the production of a longitudinal projection for a given lode showing all composite data values. All further interpretation and reserve estimation is carried out on vertical longitudinal projections. As mining proceeds, additional sample data becomes available from shrinkage stoping to add to, and refine, the grade model of the lode.

Cassiterite distribution within the lode structures

Concepts of 'ore shoots' have been applied to the lodes by many observers of Cornubian geology. Collins (1912) uses a series of picturesque terms to describe various types of distribution, all based on the practical observations of the miners of those times, which are no doubt worthy of further study. The observations of cassiterite distribution made here may be in more detail, but the basis of their description is not so dissimilar from those made years ago. Taylor (1966) carried out detailed comparative studies of cassiterite content for a number of the lodes at South Crofty. He proposed concepts which might aid further exploration or development, but which were mostly based on the behaviour of individual ore shoots within a given lode. He seems to conclude that many of the ore shoots were steeply plunging, within the plane of the lode, and this view remained unaltered.

The interpretation made here differs from that made by Taylor, and was initially based on observation which was subsequently tested by mine development, either driving or raising, and occasionally by diamond drilling. Inspection of stoping patterns, both failed and successful, suggested that the distribution of zones of cassiterite enrichment were not sub-vertically oriented. Many stopes commencing in a zone of high cassiterite values rapidly became uneconomic with height, or showed a much greater proportion of low-grade ore within a given stoping block than would have been expected given a sub-vertical ore shoot. A study of the distribution of the composited values, using a hand contoured plot of indicator values for contained cassiterite, clearly showed that the distribution of the mineralization could be described by a pattern of ellipsoids which had a relatively flat plunge and that the distribution could be realistically applied across the lode as a whole.

Figure 5 illustrates simply such a distribution by defining low and high grade areas, the terms high and low being related to indicator values.

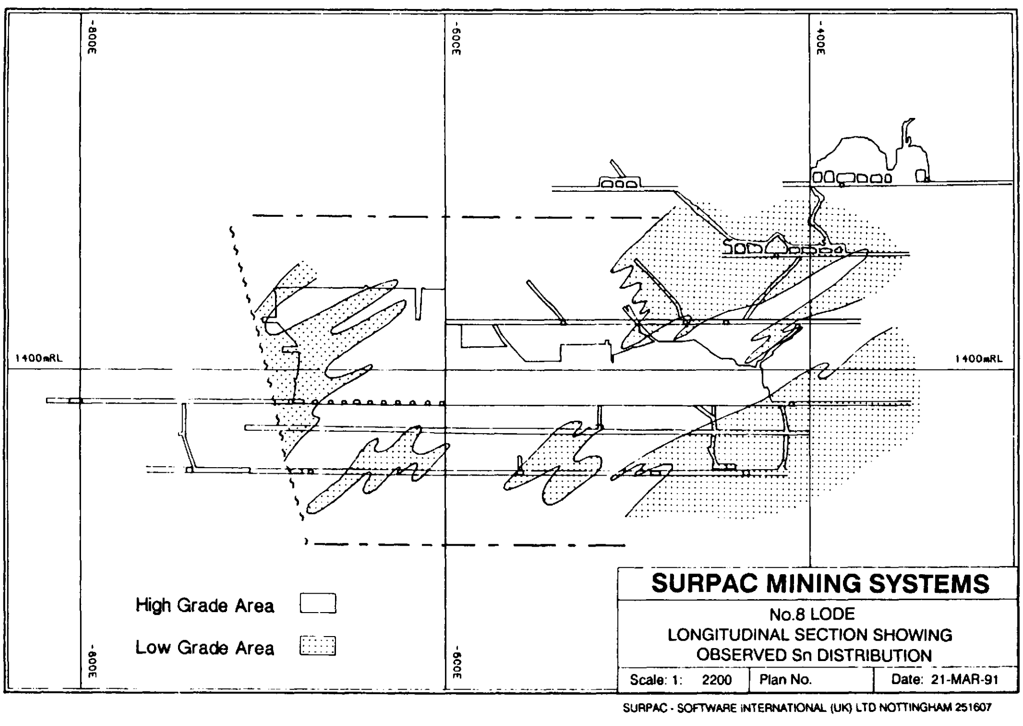

Fig. 5. Longitudinal projection of the No. 8 Lode showing the interpreted ellipsoidal pattern of cassiterite distribution.

The distribution pattern is truncated on the western side of the diagram by the eastern limit of the Great Cross-course, where the fault throw is significant. For the remainder of the lode to the east (and other lodes studied), the throw on the minor crosscourses is negligible.

The application of inclined ellipsoidal patterns can be satisfactorily extended to modelling of cassiterite distribution within the 'high grade' areas, and thus can also be used for detailed work. For those lodes that were studied in greater detail, the Type I lodes showed patterns of ellipsoids which had a plunge of some 40° from the horizontal and in a 'southwesterly' direction, whilst the Type II lodes showed a similar plunge but in a 'southeasterly' direction. With reference to Taylor's work (1966), it is interesting to note that his assessments were all of lodes which would fall into the Type II category.

Many workers have offered explanations as to the geological origin(s) of the distribution of cassiterite and/or associated copper, zinc, etc. which have varied from the descriptive (e.g. Collins 1912) to the detailed (e.g. Farmer & Halls 1990). The latter authors favour structural controls, with each paragenetic phase having a distinct structural setting. They propose that the differing paragenetic phases formed under different shear regimes and this may prove to be responsible for the observed distribution of cassiterite mineralization within the lodes. A more detailed examination of paragenesis and its relationship to grade distribution is beyond the scope of this paper.

Application of computer software

Computer software has been used in two roles at South Crofty; first, resource estimation and orebody modelling, and secondly, labour saving, with computer usage developing over a period of five or six years.

Resource estimation

Initially, LOTUS 123 spreadsheet software was used to gather sample data and composited data (calculated as described earlier) on a lode by lode basis, and still forms the vehicle for chip sample data collection. The composited values were mostly used to rapidly calculate length weighted averages for a specified drive length, as an aid to both the original method of resource estimation and the development of methods based on the ellipsoidal interpretation of cassiterite distribution. The sample data held on LOTUS 123 spreadsheets thus formed the basis for the SURPAC databases.

The original method of ore resource estimation relied heavily on the assumption that the ore shoots had a vertical orientation and simply used length weighted averages with little interpretation being applied to that estimation. As the concepts of ellipsoidal distribution developed, a system of weighting by areas of influence was used for estimation, as described in the following. In summary, this systematically gave a given drive length, having a length weighted average width and grade, an area of influence which was at least partly interpretive and allowed for the incorporation of low grade areas passing through an otherwise higher grade mining block. The width and grade estimated for a given reserve block was then calculated by area weighting for each component interpreted as forming part of that block. At this point, LOTUS 123 was used to calculate what then became a large variety of length weighted averages. Thus it became possible to utilize a method of estimation which could probably not have been achieved by hand calculation in the time available to complete the estimation process during the day-to-day demands of production. The application of geological interpretation to resource estimation became widely accepted, reflecting as it did, the known grade variation within the various lodes. Though computers were used to produce a better estimate of contained metal, this method proved laborious and time-consuming. This was mainly due to the manual construction or modification of the shapes of areas of influence within each proposed reserve block, and their area measurement. In addition, an increase in the use of longhole open stoping highlighted a need for faster and more flexible methods which still incorporated geological interpretation as part of the calculation. This arose from the need to more accurately predict likely broken grade from these stopes by estimation of the grades and tonnages of small blocks each representing perhaps a month's production. This emphasized the need to provide a greater spread of data points from which to estimate these small blocks. Thus preliminary studies were made of the ability of geostatistical methods to model the ellipsoidal ore distribution and to interpolate additional data points. For this to be achieved rapidly, the software used had to be capable of undertaking the entire process from beginning to end.

Geostatistics, as a method of estimation in the production environment, has not been widely applied within the Cornubian orefield, although a number of studies have been undertaken. This seems to be due largely to the difficulty of obtaining sufficient data/sample points to use for semi-variogram calculation, necessary to establish the parameters for geostatistical methods such as kriging. The use of in-ore drivage and development results in a highly linear pattern of sampling and thus reliable semi-variograms can only be produced in one orientation. As a result, inverse distance squared weighting methods were chosen for resource estimation using ellipsoidal search envelopes whose dimensions reflect the interpreted anisotropy of the ore distribution. The major axis of the search ellipsoid is orientated in the direction of the long axis of the interpreted ellipsoids of grade distribution, that is, approximately 'southwest' and 'southeast' in the longitudinal projection plane, for Type I and Type II lodes respectively. The ratio of major and semi-major axis lengths is used to emulate axial ratios of the grade ellipsoid. In that the veins are effectively reduced to two-dimensional orebodies when regularized on longitudinal projections, the minor axis of the search ellipsoid is of no importance. Because the search radius for the major axis of the search ellipsoid could not be set directly using semi-variogram parameters, the search radius was initially interpretive and experimental, trial and error being used to establish sufficient density of sample points between the development levels, with minimum smoothing of the data. Too much smoothing was felt to be undesirable as it was necessary to attempt to model the often rapid changes in grade over short strike lengths.

Labour saving

The choice of suitable computer software was not restricted to resource estimation using the methodology described above. Rather, software was also required to achieve considerable labour saving by performing a series of routine tasks largely associated with the programme of longhole open stoping. This mining method necessitated the construction of vertical cross-sections through development drives and orebody outline at a minimum strike interval of 3.0 m, the ring burden being 1.0 m. Fan drill patterns for the longhole drilling also had to be drawn every metre, together with calculations of tonnage broken. In addition, much of the diamond drilling effort was expended in evaluating the wider parts of the lode structures as described above. Thus a wealth of diamond drill data had to be plotted, together with associated chip sampling data, usually at more than one scale for interpretive purposes. All these tasks were performed manually, clearly consuming a great number of man-hours in simple repetitive activities.

Use of SURPAC mining software

A series of packages were evaluated, but few offered many of the facilities for the underground applications that were envisaged, being unable, for example, to produce sections through the workings, or indeed to simply pass data between geologist, surveyor and mine planner. The software also needed many geological capabilities, whilst retaining all the tools for the planner and surveyor.

The SURPAC mining software system fulfilled the needs of resource evaluation and labour saving described above, largely because of its use of 3D strings. The use of the string modelling system by SURPAC, as described by Porter (1979) and Miller (1987), offered a flexibility of data structure not found in the block modelling or gridding systems. Strings in their simplest forms are an ordered sequence of points with three-dimensional co-ordinates, with an identifier. Geographical features such as roads, rivers, contours, etc. can be easily and simply represented by strings. Underground, development drives, boreholes, orebody outlines, cross-sectional outlines and orebody models can all be represented by strings.

In that all the types of data can be accommodated by one data structure, sharing of data between the various technical departments of the mine is simply and rapidly achieved. Thus the surveyor's regular updating of the progress of both drives and shrinkage stopes allows a three-dimensional model of the workings of the mine to be continuously developed. These up-to-date models can then be directly used by the geologist, incorporating borehole or sampling data held in a SURPAC database, or using sections for geological interpretation. Similarly, the planner can take the survey model to compare actual with achieved development, or up-to-date plans can be simply and quickly prepared for mine officials. Further, the planner is able to take the combined survey and geological model of the workings and orebody and automatically design longhole drilling fans, calculate broken tonnages, etc.

The use of strings also meant that models of grade distribution could be created with considerably less data than that necessary for block modelling software. This is possible for two reasons. First, models can be divided into smaller units or layers, to be combined as required rather than held in one model, allowing individual components to be more detailed. Secondly, the modelling of the complexity of a structure or its grade distribution can be achieved using a string, rather than a large model of small blocks. The interaction of various string models provides a powerful method of evaluation and tools for further geological interpretation. This interaction is achieved by intersection of polygonal shapes. For example, a producing stope outline, defined as a string, can intersect the shape of the original mining block to calculate the remaining tonnage, or that same shape can be used to estimate the grade of the remnant block using the geostatistically derived grades. This is illustrated in Fig. 6 below. The same methods can be used to extract data, as grades or features represented by strings, from inside and outside shapes.

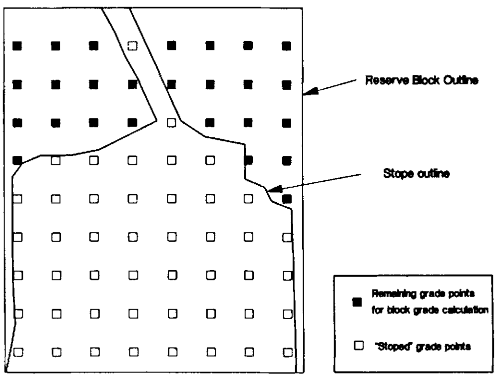

Fig. 6. Interaction of string and grade models: a working stope.

This feature can be used to overcome the problems encountered by smoothing of the data resulting from the geostatistical calculations described above. This tends to occur in areas where strong grade trends are not observed. In these cases, interpolated grades have a stronger bias than those actually observed and the distribution is over-emphasized. The solution lies in the creation of two models and their subsequent combination. First, a block model (still represented by a string) with pronounced anisotropy is created, followed by another where the anisotropy is much reduced. Secondly, the two models are combined in the following manner. Areas of either pronounced or weak distribution are identified by interpretation. These areas are then delineated as string features, either on screen, or by digitizing from a plan. These shapes can then be used to achieve a 'cut-and-paste' style of combination, i.e. the shapes delineating areas of pronounced distribution are overlaid on the grade model of weakly defined anisotropy, and the grades outside these areas are extracted, effectively producing a model with a series of holes. These same shapes are then overlaid on the grade model which was calculated to represent pronounced anisotropy, and the grades inside these areas extracted, producing a model which is a series of islands. Because the same shape was used for each process, combination is a simple matter, and indeed, much of the process is automatic. This is illustrated in Fig. 7 where Models A and B represent areas of pronounced and less well defined grade distribution respectively.

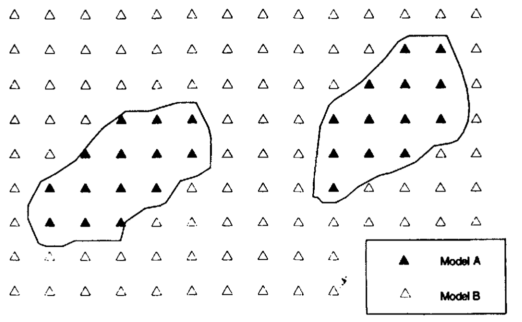

Fig. 7. Combination of grade models using string shapes.

Further applications

Once the software was fulfilling the needs for which it had been purchased, other applications were pursued. These largely took the form of illustration of the morphology of ore grade distribution of the lode structures or mineralized zones and their further interpretation. The first application was that of the production of contour diagrams of the grade distribution, for both illustrative and interpretive purposes as the time needed to produce a contour plan using manual methods was essentially prohibitive. The software's use of triangulated digital terrain models, their rapid generation and subsequent production of a contour plan, meant this was now possible, and the geologists interpretation of the lodes could be simply presented. This modelling technique constructs triangles between actual data points on the X and Y co-ordinates, with the contents of the Z field representing the highs and lows of the surface. Thus if cassiterite grades are substituted in the Z field, then the range of grades are modelled producing a contour diagram, as shown in Fig. 8, created from the digital terrain model.

The second application arises from a recent development within the SURPAC software in the form of true three-dimensional object

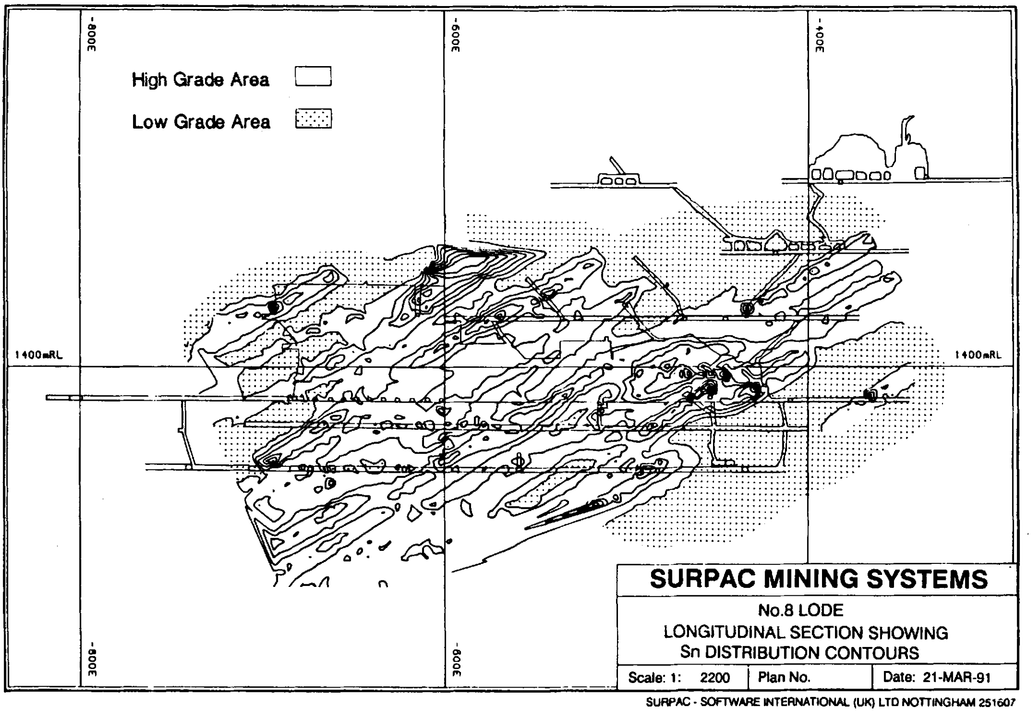

Fig. 8. Computer generated contour diagram from model of grade distribution.

modelling. This can be used to readily represent the style of orebody in a mineralized zone, such as the North Pool Zones described earlier, translating the geologists sectional interpretation into a recognizable object. This is of great value as the morphology of these zones is much more difficult to grasp when compared with the sheet-like structure of the lodes. These models are again triangulated between actual data points on the cross-sections, but three-dimensionally, rather than two-dimensionally as in the planar digital terrain model, with the sections forming a framework. The triangulation is interactive and allows for geological interpretation. This modelling technique can be also applied to the mine workings, and sections can then be taken through the complete object comprising orebody, development and stope workings, at any orientation. An example from the North Pool C Zone is shown in Fig. 9. Volume calculations for either void or solid can be made within the object.

In addition, further geostatistical work has been possible building upon the results of the interpretations and estimations described above. This has concentrated on initial attempts to establish semi-variograms in the orientation of the main development drives, as a reinforcement

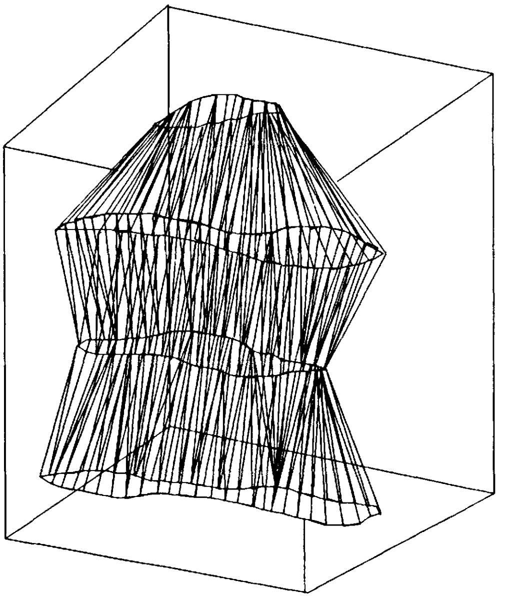

Fig. 9. Representation of complex orebody morphology using true 3D modelling techniques.

to interpretation, thus assisting in the estimation of search radii to be used in the inverse-distance

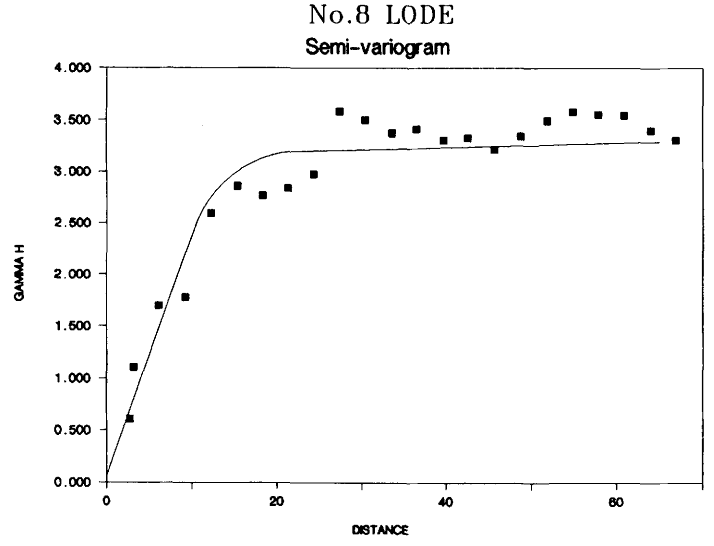

Fig. 10. Semi-variogram for the No. 8 Lode.

weighted calculations described above. This has met with some success. Figure 10 shows the semi-variogram for the No. 8 Lode, a Type I lode. This indicates an effective search radius of some 35–40 m, which matches well with observation. This semi-variogram also shows a 'hole effect' which conforms with the observed pattern of high and low grades within the lode brought about by the ellipsoidal distribution through which the drive passes.

Conclusions

Observation and study of the geology, and application of appropriate software, has provided many tools to achieve both labour saving and the desired style of resource estimation on inexpensive Personal Computers. This came at a time when efficiency and increased accuracy, flexibility and reliability of resource estimation were at a premium due to the collapse in the tin metal price following the failure of the International Tin Council.

Further work is inevitably required, and should concentrate on the relationship between lode paragenesis and structural regimes, and the ellipsoidal patterns of cassiterite distribution. It is envisaged that should such a relationship be established, and recent work by C. B. Farmer (pers. comm.) indicates that this could be the case, then geostatistical calculations could then be applied to localized sections of the lodes which conform to a particular style of paragenesis and thus likely cassiterite distribution. This probably represents a logical development of the 'cut-and-paste' work described above, and could lead to further accuracy of resource estimation.

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