

THE CASSITERITE-ANATASE-ILMENITE-MONAZITE-SULPHIDE- CHLORITE ASSEMBLAGE OF NORTH TINCROFT LODE

N. G. LEBOUTILLIER¹, R. K. SHALL¹ & C. JEWSON²



LeBoutillier, N. G., Shall, R. K., Jewson, C. 2000. The cassiterite-anatase-ilmenite-monazite-sulphide-chlorite assemblage of North Tincroft Lode. *Geoscience in south-west England*, **10**, 050-057

North Tincroft Lode (New Cook's Kitchen Mine) forms a segment of an ENE-WSW-striking lode structure that can be traced for —2 km along strike and —800 m vertically through the Camborne-Redruth mining district. Lode samples from previously undescribed shallow workings between deep and shallow adit levels (-28-45 m below surface) have been analysed by optical microscopy, SEM and XRD, and reveal a complex polymetallic mineralogy. Cassiterite, arsenopyrite, chalcopyrite and sphalerite (\pm galena inclusions) occur in a dense, non-brecciated, chlorite \pm fluorite \pm quartz matrix and are accompanied by significant monazite, anatase and ilmenite. All phases are fine-grained (<200 μ m diameter) and the paragenetic relationships suggest rapid, telescoped, infilling of the lode by cassiterite, monazite and ilmenite, in a matrix of sulphides and chlorite. Vugs within the matrix contain euhedral single crystals, twins and intergrowths of anatase and monazite, with less common cassiterite, chalcocite, chalcopyrite, bornite, cuprite, ilmenite, goethite, langite, brochantite, marcasite, arsenopyrite, pyrrhotite, sphalerite and apatite. The North Tincroft Lode, with its cassiterite-sulphide-chlorite assemblage, is faulted by Pryce's Lode at the 175 fathom level (-320 metres below surface). The mixing between magmatic-hydrothermal and meteoric fluids previously inferred to generate such assemblages must therefore have occurred early in the mineralisation history and was possibly coeval with development of cassiterite-tourmaline assemblages at depth.

¹ Camborne School of Mines, University of Exeter, Redruth, Cornwall TR15 3SE

² Lower Carneggy Cottage, Lower Carneggy, Threemilestone, Truro, Cornwall TR4 8QL

INTRODUCTION

The majority of the scientific investigations of Cornish lodes (fracture-hosted polymetallic veins) occurred during the late 19th and 20th centuries and relate to observations around and below the granite contact, where hypothermal (>300°C) mineralisation, dominated by tourmaline and cassiterite, was typically predominant. In contrast there are few detailed studies of the upper levels of such lodes, which were generally worked in the 18th and early 19th centuries. It was with this in mind that the area between the deep and shallow adit levels on North Tincroft Lode (New Cook's Kitchen Mine) was accessed, via Engine Shaft, and samples of the lode material were taken from stope pillars. The resulting mineralogical investigation, described here, has produced a snapshot of the mesothermal extension to a major hypothermal lode system that is more complex than originally anticipated.

NEW COOK'S KITCHEN MINE

New Cook's Kitchen Mine [SW 665406] was situated between Camborne and Pool (Figure 1). The mine (roughly 250 m N-S and 450 m E-W), lying between the setts (mineral lease areas) of Dolcoath Mine (to the west) and Tincroft Mine (to the east) was originally the northern part of Cook's Kitchen Mine. The New Cook's Kitchen section was divided from the parent sett in 1872 as a separate company (Morrison, 1980) and was eventually abandoned in 1893. The sett was acquired by South Crofty Mine in 1899 and in 1907 the vertical New Cook's Kitchen Shaft was begun on the sett's northern boundary and continued as one of the principal shafts until closure in 1998.

North Tincroft Lode (known as North Lode in the neighbouring Tincroft Mine) was the principal lode of the New Cook's Kitchen sett. The lode was accessed via Engine Shaft (almost central within the sett) and a number of shafts closer to the outcrop position along the southern boundary, the most important of which was East Shaft (Figure 2). Engine Shaft was sunk vertically to the 13 fathom level,

below adit (-67 metres), then was driven on a crosscourse (one of a group of NNW-SSE trending chalcidony-bearing wrench faults, that are aligned normal to the principal lode strike) with a steep easterly dip until intersecting North Tincroft lode at the 95 fathom (~174 metres) level (Dines, 1956). From this point the shaft was driven on the northerly dipping lode until the 195 fathom (~325 metres) level (just below South Crofty's 175 fathom level). New Cook's Kitchen Mine was a financial failure, losing £53,471 of shareholder's capital during its 21 year lifespan; this was not a reflection of poor grades, but of poor rates of development and the lack of a set of stamps and processing equipment to produce tin concentrate (Morrison, 1980). The North Tincroft stopes were reworked by South Crofty during the early 20th century, following significant discoveries of ore in the shallow workings around East Shaft, which for a time accounted for 33% of total production (South Crofty, 1909).

NORTH TINCROFT LODE

The North Tincroft Lode strikes ENE-WSW and crops out along the southern boundary of the sett, some 200 m south of Engine Shaft, where it dips to the north at around 30°. It passes through shallow adit level (~28 m below surface) and steepens slightly to ~35° by deep adit level (~45 m below surface), just below which it steepens markedly to ~60-65° and continues with this inclination through the granite-killas contact at the 100 fathom level (~182 metres below surface). At around the 175 fathom level (~320 metres) it is displaced by the southerly dipping Pryce's Lode with an extensional separation of ~73 metres (Figure 3). Below this intersection it is known as Main Lode and persists to South Crofty's 315 fathom level (~570 metres) where the structure hinges into the hangingwall of South Crofty's No. 1 Lode, which has been proved to a point below the 400 fathom level (~730 metres). Main Lode was South Crofty's principal lode up to the 1950's and has been correlated with East Pool Mine's Great Lode and Barncoose Lode of Barncoose Mine. The North Tincroft structure and its branches therefore persist vertically for ~800 m from surface and can be traced along strike for distances in excess of 2 km.

PREVIOUS STUDIES

Despite forming one of the major lode structures of the Camborne-Redruth Mining District comparatively little is known about the mineralogy of the North Tincroft lode system and accounts that do exist are sometimes contradictory. The shallow extension of North Tincroft Lode and its neighbours were worked from the mid-16th century onwards (Buckley, 1997), initially for tin (occurring in the gossans) and later for copper as the water table was approached. Maclaren (1919) states that North Tincroft Lode was principally a copper lode and did not produce tin until the granite contact was reached (though South Crofty records refute this); Hill and MacAlister (1906) record that the top of the tin zone in Cook's Kitchen Mine was at 200 fathoms (-365 metres) from surface (probably on Chapple's Lode), while in the neighbouring Tincroft Mine, tin was present continuously from surface, occurring with Pb, Zn and Cu sulphides. This latter paragenesis is also recorded in the shallow workings of the nearby North and South Roskear Mines (Came, 1822) together with arsenopyrite (Henwood, 1843) and oral tradition at South Crofty spoke of North Tincroft Lode being divided into a copper-rich hangingwall zone (removed at an early date) and a tin-rich footwall zone not worked until the 1870's.

Later accounts relate mainly to the down-dip extensions of North Tincroft Lode, such as the workings on Great Lode (East Pool Mine) and Main Lode (South Crofty Mine) and are supplemented by recent data from South Crofty Mine. The shallow workings are briefly described by Dines (1956, p.314) in relation to Tincroft Mine, but contain little data relating to the nature of the lode.

FIELD RELATIONS

Lode and stope geometry

North Tincroft lode was accessed via the vertical upper section of Engine Shaft, which intersects the deep adit level 45 m below surface. From this point a drive runs south for some 65 m before the lode drive is reached. The lode in this area is variably stoped above the drive and also, in places, below, with sections of the drive floor mined away. A number of drives and minor stopes on sub-parallel structures also exist.

The stopes and drive walls were coated with limonite and occasional blooms of secondary copper sulphates, which generally obscured primary contacts. All of the observed stopes had a gentle northerly dip of 30-35° with an average width of 1 metre (refer to photographs of the stopes in Deakin *et al.*, 1999, pages 20 - 25); however, the largest stope, both in terms of width and strike span, had a width in excess of 4 metres. The stope, measuring ~30 metres along strike and in excess of 50 metres up dip, is supported by a series of rock pillars and timbers (as are all the other stopes). At a distance of some 30 metres up dip from deep adit level, the shallow adit (which has been mined through) can be seen penetrating some of the pillars. Above shallow adit level the stope runs up dip, coming close to surface in the vicinity of East Shaft.

Lode mineralogy

The lode is hosted in slates (killas) of the Upper Devonian Mylor Slate Formation (Leveridge *et al.*, 1990). The slates are dark grey and hornfelsed with occasional cordierite spotting. Sampling across lode margins revealed sharp contacts of the chlorite-dominated infill with the host slates and minimal wallrock alteration. The lode is consequently interpreted as a fissure-fill type structure. The lode infill comprises chalcopryrite and arsenopyrite in a matrix of dark green chlorite with minor, light green to pale green, fluorite and quartz. The sulphides occur primarily as disseminations throughout the matrix (particularly the arsenopyrite) but also as thin discontinuous vein fills, up to 5 mm wide, and small vugs. Some samples showed small sparable (named after the similarity of crystal form to the long, tapered 'sparrow's bill' nails used by the mine timbermen) cassiterite crystals, up to 2 mm in length, occupying vugs, but these are not common. The chlorite is dense and microcrystalline (though some

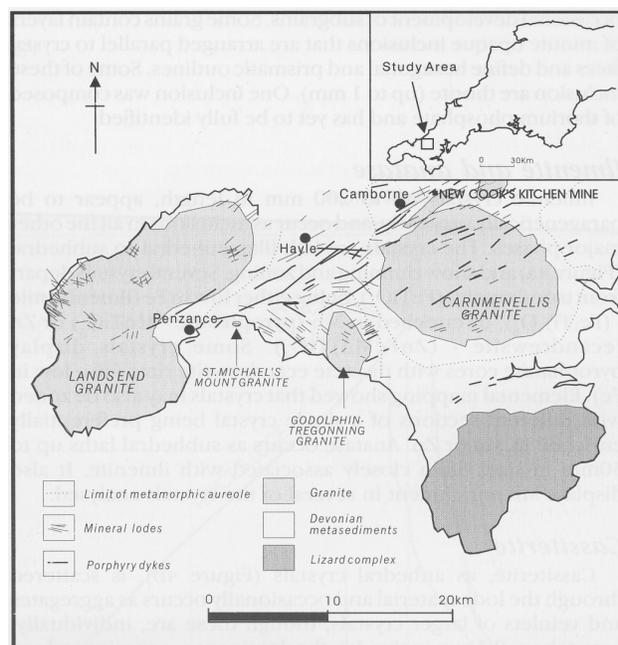


Figure 1. Sketch geological map showing the location of New Cook's Kitchen Mine.

crystals can be made out with a hand lens) with some pale green earthy patches. The fluorite occurs as anhedral crystals in discontinuous veins and vugs, sometimes singly, sometimes intimately intergrown with chlorite and sulphides. A thin veneer of limonite and occasional streaks of chalcantite ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$) and connellite ($\text{Cu}_{19}\text{Cl}_4(\text{SO}_4)(\text{OH})_{32} \cdot 3\text{H}_2\text{O}$) occurs on joint surfaces. The lode material is very dense and immediately suggested a high metal content, though from hand specimen examination it was unclear which was the dominant phase.

MINERALOGY

Analytical methods

Mineralogical analysis of the lode material was undertaken using: (i) optical examination of 10 x 10 mm fragments using a Wild M8 binocular microscope at 50-100 x magnification, (ii) transmitted light microscopy of thin-sections, (iii) SEM examination (using a JEOL 840 connected to a LINK Oxford Instruments AN10000 EDS), and (iv) XRD analysis using the Siemens Diffraktometer D5000.

Chlorite, fluorite and quartz (gangue mineralogy)

Chlorite (dominant), quartz and fluorite define a uniform matrix in which there are a large number of vugs, typically ~24 mm in diameter. Chlorite occurs as a mass of interfering rosettes of varying sizes (with rare spots of limonite). Individual subhedral to euhedral platy masses up to 0.1 mm in diameter usually vary in colour from deep to pale olive green, but are occasionally pale yellow or brown; thin slivers appear almost colourless. The chlorite species is confirmed by XRD as a ferroan member of the clinocllore family $(\text{Mg,Fe})_3\text{Al}(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH})_8$, likely to be ripidolite. Zones of parallel chlorite plates define "channels" up to 1 mm in width between the rosettes (which they do not cut); they contain very little cassiterite and are poor in sulphides (present as much smaller grains than elsewhere).

Fluorite infills irregular vugs and veins up to 50 mm in width and is typically anhedral and inclusion-rich (chlorite and subhedral to euhedral unstrained quartz); it is locally cut by narrow (<1 mm) chlorite veins.

Quartz is generally anhedral (although some amorphous masses occur), often showing undulose extinction and the occasional

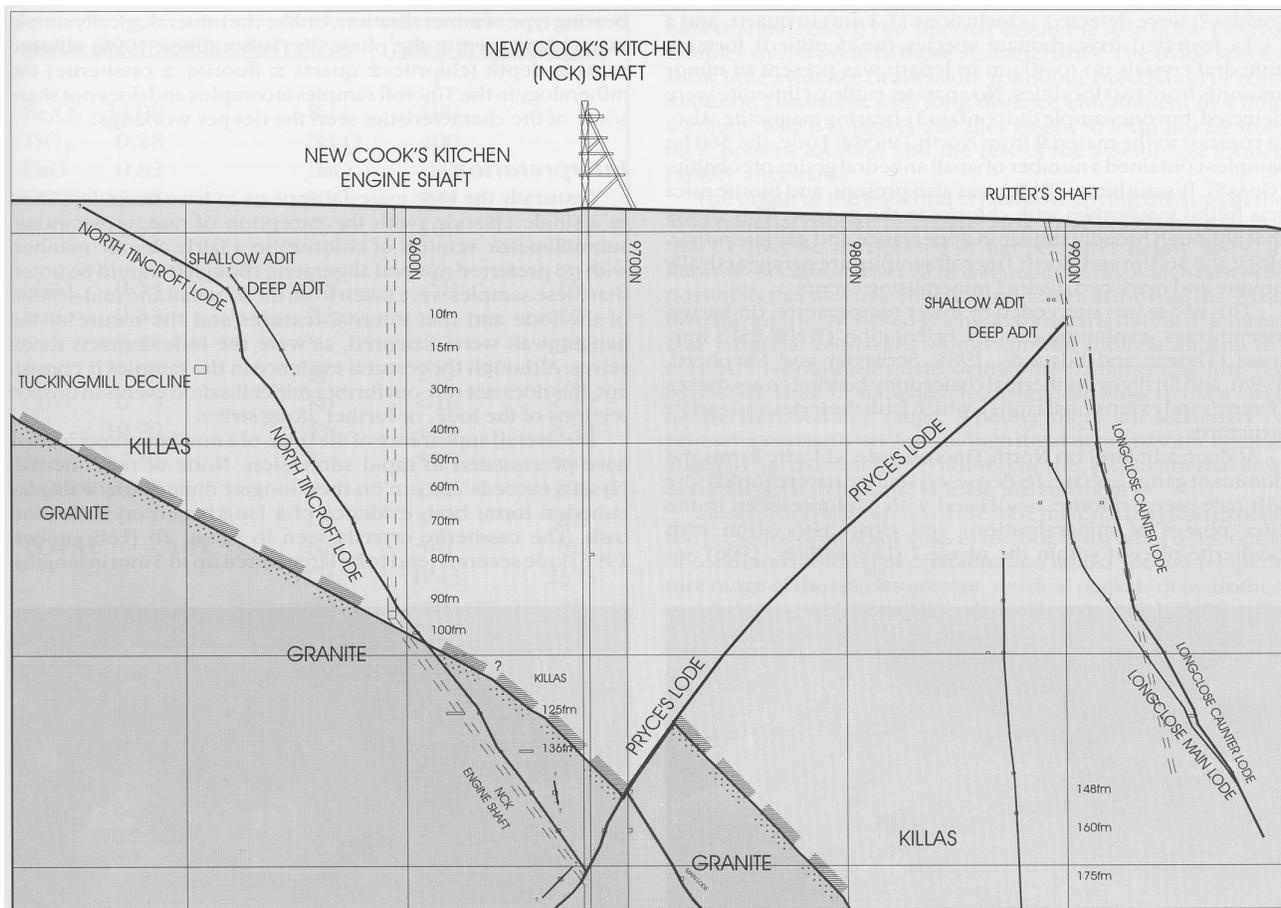


Figure 3. Long section of South Crofty Mine. Showing the position of North Tincroft Lode, Pryce's Lode, Deep Adit and Shallow Adit levels. The mine grid (100 metre squares) is metric, but levels are referred to in traditional imperial fathoms.

They are typically subhedral to anhedral in form.

Chlorite, quartz and fluorite appear to have precipitated last in the sequence. Fluorite and quartz are anhedral and quartz, in particular, occurs infilling small spaces between chlorite plates (in much the same manner as some of the monazite crystals). Chlorite (forming the bulk of the gangue) generally encloses quartz and fluorite, but rare veinlets, < 1 mm in width, were observed cutting some of the fluorite grains.

The vugs carry an extensive suite of minerals (Table 2) in addition to those described above; their relationship to the above paragenetic sequence cannot be adequately determined as they usually occur as single crystals lining the vugs. However, it is likely that they overlap with the latter part of the above sequence and continue beyond in paragenetic time.

DISCUSSION

North Tincroft Lode is hosted by a northerly dipping fault, which is cut and displaced by a southerly dipping post-granite emplacement fault (now hosting Pryce's Lode). The development of high-angle extensional faults occurs throughout the region prior to, during and after granite emplacement (Alexander and Shail, 1995, 1996; Andrews *et al.*, 1998). The Carnmenellis Granite, into which North Tincroft Lode passes at the 100 fathom (182 metres) level has been radiometrically dated at 293.7 — 289.7 Ma (Chen *et al.*, 1993; Chesley *et al.*, 1993) whilst the hypothermal 'blue peach' (tourmaline-quartz-cassiterite) assemblages of the deeper lodes at South Crofty Mine, have been dated at 286 Ma (Clark *et al.*, 1993) giving a minimum 4 million year hiatus between the onset of magmatic crystallisation and the early stages of tin mineralisation in the outer part of the granite.

Lode mineralogy and paragenesis

The main stage lodes in the deeper levels of South Crofty Mine (445 fm to 290 fm; ~815 to 530 metres) are dominated by this 'blue peach' assemblage (phase 2a of LeBoutillier, 1996). These lodes cut or reactivate earlier W-As-bearing 'quartz floors' and pegmatites (Taylor, 1965; Farmer, 1991). The lodes are characterised by brecciation textures indicative of decompressive hydraulic fracturing (Halls, 1987, 1994) and may show evidence of a number of fracturing/precipitation events. As the lodes are followed up dip the character of the gangue mineralogy changes, with tourmaline becoming less important and chlorite ± fluorite ± haematite assemblages becoming dominant. Dines (1956) describing Main Lode (the down dip extension of North Tincroft Lode) on the 175fm level records little or no tourmaline present with chlorite as the principal gangue phase, associated with fluorite and comb quartz. Brecciation textures are found infrequently at these elevations, with dilational layered infilling becoming the norm, marking a shift to less energetic fracturing processes and lower fluid pressure levels. Farmer (1991) also records the gradual decline of tourmaline away from the deeper levels of the mine, until it becomes subsidiary to chlorite above the 180 fathom level (~330 metres).

Later phases of mineralisation were also characterised by the deposition of chlorite (often emplaced along the hangingwall of the lode) in many of the lodes in the deeper levels of the mine (phase 2b of LeBoutillier, 1996), often displaying simple dilational infilling textures. A comparative set of samples (from 360 fathom level (~660 metres), South Crofty Mine) from this phase was examined by optical and SEM methods. These showed the presence of large euhedral, zoned, cassiterite crystals in a chlorite-quartz-fluorite gangue; no monazite was present, but Ce and La (oxides?) were detected as

inclusions (1-2 Am) in quartz, and a Ce/La hydrated oxycarbonate species (unidentified) forming anhedral crystals up to 40 µm in length was present in minor amounts from two localities. No anatase, rutile or ilmenite were detected, but one sample did contain Ti-bearing magnetite. Also, in contrast to the material from North Tincroft Lode, the 360 fm samples contained a number of small anhedral grains of cobaltite (CoAsS). Bismuthinite (Bi₂S₃) was also present, and biotite mica was found intergrown with chlorite in the gangue. This shows that although broadly similar in appearance and gangue mineralogy, the 360 fm and North Tincroft samples are paragenetically unique and mark two distinct mineralising events.

This phase was succeeded by lower temperature, tin-barren assemblages, exploiting caunter orientation (WNW-ESE) fractures (Thorne and Edwards, 1985; Scrivener and Shepherd, 1998), and finally by epithermal chalcidony-bearing crosscourses (wrench and extensional faults), which fault the lodes and earlier structures.

At deep adit level on North Tincroft lode, chlorite forms the dominant gangue phase. Its dense, crystalline nature (unlike the soft pale-green chlorite, associated with kaolinite, seen in the later phases of mineralisation) and close association with cassiterite place it within the phase 2 (LeBoutillier, 1996) Sn bearing type of mineralisation.

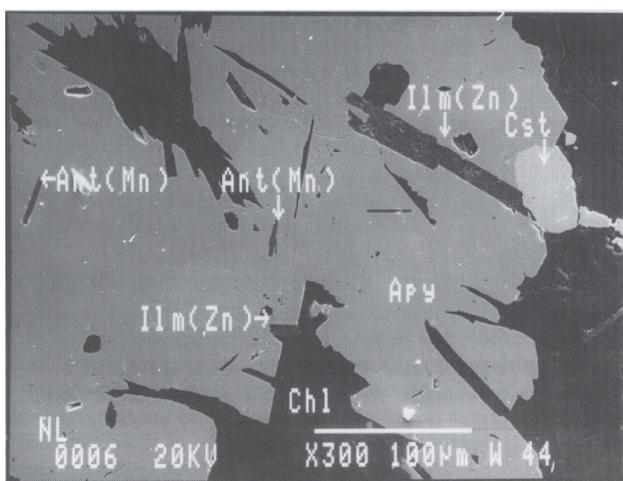


Figure 4a. SEM photograph. Anatase (Ant) and ilmenite (Ilm) crystals within arsenopyrite (Apy) & chlorite (Chl), with cassiterite (Cst). Much of the anatase is manganeseiferous (marked Mn) and much of the ilmenite is zinc-rich (marked Zn), bordering on ecandrewsite.

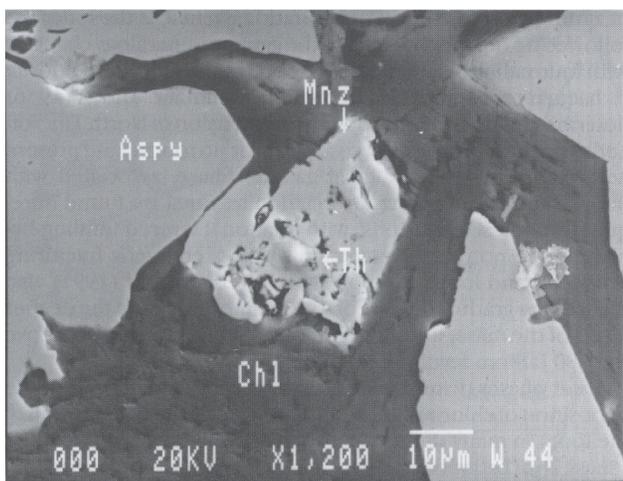


Figure 4c. SEM photograph. Anhedronal monazite crystal (Mnz) with thorite (huttonite?) inclusion (Th), within arsenopyrite (Apy) and chlorite (Chl) matrix.

Unlike the mineralogically simple assemblage seen in the phase 2b (LeBoutillier, 1996) chlorite veins at depth (chlorite ± quartz ± fluorite ± cassiterite) the mineralogy in the Tincroft samples is complex and does not share some of the characteristics seen the deeper workings.

Interpretation

Texturally the lode material appears to have been deposited in a single episode (with the exception of rare, crosscutting, submillimetric veinlets of chlorite) in a fairly chaotic manner, with no preferred mineral alignment; though it should be noted that these samples were taken from the footwall and mid-section of the lode and that internal textures and the nature of the hangingwall were obscured, as were the lode contacts themselves. Although the textural evidence in the samples is consistent, this does not rule out further mineralisation events in unseen sections of the lode, or further along strike.

The overall appearance of the ore is of a number of species that have precipitated in rapid succession. None of the 'internal' crystals exceeds 200 µm on their longest dimension or display euhedral form; both evidence of a lengthened crystallisation path. The cassiterite crystals seen in phase 2b (LeBoutillier, 1996) lode sections tend to be large (often up to 5 mm in length), euhedral and zoned. The 'internal' cassiterite seen in the Tincroft samples shows none of those

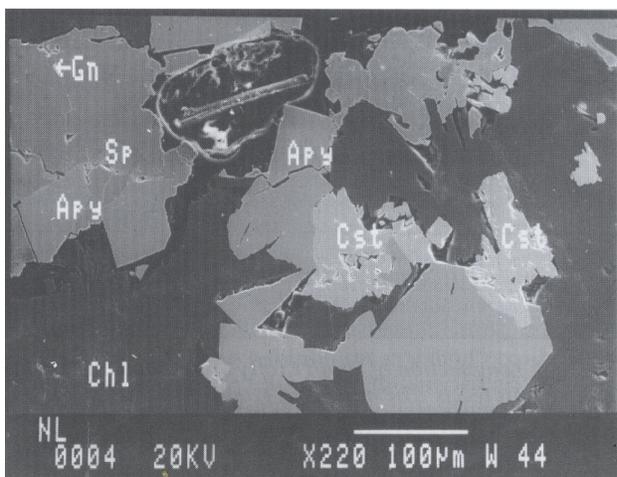


Figure 4b. SEM photograph. Anhedronal cassiterite (Cst) crystals, intergrown with arsenopyrite (Apy) and sphalerite (Sp) in chlorite (Chl). Note the inclusion of galena (Gn) within the sphalerite grain.

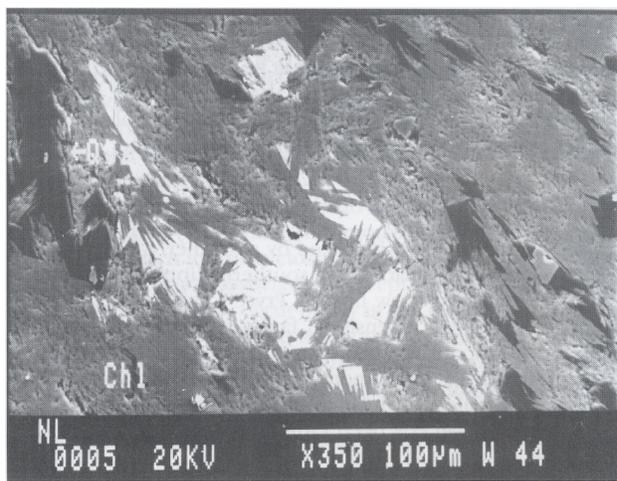


Figure 4d. SEM photograph. Late monazite (Mnz) crystals within the Chlorite (Chl) matrix, producing an 'interdigitating' texture. Here the texture is also produced by similarly late-stage anhedronal quartz (Qtz) crystals.

MAJOR and MINOR ELEMENTS WT%		TRACE ELEMENTS ppm			
		1		2	
Fe ₂ O ₃	34.08	K ₂ O	400		
TiO ₂	0.28	Na ₂ O	400		
CaO	0.82	BaO	100		
SiO ₂	13.28	NiO	100		
Al ₂ O ₃	11.99	Cr ₂ O ₃	100		
MgO	0.54	Nb	59	69	
MnO	0.33	Zr	0	67	
S	5.44	Y	12	21	
P ₂ O ₅	0.08	Sr	210	130	
CuO	0.73	Rb	<10	<10	
Sn	10.7	Th	<10	<10	
As	12.51	Co	556	561	
L.O.I%	10.73	V	212	181	
		La	413	489	
TOTAL	101.51	Nd	541	702	
		Ce	1743	2373	
		Ga	60	65	
		Pb	967	834	
		Zn	2803	2663	

Table 1. XRF whole rock analysis for a sample from North Tincroft Lode. Major oxides in wt% and trace elements in ppm (note: two samples were used in the trace element analyses).

characteristics. The oxide species show little evidence of abrasion, rounding, brecciation or comminution consistent with long distance entrainment in a fluid medium, which suggests that they began to form not far from their present location and the rest of the assemblage formed rapidly afterwards.

The origin of the euhedral crystals occupying the vugs in the lode material is open to debate; Hole *et al* (1992) have shown that Ce may be transported at temperatures below 300°C in fluoride- or carbonate-enriched aqueous fluids, which raises the possibility that the large euhedral monazites in the vugs may postdate the internally locked grains. Radiometric dating of internal and 'external' monazites would confirm the relationship between the two and give a date for this phase of mineralisation. The remaining suite of minerals occupying the vugs spans a large temperature/stability range. Whether these are secondary or primary is currently unclear, though the absence of some of these species (e.g. marcasite, pyrrhotite, cuprite, etc) in internal locations suggests that some, at least, are secondary.

The rapid crystallisation of the lode material may also explain the presence of so many vugs in the ore. With rapid telescoping of conditions leading to crystallisation across the full temperature range of the species present, residual pockets of hydrothermal brines could become sealed off as isolated 'fluid cells' encased in chlorite. If these brines still contained metal ions in halide complex form, it is logical to assume that over time with changing P/T conditions, the dissolved phases would precipitate forming euhedral crystals in the available free space. The remaining fluid would escape over time along intergrain boundaries.

The most unusual feature of the ore is the high concentrations of Ti and Ce, in levels above (in the case of Ce, far in excess of) the background found in the granites. Cerium is most likely to have been partitioned into the fluids of magmatic departure as an incompatible element (Bromley, 1989). Monazite is not recorded in the deeper levels

MINERAL SPECIES		Binocular Microscopy	PPL/XPL Microscopy	S.E.M	X.R.D
CHALCOCITE	Cu ₂ S	✓			✓
CHALCOPYRITE	CuFeS ₂	✓	✓	✓	
BORNITE	Cu ₅ FeS ₄	✓		✓	
CUPRITE	Cu ₂ O	✓			
BROCHANTITE	Cu ₄ (SO ₄)(OH) ₆	✓			
LANGITE	Cu ₄ (SO ₄)(OH) ₆ .2H ₂ O	✓			
ARSENOPYRITE	FeAsS	✓	✓	✓	✓
SPHALERITE	ZnS	✓		✓	
GALENA	PbS			✓	
Unknown Pb sulphide			✓		
NATIVE BISMUTH	Bi			✓	
PYRRHOTITE	Fe ₂ - _x S	✓			
PYRITE	FeS ₂	✓		✓	
MARCASITE	FeS ₂	✓			
GOETHITE	FeO(OH)	✓			
APATITE	Ca ₅ (PO ₄) ₃ F	✓		✓	
FLUORITE	CaF ₂	✓	✓		
ANATASE	TiO ₂	✓		✓	
ILMENITE	FeTiO ₃	✓	✓	✓	
ILMENORUTILE	(Ti,Nb,Fe) ₃ O ₆			✓	
ECANDREWSITE	(Zn,Fe,Mn)TiO ₃			✓	
PYROPHANITE	MnTiO ₃			✓	
CASSITERITE	SnO ₂	✓	✓	✓	✓
THOME	Th,U)SiO ₄			✓	
Unknown Th phosphate			✓		
MONAZITE	(Ce,La,Nd,Th)PO ₄	✓	✓	✓	
QUARTZ	SiO ₂	✓	✓	✓	✓
CHLORITE	(Mg,Fe) ₅ Al(Si ₃ Al)O ₁₀ (OH) ₈	✓	✓	✓	✓

Table 2. All mineral species identified to date from North Tincroft Lode.

A RELATIVE PARAGENESIS FOR THE NORTH TINCROFT LODGE

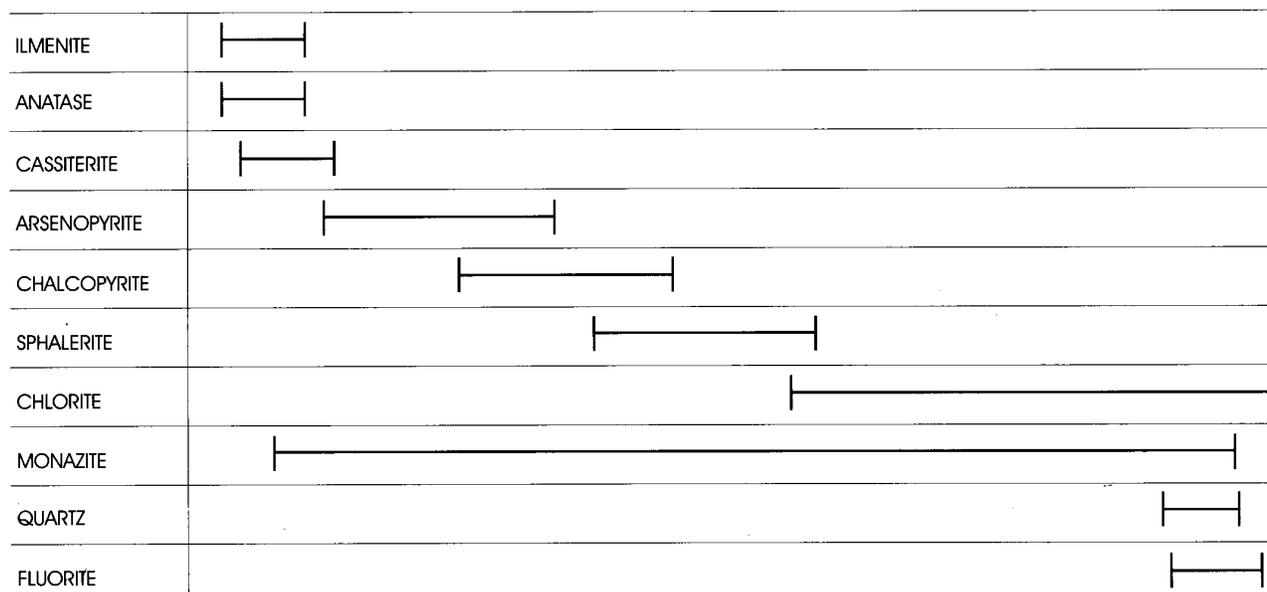


Figure 5. A relative paragenesis of the major species present in the lode material from North Tincroft Lode.

of South Crofty, either in the tourmaline- or chlorite-dominated assemblages. The source of the titanium is most likely to be from the breakdown of biotite mica in the wall rocks adjacent to the lode fissures. Tourmalinisation and chloritisation of the wall rocks would result in the breakdown of feldspars and micas (Farmer, 1991; Taylor, 1965; Scrivener, 1982) releasing Fe, Mg, Al and Ti into the reacting fluids. Such reactions have been estimated to take place at around 400°C (Alderton, 1993) initially, with fluids of magmatic origin dominating in the early stages. The Ti-bearing species represent elements 'flushed out' of the wall rocks and carried to higher elevations by fluids with an important (if not dominant) magmatic component. Ti, most likely complexed as titanium chloride, $TiCl_4$, has an aggressive chemistry and is highly reducing; it would readily form oxides and crystallise in the rising fluids (Taylor, 1979). It is this behaviour that is responsible for the appearance of ilmenite and anatase at the beginning of the paragenetic sequence.

The nature of the fluids responsible for this phase of mineralisation is open to question. Fluid inclusion studies have shown that the deeper, tourmaline-dominated, assemblages were deposited from a combination of magmatic and meteoric fluids at between 450°C-250°C (Jackson *et al.*, 1989; Scrivener and Shepherd, 1998; Alderton, 1993) with high salinities (> 20% NaCl equiv.). The Cu-Fe-As (\pm Sn)-chlorite assemblage (phase 2b equivalent; LeBoutillier, 1996) typically shows T_h values from 350°C-200°C and lower salinities (5-20% NaCl equiv.) and is thought to represent a greater input from meteoric water sources. O and H isotopic data for the hydrothermal fluids that deposited the main stage lodes suggests an overwhelmingly meteoric origin for these fluids (Jackson *et al.*, 1989), but detailed studies of how mixing of magmatic and meteoric fluids influences the isotopic ratios has still to be completed (Alderton, 1993) and the data on its own is inconclusive. Sulphur isotope ratios (Jackson *et al.*, 1989) suggest two distinct sources; one primary magmatic and a second from sedimentary diagenetic pyrite.

Temperature data from fluorite samples taken from Pryce's Lode of South Crofty Mine (Bradshaw and Stoyel, 1968) shows a temperature range from 285°C to 250°C, with a fall in temperature upwards of roughly 10°C/100 metres. Extrapolating this to the location where the current samples were taken would give a homogenisation temperature of 200°C; at the lower limit of the Cu-Fe-As (\pm Sn)-chlorite assemblage temperature range. However, the fluorite present in the lode at the sample depths (148 - 315 fathoms;

~270-570 metres) is from a later paragenetic stage (phase 3; LeBoutillier, 1996) than that of the Tincroft assemblage, which suggests temperatures of deposition for the Tincroft samples were higher.

CONCLUSIONS

At South Crofty Mine paragenetic studies have helped to develop a broad framework for the mineralisation of the mine as a whole (Farmer, 1991; LeBoutillier, 1996). The paragenetic sequence seen here (and throughout the rest of Cornwall) is complex and, on a global scale, rare, particularly in relation to the association of chlorite with cassiterite. Taylor (1979) lists only four other tin fields (Chukotka, Miao-Chang Amur and Sikhote Alin in the Russian Far East and Herberton in Queensland, Australia) that show structural and paragenetic similarities with Cornubia. The lode samples taken on North Tincroft Lode represent a paragenesis not previously described at South Crofty Mine.

The lode samples suggest rapid crystallisation from a hydrothermal fluid upon encountering a rapid change in PIT conditions, forming a telescoped deposit. The reasons for this change in conditions are unclear and could be due to a rapid drop in temperature away from the granite contact or interaction with cooler meteoric and connate waters in the killas. The lode material appears to have been deposited in a single event and is inferred to form part of a continuous depositional sequence with the 'blue peach' assemblage seen at lower levels. Not only does the lode material not resemble the chlorite-dominated assemblages seen at depth, but also the faulting by Pryce's Lode would mitigate against the North Tincroft section of the lode being reactivated during phase 2b deposition; suggesting that the lode material sampled is from an early (phase 2a) event.

The close spatial and temporal association of tin and arsenic with copper, zinc and lead points to a common origin and does not allow time for a protracted addition of these chalcophile elements to the host fluids, nor is there any evidence that these species are replacements of pre-existing minerals. The inference of a common origin suggests that zinc, copper and lead were made available by the rapid addition of meteoric waters to the ore-bearing fluids at depth, or were present in the residual fluids in the late stages of the crystallisation of the granite and that they were supplied to the magma by assimilation of the country rocks.

The nature of the ore-bearing fluids remains unclear; however, we can infer a mesothermal temperature of deposition and that the fluids had a strong magmatic component.

Since work on this project began, a number of other localities have produced a similar chlorite-anatase-monazite suite (C. Jewson, *pers comm.*). This material has been collected from mine dumps and therefore the original location within the lode system is unknown; nor is it consistent in content, some samples do not contain any sulphides or cassiterite, while others closely match the Tincroft material. All carry monazite, which may form larger crystals than seen in the North Tincroft samples, and blue to colourless anatase (in a variety of crystal forms), with rare brookite, in a chlorite matrix. Sites so far include South Tolcarne Mine (near Beacon, Camborne), South Roskear Mine (Camborne) and South Caradon Mine (near Liskeard). Ongoing studies of estuarine sediments, from around the Cornish coast (Pirrie *et al* 2000), have also detected the presence of monazite, anatase, ilmenite and other Ti species coincident with peaks in the cassiterite and Cu/Zn/Pb sulphide content of the sediments, related to past mining activity. This suggests that this paragenesis may be more common than anticipated and be typical of high-level main stage lodes across the orefield.

ACKNOWLEDGEMENTS

We would like to thank the following for their invaluable contributions to this work. At Camborne School of Mines: Fiona Thomas LRSC for obtaining the XRF results from difficult material; Tony Ball for SEM and XRD analysis and photography, and Steve Pendray and Julian Curnow for the manufacture of polished mounts and slides. Dr Matt Power for SEM analysis of the samples from South Crofty Mine; Dr Jens Andersen for discussion and constructive criticism on an earlier version of this manuscript and Simon Camm for permission to reproduce Figure 1.

Mr N J Hoppe, of Perranporth, for micro mineral photography.

David Giddings, managing director of South Crofty PLC, for access to South Crofty Mine; Paul MacDonald for arranging underground visits and Alan Reynolds for acting as guide in the Tincroft workings.

NGL wishes to thank the University of Exeter for PhD funding.

REFERENCES

- ALDERTON, D.H.M. 1993. Mineralization associated with the Cornubian granite batholith. In: PATRICK, R.A.D. & POLYA, D.A. (eds) *Mineralization in the British Isles*, Chapman and Hall, 270-354.
- ALEXANDER, A.C. & SHAH, R.K. 1995. Late Variscan structures on the coast between Perranporth and St Ives, South Cornwall. *Proceedings of the Ussher Society*, **8**, 398-404.
- ALEXANDER, A.C. & SHAIL, R. K. 1996. Late- to post-Variscan structures on the coast between Penzance and Pentewan, South Cornwall. *Proceedings of the Ussher Society*, **9**, 72-78.
- ANDREWS, J.R., ISAAC, K.P., SELWOOD, E.B., SHALL, R.K. & THOMAS, J.M. 1998. Variscan structure and regional metamorphism. In: SELWOOD, E.B., DURRANCE, E.M. & BRISTOW, C.M. (eds) *The geology of Cornwall*, University of Exeter Press, 82-119.
- BRADSHAW, P.M.D. & STOYEL, A.J. 1968. Exploration for blind orebodies in southwest England by the use of geochemistry and fluid inclusions. *Transactions of the Institution of Mining and Metallurgy* (section B), **77**, 144-152.
- BROMLEY, A.V. 1989. Fieldguide to the Cornubian Orefield. Sixth international congress on water-rock interaction, Malvern, August 1989. International Association of Geochemistry and Cosmochemistry.
- BUCKLEY, J.A. 1997. A history of South Crofty Mine. Dyllansow Turan, Truro. 208pp.
- CARNE, J. 1822. On the relative ages of the veins of Cornwall. *Transactions of the Royal Geological Society of Cornwall*, **2**, 49-128.
- CHEN, Y., CLARK, A.H., FARRAR, E., WASTENEYS, H.A.H.P., HODGSON, M.J. & BROMLEY, A.V. 1993. Diachronous and independent histories of plutonism and mineralisation in the Cornubian Batholith, southwest England. *Journal of the Geological Society, London*, **150**, 1183-1191.
- CHESLEY, J.T., HALLIDAY, A.N., SNEE, L.W., MEZGER, K., SHEPHERD, T.J. & SCRIVENER, R.C. 1993. Thermochronology of the Cornubian Batholith in southwest England: implications for pluton emplacement and protracted hydrothermal mineralisation. *Geochimica et Cosmochimica Acta*, **57**, 1817-1835.
- CLARK, A.H., CHEN, Y., FARRAR, E., WASTENEYS, H.A.H.P., STIMAC, J.A., HODGSON, M.J., WILLIS-RICHARDS, J. & BROMLEY, A.V. 1993. The Cornubian Sn-Cu (-As,W) metallogenic province: product of a 30 my. history of discrete and concomitant anatectic, intrusive and hydrothermal events. *Proceedings of the Ussher Society*, **8**, 112-116.
- DEAKIN, P.R., BUCKLEY, J.A. & RIEKSTINS, K.T. 1999. South Crofty old workings. *Penhellick Publications*. Camborne. 32pp.
- DINES, I.G. 1956. The metalliferous mining region of South-West England. 2 vols. HMSO. London.
- FARMER, C. B. 1991. Paragenetic evolution of the composite lodes at South Crofty Mine, Cornwall, U.K. *Unpublished PhD thesis*, University of London.
- HALLS, C. 1987. A mechanistic approach to the paragenetic interpretation of mineral lodes in Cornwall. *Proceedings of the Ussher Society*, **6**, 548-554.
- HALLS, C. 1994. Energy and mechanism in the magmato-hydrothermal evolution of the Cornubian Batholith - a review. In: SELTMANN, KAMPF & MOLLER. (eds) *Metallogeny of collisional orogens*, Czech Geological Survey, Prague, 274-294.
- HENWOOD, W. J. 1843. On the metalliferous deposits of Cornwall and Devon. *Transactions of the Royal Geological Society of Cornwall*, **5**, 1-386.
- HILL, J.B. & MACALISTER, D.A. 1906. The geology of Falmouth and Truro and the mining district of *Camborne and Redruth*. *Memoir of the Geological Survey of Great Britain*.
- HOLE, M.J., TREWIN, N.H. & STILL, J. 1992. Mobility of the high field strength, rare earth elements and yttrium during late diagenesis. *Journal of the Geological Society, London*, **149**, 689-692.
- JACKSON, N.J., WILLIS-RICHARDS, J., MANNING, D.A.C. & SAMS, M. 1989. Evolution of the Cornubian Ore Field, southwest England: Part II. Mineral deposits and ore-forming processes. *Economic Geology*, **84**, 1101-1133.
- JEFFRIES, N.L. 1984. The radioactive accessory mineral assemblage of the Cammenellis Granite, Cornwall. *Proceedings of the Ussher Society*, **6**, 35-40.
- LEBOUTILLIER, N.G. 1996. South Crofty Mine. Geology & mineralisation. *Penhellick Publications*. Camborne. 32pp.
- LEVERIDGE, RE., HOLDER, M.T. & GOODE, A.J.J. 1990. *Geology of the country around Falmouth: Memoir for 1:50 000 sheet 352 (England & Wales)*. BGS Publication, HMSO, London, 70 p.p.
- MACLAREN, M. 1919. A report on the mineral areas of Tehidy Minerals Ltd. *Tehidy Minerals internal report*. Camborne.
- MORRISON, T.A. 1980. Cornwall's central mines. The northern district 1810-1895. Alison Hodge. Penzance. 392pp.
- PIRRIE, D., POWER, M.R., PAYNE, A., CAMM, G.S. & WHEELER, P.D. 2000. Impact of mining on sedimentation; the Camel and Gannet estuaries, Cornwall. (*In preparation*).
- SCRIVENER, R.C. 1982. Tin and related mineralisation of the Dartmoor Granite. *Unpublished PhD thesis*, University of Exeter.
- SCRIVENER, R.C. & SHEPHERD, T.J. 1998. Mineralization. In: SELWOOD, E.B., DURRANCE, E.M. & BRISTOW, C.M. (eds) *The geology of Cornwall*, University of Exeter Press, 120-135.
- SOUTH CROFTY LTD. 1909. *Commemorative pamphlet*. Camborne. 23pp.
- TAYLOR, R.G. 1965. Geology and structural control of ore deposition at South Crofty Tin Mine, Cornwall, U.K. *Unpublished PhD thesis*, Royal School of Mines, London.
- TAYLOR, R.G. 1979. Geology of tin deposits. *Elsevier*, Amsterdam, 543 p.p.
- THORNE, M.G. & EDWARDS, R.P. 1985. Recent advances in concepts of ore genesis in South West England. *Transactions of the Royal Geological Society of Cornwall*, **21**, 113-152.