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CHARACTERISTICS AND DEVELOPMENT OF CARBONA-STYLE REPLACEMENT TIN MINERALIZATION IN WEST CORNWALL

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Granite-hosted cassiterite-bearing replacement bodies or "carbonas" represent a restricted style of tin mineralization found in the Cornubian orefield. This paper reviews historical sources and presents new data on carbonas which occur in the Lands End and Carnmenellis Granites. On a county-wide scale their historical tin production is low, but individually they may contain in excess of 100,000 tonnes of ore with a grade of up to 1.6 % Sn. In addition, some of the bodies contain small-scale, economic copper ores. The carbonas are irregularly- shaped bodies of mineralized/altered granite which sometimes show a gross tabular or pipe-like geometry. The pipe-like bodies have a maximum diameter of 30 m with a long axis up to 200 m in length, and they show vertical, horizontal or inclined attitudes. The tabular bodies may have strike lengths up to 150 m, widths up to 15 m and down-dip extent up to 100 m, in general however their dimensions are smaller. Carbonas are characterised by the pervasive hydrothermal alteration of the granite to chloritic, sericitic and tourmalinitic assemblages which may be strongly overprinted. Mineralization consists of disseminated cassiterite with arsenopyrite, specular hematite, pyrite, quartz and fluorite, and rarely chalcocite, bornite and chalcopyrite. Published fluid inclusion data for these deposits are absent, but results of current studies show dominance of two phase liquid-vapour inclusions characterised by a homogenisation temperature range of between 125 and 398°C and a salinity range of 5.5 to 22.1 equiv. wt. % NaCl. These fluids are believed to be dominantly magmato-hydrothermal in origin, with some evidence for late-stage meteoric fluid involvement during reactivation. Studies of quartz-hosted, healed microfracture planes within the mineralized alteration zone reveal strong microfracture control on fluid flow pathways, alteration intensity and ore localization. It is suggested that the mode of carbona development defines their detailed geometry. The formation of localized microfracture zones about a narrow vein/fracture resulted in dominantly tabular-shaped bodies. Pipe-like bodies are more problematic, but were probably related to the intersection of two or more different fracture sets along an irregularly shaped fracture zone.

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INTRODUCTION

Granite-hosted (endogranitic) tin mineralization in southwest England is characterised by fracture systems which show marked variations in their time of formation, alteration, distribution, structure and geometry. The classifications of Hosking (1964; 1969; 1988) and Taylor (1979) recognise five styles of endogranitic tin mineralization: 1) lodes; 2) stockwork systems; 3) floors; 4) replacements and carbonas and 5) disseminations within dykes. Within the orefield, three principal mineralizing stages are recognised (Bromley and Holl, 1986; Jackson *et al*., 1989):- a pre-batholith stage of sediment-hosted mineralization (Fe-Mn-Cu); a syn-batholith (or main-stage) characterised by SnW-bearing stockwork mineralization followed by (Sn)-(Sn-Cu)bearing lode-style mineralization with which the carbona-style deposits are believed to be associated, and a post-batholith stage of epithermal (or crosscourse) vein mineralization (Zn-Pb-Ag etc.) and pervasive granite kaolinization. Most tin production has been derived from complex lode zone systems (Farmer and Halls, 1993; Dominy and Camm, 1996), but a number of mines have been reliant on carbona deposits. Irrespective of style, mineralization is often located near porphyry dykes, along the axis of the granite batholith, or commonly at the batholith margins/roof zones (Jackson *et al*., 1989). Pervasive wallrock alteration zones are a common feature of the lodes and often contain economic amounts of tin mineralization distributed over substantial widths (Fanner and Halls, 1993; Dominy *et al*, 1996). Wallrock alteration is an important characteristic of carbona systems, which represent regions of wholesale wallrock alteration/replacement by metasomatic processes.

This paper reviews a number of carbona systems which have received little attention in recent years' because of lack of exposure and exploration activity within the orefield. Most of the information has been acquired through literature searches and study of abandoned mine plans. All aspects of deposits are reported including mineralogy, structure, grade and tonnage. Where tonnage and grade data are presented, either historical sources or calculations by the authors based on inferred volumes and a bulk tonnage factor (density) of 2.65 tonnes/m^3 were used. New fluid inclusion data are presented for three carbona deposits, one of which is described here for the first time. Similarly, lithogeochemical data of carbona samples are also provided for the first time for one deposit.

DEFINITION AND CHARACTERISTICS OF CARBONAS

Although carbona orebodies are not widespread in south-west England and contributed negligibly to the total tin output of the region, a small number of mines were developed because of the presence of a carbona and made substantial profit. Henwood (1843) suggests that the word carbona originates from the Cornish language, but Hunt (1884) reports that it is an *Aramaic* term meaning "*a place rich in good things - a treasury*". Moissenet (1877) and Collins (1912) describe carbonas as "*irregular tin deposits occurring in granitd*". Phillips and Louis (1896) provide a similar definition, but erroneously include closely-spaced vein systems which are usually termed stockworks (Collins, 1912; Dominy *et al*., 1995a). Hill and MacAlister (1906) describe carbonas as "*irregular, more or less horizontal pipes, passing into the [granite] country rock along cracks...*" with reference to the St. Ives Consolidated Mine Great Carbona body. Spargo (1865) records "*..extraordinary excrescences of ore in the sides [of lodes]*" called carbonas within the St. Ives Consolidated Mine. The feature of alteration halos about lodes is recognised by Foster (1855) who stated that "*many of the....most productive tin lodes in Cornwall are simply tabular masses of altered granite adjacent to fissures*", but he does not use the term carbona. Jackson (1975) describes a metasediment-hosted deposit related to granite tongues within the Levant Mine as a carbona, this does not conform to the common granite-hosted definition. In the Camborne-Redruth district the term has been used imprecisely to describe irregular alteration halos about veins (Hill and MacAlister, 1906).

There is thus some confusion in the literature to the precise definition of carbonas, however it is clear that the key points in any definition must be "irregular", "tin-bearing" and "altered granite". The authors suggest a definition of *"irregularly shaped bodies of highly altered tin-bearing granite"* which is similar to that proposed by Hosking (1964; 1988) and the majority of earlier workers (op. cit.).

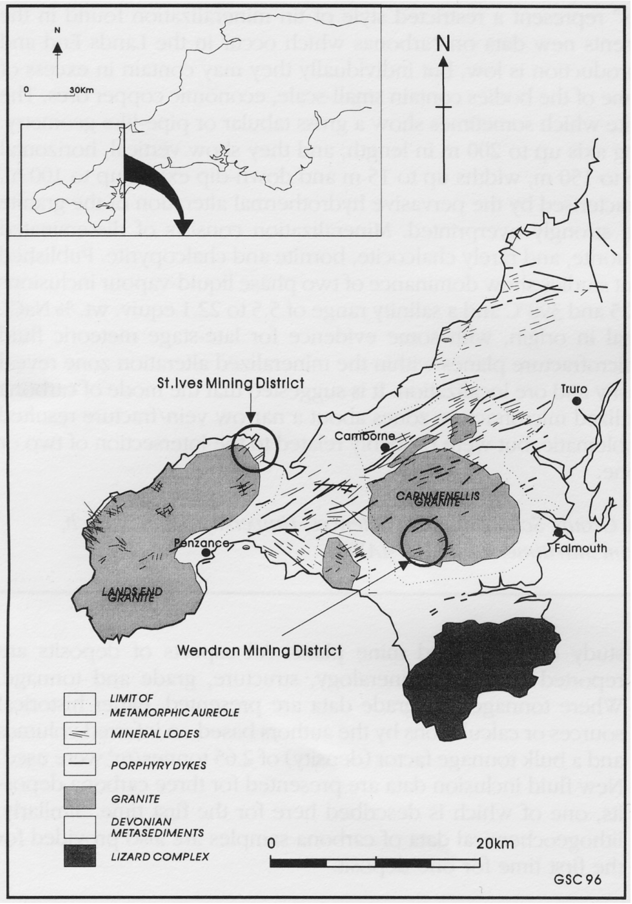

Figure 1: Map showing the location of the Lands End and Wendron "carbona" areas.

Geographically, the carbonas have been principally reported in the roof/contact zones of the Lands End (St. Ives district) and Carnmenellis (Wendron district) granites in western Cornwall (Figure 1). The literature and mine records confirm a strong degree of irregularity is common to all carbonas, however one of two gross geometries is often recognisable: i) pipe-like or ii) tabular bodies, a feature noted by Hosking (1964; pers. comm.). Pipes have a maximum diameter of 20-30 m, a long axis of up to 200 m and may show vertical, horizontal or inclined attitudes. The tabular bodies display strike lengths up to 150 m, widths up to 15 m and down-dip extent up to 100 m; in general however their dimensions are smaller. The volume of carbonas is highly variable, with small bodies representing <1,000 m^3 and larger ones >100,000 m^3 of mineralized/altered rock. Due to the small sizes and relative rarity of carbonas, accurate production records are not available as they are often included in the overall mine production figures for some lode-style deposits. Their estimated tonnages probably ranged from <1,000 tonnes up to in excess of 150,000 tonnes. In many cases, grade appears to have been 0.5-1.0 % Sn, however localized high grade regions were probably in excess of 1.5 % Sn in common with lode-style deposits (Collins, 1912; Dines, 1956).

Mineralogically, carbonas are also highly variable. Chloritization, sericitization and tourmalinization of granite are the common alteration types within the mineralized envelope, with barren rocks beyond showing varying degrees of kaolinization and sericitization. The alteration assemblage may contain tourmaline, white mica (gilbertite and muscovite), quartz, fluorite, chlorite and feldspar. The principal ore mineral present is cassiterite and other ore minerals reported include chalcopyrite, chalcocite, bornite and rarely sphalerite and wolframite. Non-economic minerals reported include arsenopyrite, pyrite, siderite and specular hematite.

ST. IVES DISTRICT CARBONAS

The St.Ives district, stretching from Zennor in the south to Hayle Estuary in the north, was one of the most notable mining areas in Cornwall. Mines formerly worked included; St.Ives Consolidated Mines, Providence Mines, Wheal Trenwith, Wheal Reath and Giew Mine (Dines, 1956; Noall, 1982; 1993).

St. Ives Consolidated Mines

The Great Carbona of St. Ives Consolidated Mines [SW 506 3971 is probably the most noted in the orefield (Henwood, 1848, 1865; Phillips and Louis, 1896; MacAlister, 1907; Collins, 1912; Dines, 1956; Noall, 1993) and was described by Hill and MacAlister (1906) as pipe-like. It was discovered in the 1830s whilst working the Standard Lode (lode-style deposit) between the 35 and 77 fathoms levels, when the workings intersected three sub-horizontal (tabular?) carbonas named No. 1, Lawrys and Great (Figure 2). These bodies were followed and found to widen and finally merge to form The Great Carbona below the *77* fathom horizon (Figure 2).

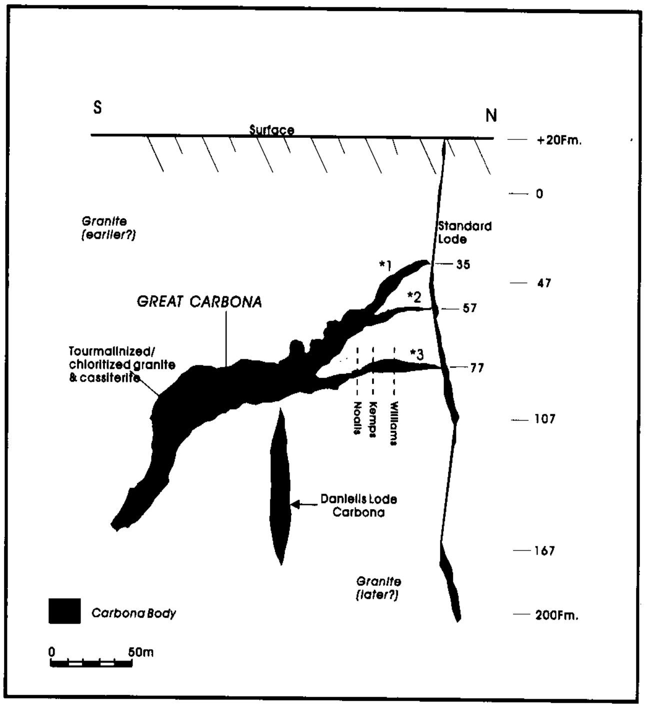

*Figure 2. Cross-section of the St. Ives Consols Great Carbona system. No. 1 (*1) and Lowrys (*2) carbonas were intersected and followed on the 35 and 57 fathom levels respectively. The Great Carbona was defined from the 77 fathom level (*3) and southwards where it enlarged greatly. The arched shape of the body is believed by Hosking (1969;1988) to mirror the contact between two granite stages. Daniells Lode carbona lies directly beneath the Great. Redrawn and edited from Hosking (1988).*

The Great Carbona system plunges at up to 40° towards the south. It displays a diameter range from about 1 to 20 m with an average of 10 m and a down-dip extent of some 235 m. Mineralogically it is characterised by alkali feldspar, quartz, chlorite, tourmaline and cassiterite with minor fluorite, chalcopyrite, bornite and pyrite. The wallrocks show a gradual transition from relatively unaltered granite to mineralized granite (Phillips and Louis, 1896) and where strong mineralization was absent the body could be followed as a narrow vein with a weak alteration selvage. No tonnage for the system is quoted in the literature or mine records but, based on the quoted dimensions, must have been in excess of 80,000 tonnes. Collins (1912) quotes an average grade of about 1% Sn for the Great Carbona.

Below the Great Carbona lay the sub-vertical tabular Daniells Lode carbona (Figure 2). The structure was up to 12 m wide, traceable along strike for 145 m and down-dip for 110 m. It was larger than the Great, and probably contained in excess of 175,000 tonnes of ore at a grade suggested by Collins (1912) to be higher than the Great's average of 1% Sn. Mineralogically Daniells Lode carbona showed the same characteristics as the Great Carbona, but does not appear to be structurally linked to it.

Providence Mines

A number of carbona bodies were reported within the Providence sett [SW 523 384] which were generally related to lodes (Henwood, 1865; Collins, 1912; Dines, 1956). The old mine plans show seven bodies, five related to the north wall of the Standard Lode, and two south of it. The bodies varied considerably in size, as shown by their estimated tonnages: No. 1- 31,500 tonnes; No. 4- 200,000 tonnes; No. 5- 11,000 tonnes; No. 6-18,000 tonnes and Unnamed- >5,000 tonnes. The Nos. 2 and 3 carbonas were located to the south of Standard Lode and appear to be smaller than the others. Collins (1912) described the No. 3 carbona which was related to the intersection of the Wheal Comfort and Wheal Laity Lodes 190 m below surface. He reported that, close to the contact with Comfort Lode, the carbona contained a rich mass of quartz, feldspar and tourmaline with cassiterite in an area 5 m wide and 10 m long. Some 10 m below this point the carbona reduced to a narrow vein which continued to some depth. No information was available as to the grade of any of the carbonas within the sett.

WENDRON DISTRICT CARBONAS

From the 17th century onwards the Parish of Wendron saw surface and underground mining commence alongside already well established tin streaming activities (Hamilton-Jenkin, 1978; Brooke, 1994). The majority of mines depended upon lodes for tin production, but in a few cases production came exclusively from carbonas (Trounson, 1989). The total tonnage of ore worked from the carbona systems is not known, but estimated to have been in excess of a few 100,000 tonnes (Dominy, 1987).

East Wheal Lovell

The carbona in the Fatwork section of the mine [SW 704 318] was perhaps the most notable in the area (Foster, 1878; Symons, 1884; Hill, and MacAlister, 1906; Dines, 1956). The carbona was pipe-like in form and Foster (1878) described it as a *"long irregular cylinder with an elliptical base generally from 12 to 15 feet long by 7 feet wide"* (Figure 3). Symons (1884) described the orebody thus, *"they were not formed in veins, but apparently by the infiltrations of the tin oxide into the walls, which, spreading to a distance of some feet replaced the granite"*. The cross-section of the body in Figure 3 shows a series of pipe-like bodies interconnecting with irregular bodies. Abrupt changes in dip are also observed on some of the pipes, which range from vertical to about 45°. The North Lode was related to a 80° south-west dipping vein which had a strike of 025°. The narrow vein was sometimes only seen as a joint in the granite and was infilled by quartz with minor clay and hematitic material. Along either side, wide zones of granite replacement and cassiterite mineralization occurred characterised by quartz and gilbertite with fluorite, pyrite, chalcopyrite, chalcocite, bornite and siderite (e.g. the carbona). Cunnack (Brooke, 1993) reports that the ore was of great richness, but below the 90 fathom level the cassiterite disappeared and the body became dominated by gilbertite mica. Dines (1956) reports that in cassiterite-rich regions the granite was strongly kaolinized, though very locally. The distribution of tin within the carbona was not uniform, but the ore-zone was followed down-dip from the 40 to the 100 fathom level (108 m). The carbona also contained small amounts of copper ore of which there is no recorded production.

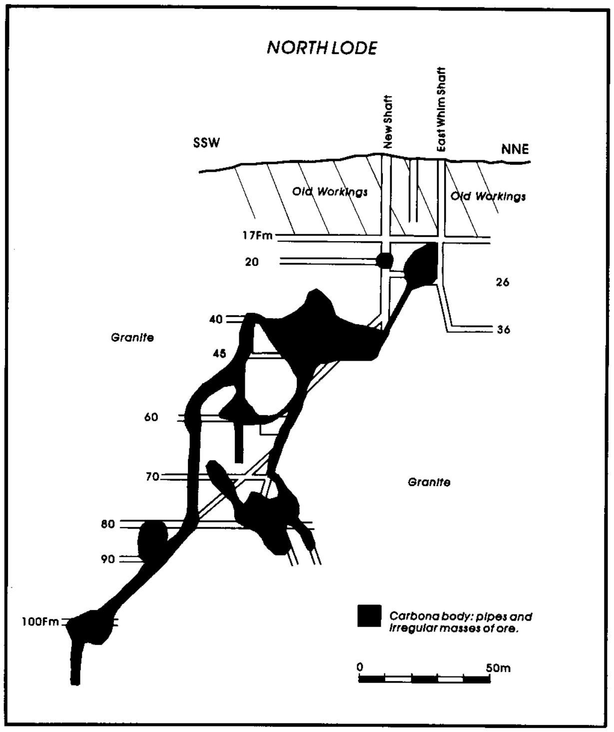

Figure 3: Cross-section of Fatwork section of East Wheal Lovell showing the North Lode carbona. Vertical to inclined pipe-like bodies are linked to irregular masses. Redrawn and edited from Le Neve Foster (1978).

South Wendron Mine

The deposit at South Wendron [SW 705 301] was a pipe-like body with an oval section measuring 3 m by 6 to 18 m in plan (Hill and MacAlister, 1906; Dines, 1956). The body contained cassiterite, quartz, chlorite, gilbertite, fluorite and tourmaline with pyrite and chalcopyrite (Foster, 1878). Production from the mine was small, with only 9.6 tons of tin concentrate produced between 1875 and 1880 (Burt *et al.,* 1987).

Balmynheer Mine

This tabular body [SW 344 704] was described by Hill and MacAlister (1906) and Dines (1956) and was characterised by a 0.15 m wide quartz and clay vein which had a strike 058° and dip of 60° towards the north. The carbona was located on the footwall of the vein and varied in thickness between 9 and 15 m. It had a strike extent of about 65 m and a general dip in the same angle and direction as the vein. Cunnack (Brooke, 1993) reports that the mine was worked to a depth of about 100 m, but tin values became poor at depth. Mineralogically the carbona contained cassiterite, quartz, gilbertite, chlorite, pyrite and sphalerite with minor wolframite. In 1876 some 2,200 tons of ore (approx. 0.9 % sn) were extracted (Burt *et al.*, 1987).

Halabezack Farm

This little known deposit near Porkellis, was reported by Fox (1868) who describes an open pit and adit worked for tin. The carbona was associated with a 0.6 m wide quartz/clay vein which displayed an east-west strike and dip 62° north. Cunnack (Brooke, 1993) states that the mineralization was hosted within a quartz-porphyry granite variant known locally as "elvan". The zone of alteration and mineralization was 20 fathoms wide (36 m) and worked to a depth of about 80 fathoms (144 m). Mineralogy was dominated by cassiterite with specular hematite and pyrite, and presumably chlorite etc. Tin grades varied from 0.3 to 1.7 % (Fox, 1868) though Cunnack (Brooke, 1993) suggests an average grade of 0.7 % Sn, no tonnage information is available.

Wheal Roots

This little known mine [SW 682 315] was first reported by Hamilton-Jenkin (1978) who considered it to be part of Wendron Consols Mine, following its discovery during the driving of an adit for the purpose of tourism. By 1987, the majority of the original Wheal Roots workings were cleared, and the northernmost stope or "carbona chamber" was accessible. The carbona was tabular in form, centred on a narrow (0.05-0.1 m) 058/85° north-trending vuggy quartz/clay vein and comprised of chlorite, quartz, white mica, cassiterite, specular hematite with minor siderite, fluorite and pyrite. At the base of the stope chamber (38 m below surface) the body was approximately 3 m wide, centred on the quartz vein, and about 4 m wide at its widest point. XRF analysis of tin in 12 samples gave an average value of 0.42 % (range: 0-1.36 %, σ: 0.38 %). Based on exposure within the mine (1993) the carbona probably contained a minimum tonnage of 1,500; with a grade probably below 1 % Sn.

WHOLEROCK GEOCHEMICAL STUDIES

Major element analyses of six samples from the core of the Wheal Roots carbona are shown and compared with analyses of fresh granite in Table 1. Carbona and granite analyses were performed using ICP-AES on samples prepared by a standard lithium metaborate fusion technique. Selected oxides in both the carbona and granite samples were ratioed to silica to show relative enrichment and depletion in concentration (Table 1). Most notably Mg and Fe are enriched in the carbona, which is consistent with extensive chlorite development, Fe enrichment is also explained by the presence of specular hematite. Ca is also enriched in the carbona and can explained by the development of fluorite within the alteration assemblage, while depletion of Na and K is controlled by the dissolution of feldspars during alteration, although the presence of white mica within the altered rock tends to buffer the K concentration. Tin is enriched (x 340) in the carbona samples compared to an average of 14 ppm generally reported from unaltered Carnmenellis granite (Alderton, 1993).

Element	Carbon	Roots Granite[1]	Other Granite[2]
SiO_2	70.55	71.93	72.02
Al_2O_3	12.35	15.64	14.98
TiO_2	0.2	0.22	0.23
MgO	0.85	0.41	0.35
MnO	0.09	0.05	0.05
ΣFeO	6.42	1.65	1.51
CaO	2.16	0.7	0.64
Na_2O	1.19	2.93	3.05
K_2O	4.1	5.39	5.27
P_2O_5	0.19	0.23	0.24
Total	98.1	99.15	98.34
Sn	0.48	[3]bdl	[3]bdl
Element ratioed to SiO_2 x 1000			
MgO	12	5.7	4.8
ΣFeO	90	22.9	20.9
CaO	30.6	9.7	8.8
Na_2O	16.8	40.7	42.3
K_2O	58.1	76.4	73.1
No. Samps	6	5	4

[1] Fresh granite from No. 1 level Wheal Roots.
[2] Fresh granite from Hemiss Quarry.
[3] bdl below detection limit for XRF.

TABLE 1. Average major element values (wt. %) by ICP-AES for altered carbona granite and fresh granite from Wheal Roots and elsewhere in the Wendron area. Tin analysis by XRF.

FLUID INCLUSION STUDIES

Fluid inclusion studies have been undertaken for the first time on carbona samples to elucidate the nature of the mineralizing fluids. Microthermometric analyses were carried out using a Linkam heating-freezing stage, on doubly polished 100 pm thick thin sections. Calibration was undertaken using both high purity compounds and synthetic fluid inclusions and the homogenization temperature quoted represents the disappearance of the vapour bubble. No pressure corrections have been applied to the homogenization temperature data, which must be regarded as the minimum trapping temperature. Salinity values were determined from the last ice melt temperature using Flincor computer software (Brown, 1989). Fluid salinity is expressed as equivalent weight percent sodium chloride (equiv. wt. % NaCl). Fluid composition was determined by comparison of first ice melting temperature (eutectic temperature) with those quoted in Shepherd *et al.* (1985). The recognition of primary inclusions was difficult because of the lack of crystal faces so in most cases secondary and pseudo-secondary inclusions were investigated.

St. Ives Consolidated Mines, Great Carbona

Microthermometric measurements were undertaken on quartz-hosted inclusions from a sample formerly in the collection of the late Professor K. F. G. Hosking. The sample was dominated by cassiterite intergrown with tourmaline, chlorite and quartz and was reported to

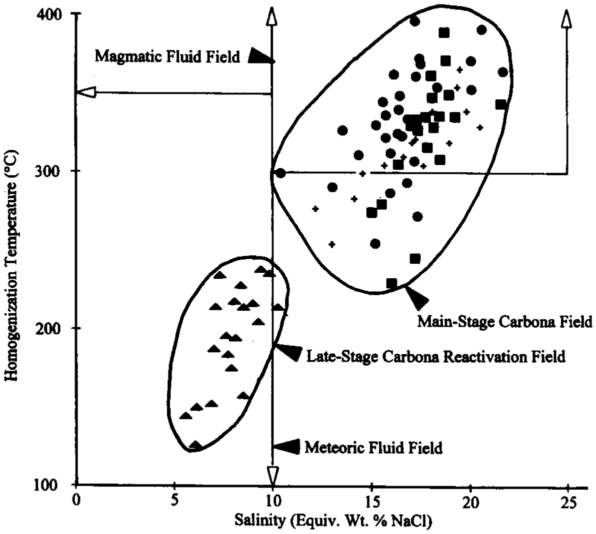

Figure 4: Homogenization temperature and salinity plot for fluid inclusions from the St. Ives Consols, Wheal Roots and East Lovell carbonas. Main-stage carbona fluids: Filled circles- St. Ives Consols, squares- Wheal Roots and crosses- East Wheal Lovell. Late-stage carbona reactivation fluids: triangles-Wheal Roots. Cornubian magmatic and meteoric fluid fields based on Alderton (1993).

have been collected from the 77 fathom level of the Great Carbona. The inclusion population was dominated by the liquid-vapour type, with a smaller number of liquid- and vapour-only inclusions. Homogenization temperature and salinity values ranged from 256 to 398°C and 10.4 to 23.3 equiv. wt. % NaCl respectively (Figure 4). The inclusions showed a dominant eutectic temperature close to -20.8°C, implying a $NaCl-H_2O$ fluid composition, though a few yielded temperatures near -22.9°C suggesting a $NaCl-KCl-H_2O$ composition.

East Wheal Lovell, North Lode Carbona

Microthermometric measurements were undertaken on quartz-hosted inclusions from a sample reported to be from the 50 fathom level. The sample of strongly chloritized granite was dominated by dense chlorite aggregates intergrown with tourmaline and minor cassiterite and quartz. The inclusion population was composed dominantly of the liquid-vapour type, though a small number of liquid- and vapour-only types were observed. Homogenization temperature-salinity measurements showed ranges of 253-367°C and 12.3-21.6 equiv. wt. % NaCl respectively (Figure 4). Only four eutectic temperatures were determined which suggested a $NaCl-KCl-H_2O$ composition.

Wheal Roots Carbona

Measurements were undertaken on inclusions hosted in quartz from the pervasively altered centre of the carbona. The inclusion population was dominated by the liquid-vapour type, though a lesser number of liquid-only inclusions were also observed. Homogenization temperature and salinity values ranged from 125 to 398°C and 5.5 to 22.1 equiv. wt. % NaCl respectively. The data fall into two groupings; i) 125 to 236°C (5.5 to 10.2 equiv. wt. % NaCl) and ii) 233 to 398°C (15 to 22.1 equiv. wt. % NaCl: Figure 4). The group i) inclusions indicated a $NaCl-H_2O$ fluid composition whereas group ii) inclusions showed both $NaCl-H_2O$ and $NaCl-KCl-H_2O$ compositions.

Microthermometric studies of carbona-hosted fluid inclusions reveal an overall homogenization temperature range of 125 to 398°C and a salinity range of 5.5 to 22.1 equiv. wt. % NaCl (Figure 4). Comparison with other studies from the orefield suggests that data in the range 233 to 398°C are magmato-hydrothermal fluids in origin. This conclusion is in-line with Alderton (1993) who suggests a homogenization temperature and salinity range of 300-500°C and 10-25 equiv. wt. % NaCl respectively for main-stage Sn-Cu mineralizing fluids. The lower temperature-salinity group (i) data for the Wheal Roots carbona are typical of dominantly meteoric fluids within the range <200-350°C and <10 equiv. wt. % NaCl (Alderton, 1993) associated with late-stage fracture reactivation.

MICROFRACTURE STUDIES

Carbonas are characterised by large volumes of pervasively altered granite which is often associated with a variable narrow macro-fracture. Studies were undertaken to evaluate the role of microfracturing in carbona development. The granitic rocks of south-west England contain numerous microfractures which are microscopically observed in quartz as multiple planes of healed secondary fluid inclusions (Dominy *et al.,* 1995b; Westerman, 1995; Dominy *et al.,* 1996). These microfractures represent either healed tensile or shear fractures, which can be differentiated by observation of their morphology, orientation and shape of contained inclusions (Krantz, 1983; Lespinasse and Cathelineau, 1990; Westerman, 1995). Microfracture displacement can be observed along some grain boundaries and at the intersections of two or more microfractures.

The real-space three-dimensional orientation of the microfractures can be determined using field oriented samples (Prior *et al.,* 1987) followed by studies using a Universal Microscope Stage (U-stage) technique (Westerman, 1995; Passchier and Trouw, 1996). In this study, two orientated, doubly polished, thin sections 100 ìm thick were prepared for a sample collected from Wheal Roots. These were cut along mutually perpendicular planes so that microfractures in all possible orientations could be studied. A number of standard thin sections were also prepared so that microfracture densities could be determined.

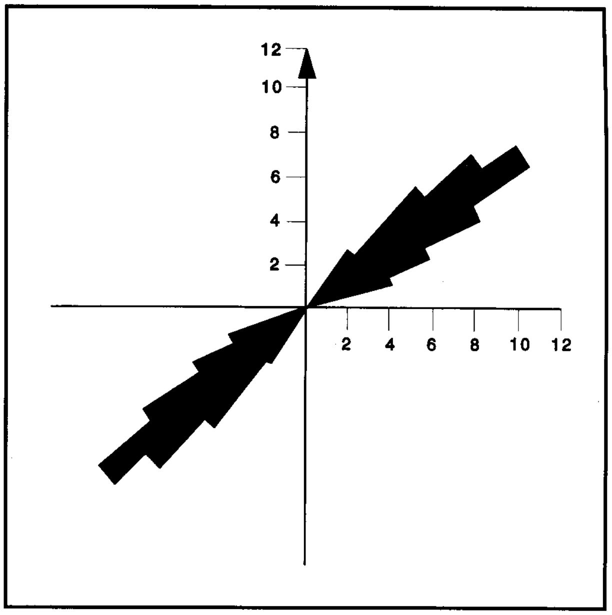

Figure 5: Rose diagram showing the dominant strike orientations of microfracture planes hosted in quartz within the Wheal Roots carbona. All planes show dip values in excess of 75°.

U-stage measurements on the sample revealed that the inclusion planes showed a preferred strike orientation about the long axis of the carbona (055-060°) ranging from 035° to 075° (Figure 5). Dip values of the planes were generally >75° with a dominant direction northwards, although a few south-dipping ones were seen. These observations corroborate with previous findings, which show that microstructures generally mirror macrostructures within the granites of south-west England (Dominy *et al.,* 1995b; Westerman, 1995; Dominy *et al.,* 1996). Preliminary microthermometric studies of plane-hosted inclusions reveal the same homogenization temperature-salinity groupings and characteristics as previously reported in this paper. Table 2 shows microfracture and fluid inclusion data that demonstrate a high density within the carbona body. Weakly sericitized granite on the carbona margin shows some development of microfracturing, but less than that of the orebody. The higher values are in agreement with previous studies in south-west England and elsewhere which demonstrate a "steam aureole" effect around fossil fluid channelways in granites (Yermakov, 1967; Dominy, 1993; Dominy *et al.,* 1996a).

Sample No.	Granite Type	Position[1]	MF Density[2]	FI Density[3]
WR/01	Chloritized	0.05	16	1347
WR/02	Chloritized	0.2	13	1198
WR/05	Chloritized	0.35	11	1011
WR/06	Chloritized	0.45	8	679
WR/07	Sericitized	0.8	5	495

[1] Position in m from the central quartz vein within the carbona.
[2] Density of microfractures in number per mm.
[3] Density of fluid inclusions per mm^2.

TABLE 2: Table of microfracture density data from a 0.8 m traverse from the central quartz vein within the Wheal Roots carbona. Samples 01 to 06 within carbona, 07 outside.

DISCUSSION

Carbonas are an unusual style of tin mineralization observed in the south-west England orefield. Their genesis is likely to relate to the main-stage tourmaline-cassiterite mineralization which occurred between 287 and 284 Ma (Chesley *et al.,* 1993; Chen *et al.,* 1993). They are dominated by zones of pervasive wallrock alteration in which cassiterite has been deposited erratically, but in enough quantity to have been of economic importance. Over the entire orefield the historical output of tin from carbonas has been minimal, but locally they were of importance. Consequently, carbonas represent relatively small tonnage bodies with highly variable grades. Carbona-style mineralization appears a peculiarity of Cornwall however, Hosking (1988) reports that the Sungai Besi Mine in Malaysia contained a number of carbonas developed in granite just below a marble cover. This style of mineralization probably does exist in other granite-hosted tin provinces, but have not been recognised as such.

Fluid inclusion data presented in this paper show the carbona-fluids plot in the same field as those of a magmato-hydrothermal origin (Figure 4), thus revealing a genetic link with the main-stage mineralizing fluids described by Alderton (1993). Later reactivation of the narrow vein(s) which pass through some of the bodies was probably related to lower temperature-salinity meteoric fluids, as seen in the Wheal Roots carbona.

The formation of most types of hydrothermal mineral deposits requires the focusing of substantial volumes of fluid along discrete, well-defined channelways often on a large scale. Within a single deposit the concentration of ore is like-wise reflected by small-scale channelling of fluid flow along fractures. Microscopic studies of samples from the Wheal Roots carbona reveal a general microfracture trend within ±020° of the direction of the body and a higher density of microfractures and fluid inclusions about the body (Figure 5; Table 1). This is a characteristic of other vein-related systems throughout the orefield, in which microfractures exerted a strong control on fluid flow and the distribution and intensity of alteration (Westerman, 1995; Dominy, 1993, 1994; Dominy *et al.,* 1996). The narrow "in-carbona" veins and associated microfracture systems suggest that carbona development was dominantly fracture-controlled. Variations in fracture development about a planar or linear conduit are believed to give rise the overall tabular or pipe-like carbona geometries. Tabular bodies display the simplest model for development involving the initial formation of a precursory macrofracture and possibly some microfractures. This shows local spatial variations and, when re-activated, results in the formation of a more localized microfracture zone with some void space possible. Fluid flow through this high permeability and connectivity zone results in wallrock alteration and mineralization (Figure 6). The development of the pipe-like system is more complex and may involve the intersection of two or more differently oriented fracture sets (Figure 7). It has long been recognized that movement along an irregular fracture plane results in the development of dilatent zones of high fluid permeability, and thus act as loci for mineral deposition and water/ rock interaction (Newhouse, 1940). An initial fracture forms which is intersected by a further plane(s) at an angle to it, resulting in a linear zone of high permeability and connectivity. The strike and dip of the intersecting fractures defines the connection zone which will be in the gross form of a pipe. The focused flow of fluid along this zone will result in wallrock alteration and mineralization. In either case, carbona development is related to a complex multi-stage history of fracturing, fluid flow, and mineral deposition. The more irregular carbonas probably reflect a more complex pattern of feeder fracture, microfracture and fluid flow.

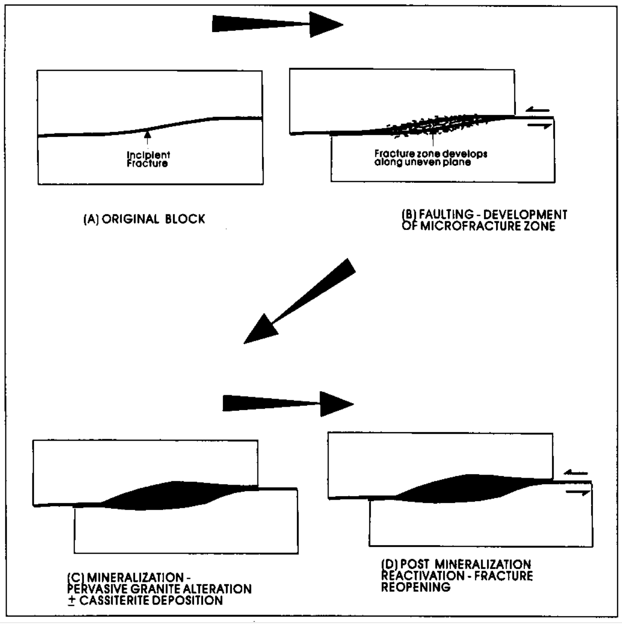

Figure 6: Stages in the development of a tabular carbona.

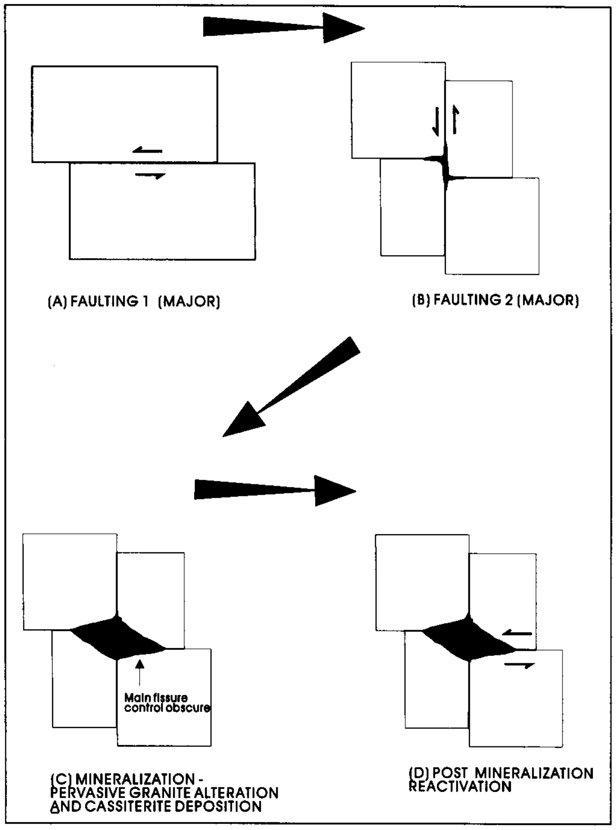

Figure 7: Stages in the development of a pipe-like carbona.

Pervasive granite alteration, a characteristic of carbonas, is significantly wider than the associated macro-fracture(s). The alteration can be considered in terms of hydraulic disequilibrium between the fracture fluids and the pore fluids within the wallrock, as well as the chemical disequilibrium between the mineralizing fluid and the wallrock minerals. Since these fluids were dominantly formed at magmato-hydrothermal temperatures and confined at lithostatic pressures, they were able to produce gross metasomatic changes in the wallrocks, leading to mineralogical and textural reconstitution (Halls, 1987). Theoretical modelling suggests that diffusion can account for alteration zones up to about 5 m in width, but larger zones must involve the bodily flow of fluid through the rock (Zharikov and Zaraisky, 1991). Within the carbonas fluid flow was dominantly via microfractures which enhanced access to grain boundaries and permeability. Localized variations in, and interplay between vein and wallrock fluid pressure, linked with rock permeability controlled fluid flow (Fp). Maximum flow occurred where $Fp_{(vein)} > Fp_{(wallrock)}$ and where permeability was high. The irregular geometry of the alteration zone was related to structural complexities, and fluid pressure and permeability variations within the granite resulting in weak or strong water/rock interactions.

Hosking (1969; 1988) proposed that the St. Ives Consolidated Mines Great Carbona body developed at the contact of an earlier and later granite, replacement was most marked where the contact was strongly arched (Figure 2). This idea was based on the possible presence of a contact feldspar-rich pegmatite zone (stockscheider) which may have been chemically more reactive and potentially more permeable. The role of fracture formation in this model is difficult to envisage, however the zone may have acted as a region of weakness allowing preferential fracture formation. This model suggests that the mineralizing fluids were related to the later granite which is in agreement with current thinking where the main magmatism was followed by a later magmatic stage (Bromley and Holl, 1986; Willis-Richards and Jackson, 1989; Alderton, 1993).

Chloritization is the most common alteration type observed and reported within the carbonas. It is related to a postulated influx of Mg-Fe-bearing fluids which result in the replacement of feldspar and biotite by chlorite and white mica. White mica is usually associated with the chlorite and is likely to have formed by an excess Fr ions generated during alteration. Major element geochemistry of carbona rocks from Wheal Roots confirm enrichment in Mg and Fe (chlorite development) and Ca (fluorite development) and the depletion of Na and K (removal of feldspars). Experimental studies of Jackson and Helgeson (1985) have shown that an increase in pH can be important for destabilizing Sn-bearing complexes. Eadington (1985) states that alteration is a factor in the deposition of cassiterite, where both the pH and redox state of the fluids will be controlled by fluid/ rock reactions. Much of the wallrock alteration that took place within the carbonas involved Fr metasomatism (e.g. chloritization and sericitization); the consequent removal of Fr ions from the fluid would aid the deposition of cassiterite. Fluid inclusion minimum trapping temperatures indicate that mineralization and alteration took place between 233-398°C which is in agreement with the cassiterite precipitation range (250-400°C) reported by Eadington (1985).

In conclusion, carbona systems, whilst historically relatively unimportant, prove to be a complex and fascinating style of tin mineralization. Work to further our understanding of these bodies is unlikely since, except for Wheal Roots, they are no longer accessible. As elsewhere in the orefield, their genesis is related to complex micro- and macro-fracture development which controlled fluid flow through enhanced rock permeability and fracture connectivity (Dominy *et al.,* 1995b; 1996). Mineralizing fluids are believed to be magmato-hydrothermal in origin linking them closely with the main-stage fluids of the lode-style deposits, though meteoric fluids were dominant during late-stage reactivation.

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