

## CROSSCOURSES IN SOUTH CROFTY MINE, CORNWALL: FURTHER STUDIES OF PARAGENESIS AND STRUCTURE

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The east-north-east-trending composite tin-bearing lodes at South Crofty Mine are cut by a series of crosscourse structures. These crosscourses are hosted in sub-vertical, north-north-west—south-south-east to north-south-trending strike-slip faults that displace the tin lodes by distances from a few centimetres up to 110 metres. Two scales of structure can be recognised; i) broad zones of ramifying fractures and alteration, and ii) discrete quartz- and/or fluorite-filled extensional veins. The first type is characterised by zones of intense microfractures, argillic alteration and quartz veins. The main structure of this type within the mine is the Great Crosscourse which reaches some 100 m in width, with a right-lateral displacement of 110 m. The second type is more common, with fillings of quartz and chalcedony and variable amounts of fluorite, pyrite, hematite, chlorite and siderite. The extensional veins display massive to drusy quartz with banded and vuggy textures. The present studies have shown that the main lodes were reactivated after crosscourse formation which, in places, has resulted in the stepped displacements of the crosscourses. Fluid inclusion studies reveal homogenisation temperatures in the range of <100 to 175°C and salinities in the range <1 to 23 eq. wt % NaCl. Some inclusions contain a CaCl<sub>2</sub> component and are considered to represent basinal brines with CaCl<sub>2</sub>/NaCl ratios of about 1:1.2. The basinal brines are considered to have been derived from an adjacent sedimentary basin during strike-slip faulting.

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### INTRODUCTION

Late hydrothermal events in the Cornubian orefield are characterised by north-north-west- to north-trending silica-rich Pb-Zn-F-Ba-U bearing veins, known locally as "crosscourses" (Collins, 1912). These structures are economically less important than the main W-Sn-Cu bearing lodes, being representatives of an extensive system of faults and major fracture zones which are seen to cut, displace or terminate the main lodes. The crosscourses are variably mineralized and in places, have yielded substantial tonnages of Pb-Zn-Ag ores, fluorite and barite (e.g. in the Tamar and Teign valleys) whereas in the china clay pits they are characterised by quartz/chalcedony, iron oxides and kaolinite (Dominy, 1993). Throughout the orefield the main lodes are cut by thin clay-filled crosscourses known as "fluccans" which may displace them by up to 100 m, as at Penhalls Mine in the St. Agnes district (Dines, 1956).

South Crofty, located between Redruth and Camborne, is the only working metal ore mine in the county at present (Figure 1); it exploits a group of steeply dipping, east-north-east-trending composite cassiterite-bearing lodes which are cut by uneconomic crosscourse structures. There is evidence to suggest that some crosscourses may have existed at the time of lode formation and were later reactivated (Taylor, 1965a). The distribution of ore shoots within the lodes is not governed by their proximity to crosscourses, unlike the main lodes of Geevor Mine in west Cornwall which are known to post-date some crosscourse structures (Garnett, 1961). Similarly, Hosking (1974) reports that the formation of the Wheal Vor (Breage district) lodes was controlled by crosscourse reactivation. The general characteristics of the South Crofty crosscourses are well known from earlier studies (Taylor, 1965a/b; Scrivener *et al*, 1986) but variations in their structural development and paragenesis justify further detailed studies of vein mineralogy, structure and fluid inclusions.

This study is mostly concerned with structures exposed within the Roskear section of the mine on the 400 and 420 fathom levels and in the North Pool Zone on the 380 fathom level. However observations

from elsewhere in the mine are included where relevant.

### SOUTH CROFTY MINE MINERALIZATION

The main composite lodes of South Crofty are hosted in the Carn Brea granite which is part of the nearby Carnmenellis pluton. The geology and mineralization of the mine was described by Taylor (1966) and more recently by Farmer and Halls (1993). The author recognises four styles of mineralization, of which types 2 and 3 dominate the main composite lodes.

1. *Quartz floors.* These are early, flat-lying quartz veins with wolframite, arsenopyrite, lollingite and, rarely, stannite.
2. *Tourmaline veins.* These are dominated by thin black tourmaline net-veins (up to 5 mm thick), cut by blue tourmaline (or peach) veins (up to 3 m in width) which are cassiterite-bearing. The wallrocks are typically pervasively tourmalinized and may be mineralized with cassiterite. This style forms the dominant economic source of tin mineralization within the mine.
3. *Chlorite veins.* These were deposited during reactivation of stage 2 tourmaline veins. Some lodes are up to 3 m wide, are cassiterite-bearing and dominated by a chlorite, hematite, fluorite, quartz and sulphide mineral assemblage with wallrock chloritization and hematization.
4. *Crosscourses.* The crosscourses are vertical- to sub-vertical, north-north-west to north-south-trending strike-slip fault structures that displace the main lodes. Two scales of structure can be recognised i) broad zones of ramifying fractures and associated alteration and quartz veining, and ii) discrete extensional fractures with well-developed quartz, fluorite and chalcedony fillings.

### FRACTURE ZONE CROSSCOURSES

The fracture zone type of crosscourse is characterised by ramifying networks of intense microfractures and quartz veins with variable amounts of argillic and hematitic alteration. The main structure of this

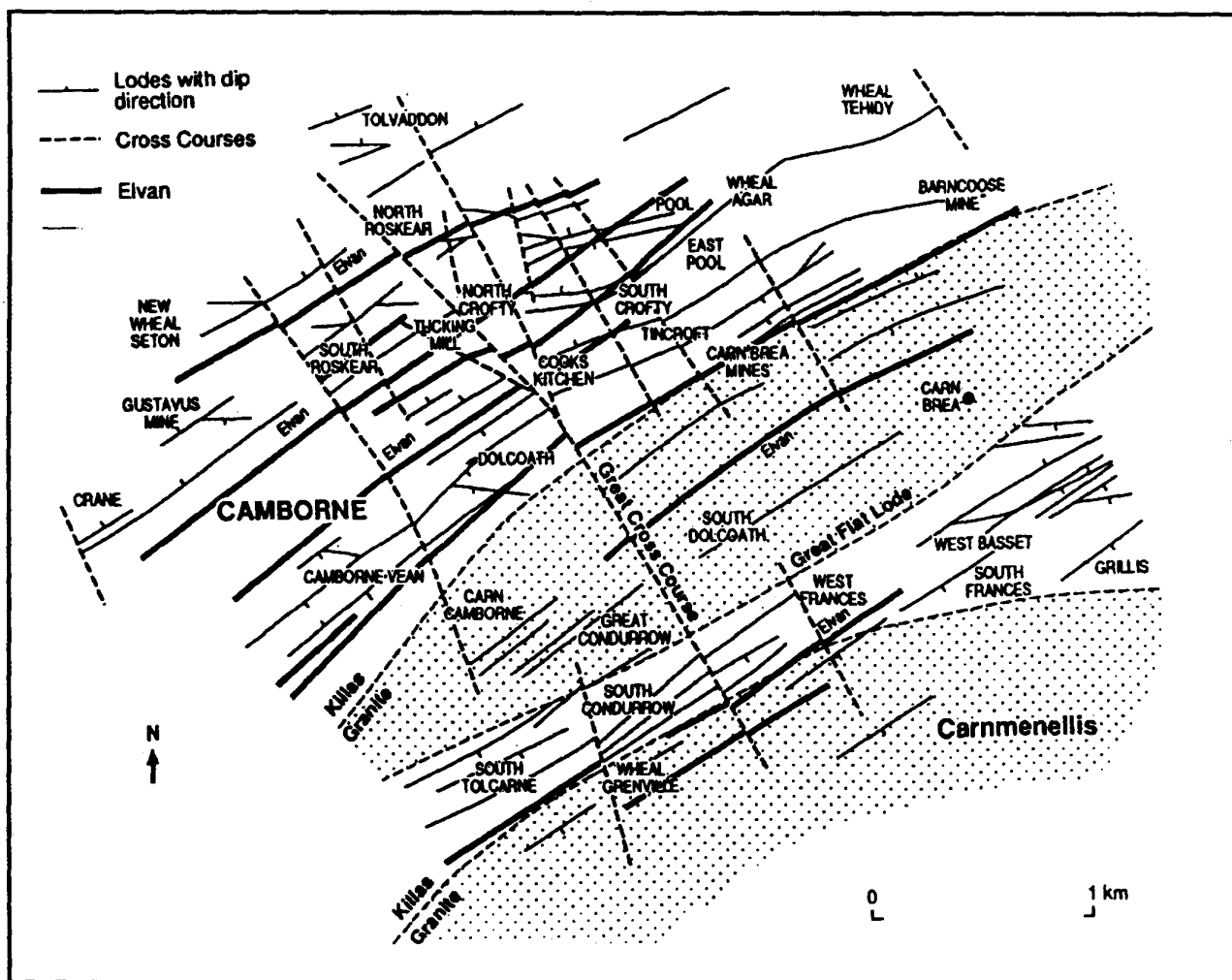


Figure 1. Relationships of the main features of the geology of the Camborne-Redruth mining area. The names of the old mines which now form South Crofty are retained and relate to the names of lodes within the mine. The Great Crosscourse is shown running from the northwest to the southeast. Diagram taken from Farmer and Halls (1993) and based on one of Dines (1956).

this type within the mine is the 100 m-wide Great Crosscourse (Figure 1) which effectively divides the mine and can be traced as a surface topographic feature for five kilometres. The Great Crosscourse shows an overall right-lateral offset of some 110 m due to a combination of strike-slip faulting and some rotational movement. This figure is based on the correlation of the No. 8 Lode to the Roskear A Lode and the No. 4 Lode to the Roskear B Lode. This displacement value agrees with the figure proposed by Taylor (1965a), the centre of rotation is located to the south of the current mine workings (Grabble, 1992).

The granite in the crosscourse zone has a ramifying fabric of microfractures as a result of brittle deformation. This fabric is locally cut by quartz-filled extensional veins which postdate the main fracture zone formation. The extensional quartz veins are found in a central core of the crosscourse and are associated with collomorphic silica-cemented breccias containing fragments of blue tourmaline vein.

Mineralogical studies (XRD) undertaken on the altered granite reveal that it contains up to 35% kaolinite, 5% smectite, 10% mica and the rest quartz and feldspar. The altered granite is variably red to yellow iron stained and is highly friable which gives rise to support problems in the levels.

Other fracture zone crosscourses include the north-north-west-trending Camborne Consols and Stray Park crosscourses. Where these cut the Dolcoath North Lode (315 fathom level) they are about 2 m wide with a lateral displacement of less than 1 m.

## EXTENSIONAL CROSSCOURSES

The extensional type of crosscourse fracture is the most widespread in the mine, with vein widths from a few centimetres to about two metres. These veins typically show a left- or right-lateral displacement rarely exceeding 2 m. A swarm of sub-parallel individual veins may be up to 4 m wide and show a lateral displacement of up to 6 m (e.g. the Red River Crosscourse cutting No. 8 Lode on the 425 fathom sub-level). There is little wallrock alteration associated with these veins except a small amount of local silicification and kaolinization. These fissures are filled chiefly by quartz and chalcedony, together with variable amounts of fluorite, pyrite, chlorite, siderite, calcite, hematite and mineral pitch.

Three main variants in paragenetic development of the extensional veins are seen:

- 1) Massive milky to clear coarsely-crystalline quartz with open drusy vugs and massive hematitic infill. The open druses are up to 20 cm wide with large euhedral quartz crystals (up to 5 cm long) covered with small siderite crystals and dustings of hematite and/or chlorite. The massive hematitic infill is attributed to vein reactivation and is associated with the deposition of further clear/milky quartz. Breccias are formed in the veins where they cut the main lodes and blue tourmaline vein fragments are cemented by later quartz.

- 2) Veins with banded and vuggy textures are formed by chalcedony; jasper and kaolinitic clay. The vugs are generally small (<10 cm in width) and contain euhedral quartz crystals (up to 2 cm long), the open vug space is usually filled with either massive kaolinitic clay or hematite and/or chlorite. The chalcedony and clay within the banding are often intimately mixed in successive layers. Episodic flow and deposition of chalcedony in a dynamic regime has given rise locally to breccia and cockade textures cemented by matrices of later jasper, quartz and chalcedony with chlorite. Veins with these characteristics are also observed in the chlorite-rich portions of the main lodes (e.g. Roskear D Lode, 410 fathom sub-level).
- 3) Massive fluorite-filled veins up to 0.5 m in width. Crosscourses of this type have been observed in the North Pool Zone (360 fathom level) and are hosted in north-east-dipping normal fault structures which have an oblique component. Apparent displacement of the North Pool B2 lode is about 3 m to the left. The main crosscourse shows multiple movement, though a branch of it contains a single episode of fluorite deposition.

The present studies have shown that in places the main lodes were reactivated, leading to stepped lateral displacements of the crosscourse veins reaching several tens of centimetres (e.g. Roskear B Lode, 420 fathom level). The reactivation was dominated by right-lateral displacement as a result of strike-slip faulting, and can be traced as a hematite-filled fault plane that runs within the lode, such as those seen in the Roskear B Lode (1340W) shrink stope (Dominy, 1994).

#### FLUID INCLUSION STUDIES

Microthermometric analysis was carried out using LinkamTHMS600 and TH600 heating-freezing stages. Calibration was undertaken using both high purity compounds and synthetic fluid inclusions. Doubly polished 100 µm thick sections were prepared for study. The homogenization temperature quoted represents the disappearance of the vapour bubble. No pressure correction has been applied to

homogenization temperature data, which must be regarded as the minimum trapping temperature. Salinity values were determined from the last ice melt temperature using Fincor software (Brown, 1989). Fluid salinity is expressed as equivalent weight percent sodium chloride (eq. wt. % NaCl). Fluid composition was determined from the first ice melting temperature (eutectic temperature) using the values quoted in Shepherd *et al.* (1985). Where low eutectic values indicate a CaCl<sub>2</sub> fluid component, hydrohalite melting temperatures were used to determine the CaCl<sub>2</sub>/NaCl ratios from the NaCl-CaCl<sub>2</sub>-H<sub>2</sub>O ternary system documented in Shepherd *et al.* (1985).

Fine-grained quartz and chalcedony in the crosscourse veins contain abundant small, irregular and monophasic fluid inclusions; these are impossible to study using microthermometry. However, coarsely-crystalline and euhedral quartz biphasic (liquid+vapour) inclusions are the most common with some monophasic (liquid only) inclusions. The monophasic inclusions are secondary in origin and the biphasic inclusions are generally primary. Biphasic inclusions show degrees of fill greater than 0.8 and display both angular and spherical morphologies. A small number of biphasic inclusions contained a solid phase which was determined by SEM to be hematite.

Measurements on fluid inclusions from quartz in a crosscourse cutting the Roskear D Lode (420 fathom level) in this study have yielded a homogenization temperature range from <100° to 175°C and a salinity range from <1 to 23 eq. wt. % NaCl (Figure 2).

Primary biphasic inclusions hosted in milky/clear quartz from the vein margin gave a homogenization temperature range from <100° to 175°C, and a salinity range from <1 to 10 eq. wt. % NaCl (Figure 2). These inclusions generally had eutectic temperatures (-21°C) which indicated an NaCl dominated composition, and relatively few inclusions displayed a CaCl<sub>2</sub> component indicated by a eutectic temperature of about -55°C.

Inclusions in clear quartz from the reactivated central portion of the same vein show a homogenization temperature range from 100° to 175°C and a salinity range from 1 to 23 eq. wt. % NaCl. The dominant angular inclusions (primary and secondary) have a high

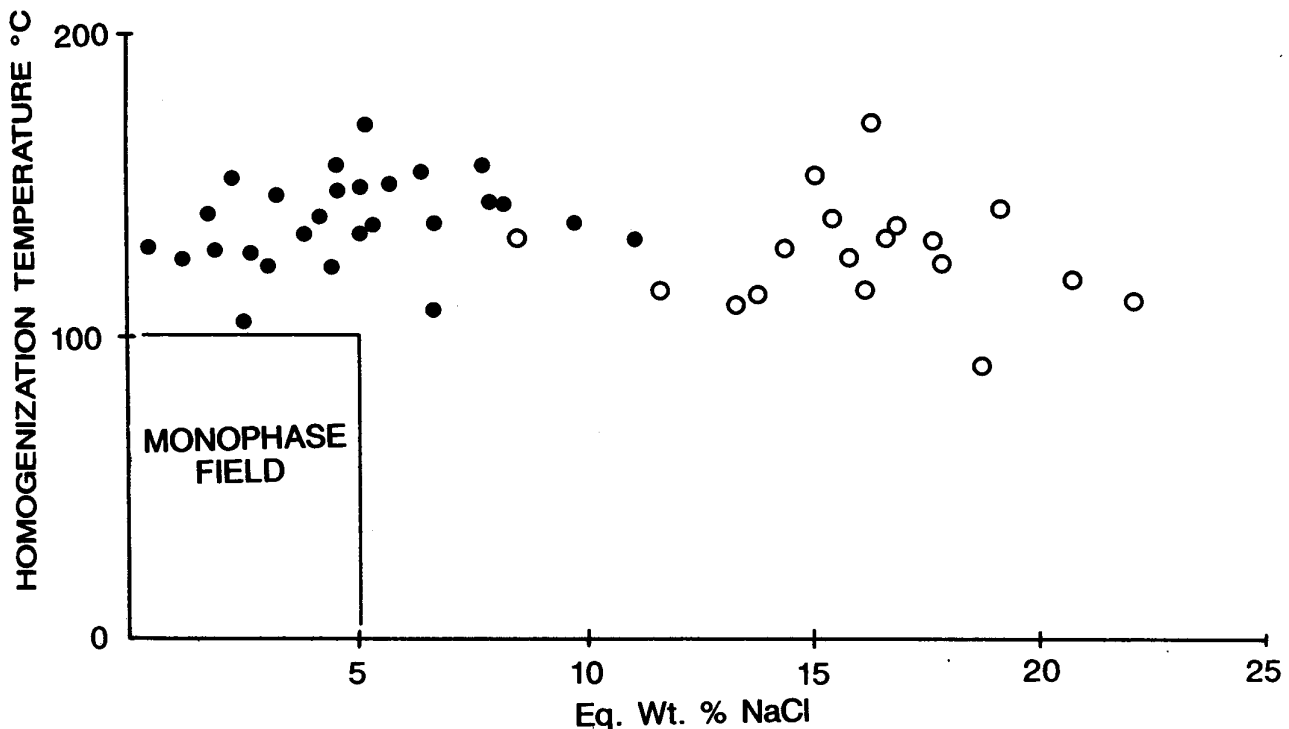


Figure 2. Homogenization temperature and salinity plot for fluid inclusions from an extensional quartz crosscourse cutting the Roskear D Lode (420 fathom level). Two populations are recognised; a low salinity meteoric fluid and a high salinity basinal brine. Filled Circles: primary inclusions hosted in milky/clear quartz from the vein margin and Open Circles primary and secondary inclusions hosted in clear quartz from the vein centre.

salinity range of 15 to 23 eq. wt. % NaCl (Figure 2). Eutectic temperatures of approximately -55°C suggest a CaCl<sub>2</sub> component to the fluid, hydrohalite melting temperatures (six readings) for these inclusions give a CaCl<sub>2</sub>/NaCl ratio range of 1:1 to 1:1.4.

Preliminary fluid inclusion studies (ten paired data points only) on crosscourse hosted fluorite from the North Pool Zone (360 fathom level) show a homogenization temperature range from 105° to 137°C and a salinity range from 11 to 22 eq. wt. % NaCl. Eutectic temperatures of approximately -55°C suggest a CaCl<sub>2</sub> component to the fluid and one hydrohalite melting temperature determination shows the fluid to have a CaCl<sub>2</sub>/NaCl ratio of 1:1.1. These results are in broad agreement with the quartz hosted inclusions and confirm the presence of basinal brines in the crosscourses.

Microthermometric data from quartz in a crosscourse vein cutting Pryces Lode was reported in Scrivener *et al.* (1986). Homogenization temperatures in the range from 132° to 180°C and salinities from 7 to 18 eq. wt. % NaCl were measured. In most cases the eutectic temperatures inferred the presence of CaCl<sub>2</sub> in the fluids, and hydrohalite melting temperatures for the more saline biphasic inclusions indicated a CaCl<sub>2</sub>/NaCl ratio of about 1:1.

### GEOCHRONOLOGY

Recent U-Pb data for the Carnmenellis Granite and its satellite Carn Brea Granite, which hosts the South Crofty lodes, indicate emplacement at 294±1 Ma (Chesley *et al.*, 1993; Chen *et al.*, 1993). Earlier Rb-Sr data from Darbyshire and Shepherd (1985; 1987) give a mineral isochron age for the Carnmenellis Granite of 290-12 Ma. Plateau Ar-Ar ages for muscovites from early hydrothermal tourmaline veins at South Crofty range from 284±1 Ma to 287±1 Ma (Chesley *et al.*, 1993; Chen *et al.*, 1993), while muscovite from a later fluorite-quartz vein yielded an age of 269±1Ma (Chen *et al.*, 1993). An Rb-Sr isochron from inclusion fluids from a cassiterite-bearing vein at South Crofty gives an age of 269±4 Ma (Darbyshire and Shepherd, 1985), and an Sm-Nd isochron for fluorite from a similar structure an age of 259±7 Ma (Chesley *et al.*, 1991).

The works cited above permit the construction of a schematic chronology for the history of the Carnmenellis Granite and subsequent mineralization at South Crofty Mine:

Granite emplacement and cooling 295-290 Ma

Stage 1) (Quartz floors)	290-287 Ma
Stage 2) (Tourmaline veins)	287-284 Ma
Stage 3) (Chlorite veins)	273-252 Ma

The mineralizing events responsible for the tin, tungsten and base metal deposits range from Early to Late Permian in age, with a protracted period of Stage 3) mineralization. Field relations described above suggest that the Stage 3) veins are succeeded by the formation of fracture zone crosscourses and these in turn by extensional crosscourses.

### DISCUSSION

The crosscourses of South Crotty reflect a period of north-south shearing followed by east-west crustal extension which lead to the development of extensive north-north-west to north-south-trending fracture systems throughout the orefield. Two scales of crosscourse are recognised; the large fracture zone type and the smaller extensional vein type.

The Great Crosscourse is likely to represent a pre-granite strike-slip fault which was episodically reactivated during the Late Permian/Early Triassic. This reactivation and led to the influx of silica-rich fluids, which resulted in the deposition of extensional quartz veins within the fracture zone. The diverse textures of the veins indicate episodic fluid flow at temperatures below those of the main lodes. The fault zone was later pervaded by low temperature fluids (<200°C) which resulted in the pervasive destruction of the host granite feldspars to a kaolinite-smectite dominated assemblage.

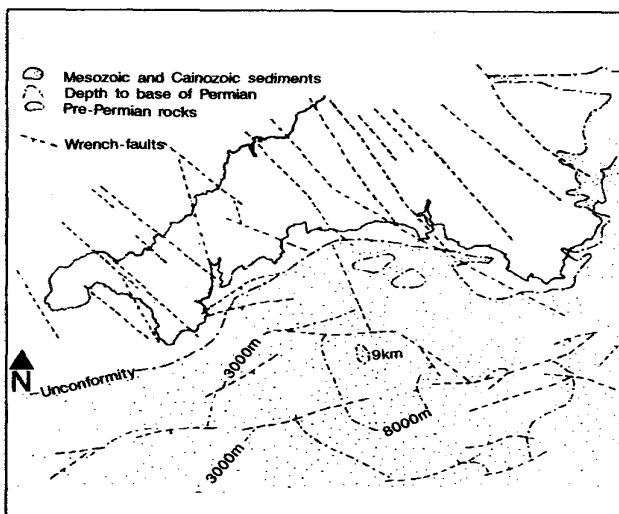


Figure 3. Map showing the position of the Cornubian Massif in relation to the proximal sedimentary basins and associated major strike-slip faults. After Jackson *et al.* (1989).

The onset of extensional crosscourse mineralization was marked by the deposition of quartz veins associated with chlorite and hematite within the chlorite type veins of the main lodes. A change in regional stresses resulted in the north-north-west to north-south-trending extensional veins which were reactivated on a number of occasions and were associated with further chlorite and hematite deposition. Crosscourse formation was followed by main lode reactivation which resulted in localised faulting along the main lodes characterised by the deposition of hematite and pyrite.

Fluid inclusion studies of extensional vein quartz reveal the presence of two fluid types: the first type is characterised by a low salinity (NaCl) meteoric fluid and the second shows characteristics of high salinity, CaCl<sub>2</sub>-bearing basinal brines. Previous fluid inclusion work at South Crofty reported by Scrivener *et al.* (1986) reveals the presence of both meteoric and basinal brine components in the crosscourses. This is further corroborated by Alderton (1978) who drew attention to the differences in homogenization temperature and salinity characteristics between the main lodes and the crosscourse veins in the southwest.

The mineralization and fluid origins can be most readily explained by using a model of mixing of meteoric and basinal brines based on a model proposed for the Tamar Valley by Scrivener and Shepherd (1987) and Scrivener *et al.* (1993; 1994). The basinal brines were probably expelled from sedimentary basins proximal to the Cornubian Massif along major north-northwest-trending strike-slip faults (e.g. Gleeson *et al.*, 1993; Figure 3). Fluid flow along the faults is believed to be related to seismic pumping (Sibson *et al.*, 1975) and density driven circulation (Scrivener *et al.*, 1994). These fault-bounded basins are situated to the north and south of the region, and contain up to 8 km thickness of sediments, ranging in age from Permian to Recent (Smith, 1992). Recent work of Scrivener *et al.* (1994) has demonstrated a Triassic age (236±3 Ma) for north-south-trending Pb-Zn-Ag crosscourse veins in the Tamar Valley and have suggested that basinal brine movements occurred at that period on a regional scale. It is considered probable that the extensional veins at South Crofty are of similar age to the fracture zone crosscourses developed in the Late Permian/Early Triassic. The long-ranging involvement of basinal brines throughout the Permian and Triassic would include the formation of Stage 3) chlorite veins and supports the view of Scrivener *et al.* (1986) that CaCl<sub>2</sub> brines may have been involved in the later episodes of tin mineralization. Extensional vein deposition was characterised by mixing of basinal brines with meteoric fluids at structural intersections; this led to the deposition of the silica- and iron-oxide-rich assemblages characteristic of the South Crofty crosscourses.

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