Monazite in polymetallic chlorite-(tourmaline)-quartz-(fluorite)-cassiterite-sulphide lodes and its potential for constraining the chronology of magmatic hydrothermal mineralisation in Cornwall

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Monazite [(Ce, La, Th, Nd, Y) PO_4] occurs far more widely within the magmatic hydrothermal lode systems of Cornwall than has been previously recognised. *In situ* and mine dump specimens analysed by binocular and transmitted light microscopy, SEM, XRD and whole rock XRF reveal a near ubiquitous association of hydrothermal monazite with polymetallic chlorite-(tourmaline)-quartz-(fluorite)-cassiterite-sulphide mineralisation. The assemblage is interpreted to represent an early lode paragenesis formed by mixing of magmatic hydrothermal fluids with meteoric and/or metamorphic fluids derived from the country rocks. Such a model may explain why these assemblages are not observed in mines that have worked at greater depths within the granite. Major advances in understanding the chronology of granite magmatism across SW England using U-Pb monazite and xenotime methods have not, to date, been matched by the same level of success with respect to the development of the productive major lode systems. This discovery of widespread hydrothermal monazite raises the potential for high precision U-Pb dating of such mineralisation across the Cornubian Orefield. Where paragenetic relationships can be established it may also be possible to construct a fine-scale chronology for individual lode systems.

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INTRODUCTION

Monazite occurs as a cerium (Ce) or lanthanum (La) phosphate [(Ce, La, Th, Nd, Y) PO_4] and, although commonly regarded as an accessory mineral in acid igneous rocks, can form in a variety of settings including diagenetic (Evans and Zalasiewicz, 1996; Evans *et al.*, 2002), low- to high-grade regional metamorphic (Rasmussen *et al.*, 2001; Foster *et al.*, 2002) and hydrothermal (Vielreicher *et al.*, 2003). The first recorded occurrence of monazite within the British Isles was at Lanterdan Quarry, near Tintagel (Miers, 1885; Bowman, 1900; Collins, 1892). It was subsequently identified in all of the principal granite plutons in Cornwall (Ghosh, 1928; Chatterjee, 1929; Jefferies, 1984; Floyd *et al.*, 1993; Lucas, 1993). Monazite was identified as a common accessory mineral in metasediment-hosted hydrothermal veins in general (Bromley, 1989) and has since been described in detail from locations of this type at Penberthy Croft and Croft Gothal mines in west Cornwall (Betterton, 1996a,b). The widespread occurrence of detrital monazite within Cornish estuarine sediments, in part derived from fluvial catchments in former mining areas (e.g. Pirrie *et al.*, 1999; 2000; 2002a,b), suggests that this latter setting might be far more common than previously recognised. This paper provides preliminary data from *in situ* and mine dump samples that: (i) confirm a near ubiquitous occurrence of hydrothermal monazite within polymetallic chlorite-(tourmaline)-quartz-(fluorite)-cassiterite-sulphide lodes, and (ii) highlights its potential for high precision U-Pb dating of magmatic hydrothermal mineralisation across the province.

METHODS

Examination of lode material from a total of ten mines across Cornwall (see Figure 1), taken from dumps and shallow underground exposures, was undertaken using: (i) optical examination of 10×10 mm fragments using a Wild M8 binocular microscope at 50-100 $\times$ magnification, (ii) transmitted light microscopy, (iii) Scanning Electron Microscope (SEM) examination (using a JEOL-840 connected to a LINK Oxford Instruments AN10000 EDS), (iv) X-Ray Diffraction (XRD) analysis using a Siemens Diffractometer D5000, and (v) X-Ray Fluorescence (XRF) analysis using a Phillips PW1400.

MONAZITE IN POLYMETALLIC CHLORITE-(TOURMALINE)-QUARTZ-(FLUORITE)-CASSITERITE-SULPHIDE LODES

Great Condurrow and South Tolcarne mines

SEM analysis of samples from the granite-hosted Llandower Lode within Great Condurrow Mine (NGR SW 660 393) indicated an assemblage of cassiterite, chalcopyrite, pyrite, arsenopyrite, sphalerite, bismuthinite and anatase within a chlorite-quartz groundmass. Monazite is present as scattered subhedral crystals (up to 100 μm) with inclusions of thorite [(Th, U) SiO_4] and thorianite (ThO_2). Mine dump vein samples additionally contain a second generation of monazite within vugs as euhedral crystals up to 100 μm in diameter. A similar assemblage, along with secondary cuprite (Cu_2O) and torbernite ($Cu(UO_2)_2(PO_4)_2.8-12H_2O$), occurs in a lode sample from the adit level of nearby South Tolcarne Mine (NGR SW 656 384). Transmitted light microscopy indicates that the chlorite groundmass occurs as part of a breccia containing clasts of almost completely chloritised biotite and small, irregular and fractured clasts of tourmaline and feldspar.

North Roskear and North Pool mines

Mine dump lode samples from North Roskear Mine (NGR SW 658 413) and North Pool Mine (NGR SW 675 423) reveal a similar paragenesis to that above with monazite, typically anhedral to subhedral up to 100 μm in diameter, interlocked with all other
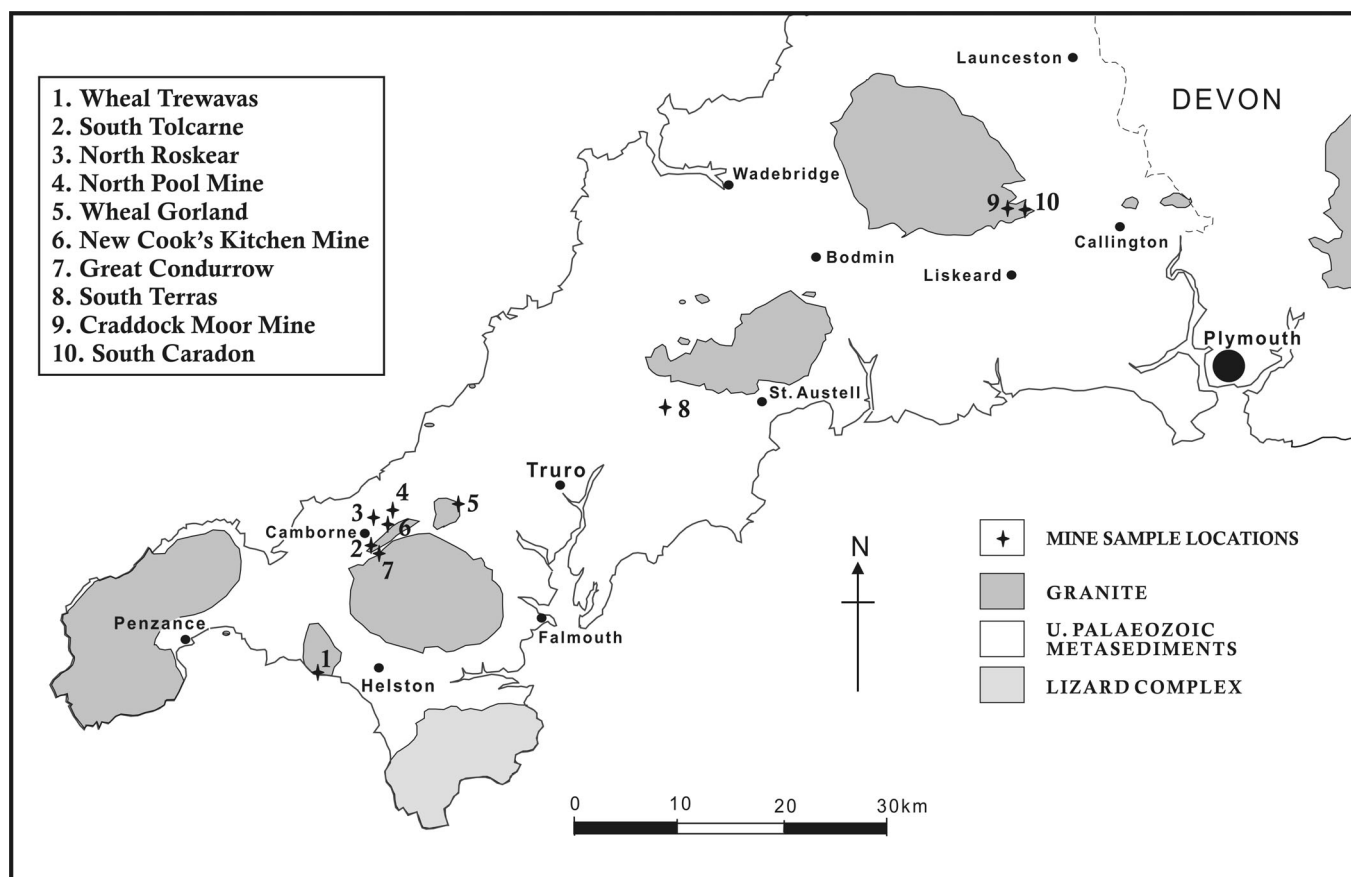
Figure 1. *The location of the mines, with monazite-bearing assemblages, sampled in this study.*

phases in a chlorite-quartz groundmass. The North Roskear sample also contains a second generation of monazite within vugs (similar to Great Condurrow), while the North Pool sample has a cassiterite-galena-sphalerite-arsenopyrite-chalcopyrite-monazite-chlorite-anatase-quartz assemblage, in which galena is unusually abundant.

Mine/Sample Location	Cerium in ppm
South Caradon Mine	123
Craddock Moor Mine	145
South Terras Mine	282
Wheal Gorland (1)	234
Wheal Gorland (2)	802
North Pool Mine	155
Great Condurrow Mine (1)	231
Great Condurrow Mine (2)	62
Great Condurrow Mine (3)	1004
South Tolcarne Mine	221
New Cooks Kitchen Mine (1)	871
New Cooks Kitchen Mine (2)	58
New Cooks Kitchen Mine (3)	955
New Cooks Kitchen Mine (4)	161
New Cooks Kitchen Mine (5)	17
New Cooks Kitchen Mine (6)	121
New Cooks Kitchen Mine (7)	84
New Cooks Kitchen Mine (8)	2373

Table 1. *Cerium values in ppm for analysed bulk lode material from selected mines/parageneses sampled in this study.*

New Cook's Kitchen Mine

One of the best exposures of a shallow polymetallic lode occurs in the stopes at deep adit level (~45 m below surface) on North Tincroft Lode within the former New Cook's Kitchen Mine (NGR SW 664 408). The lode is hosted by slates of the Mylor Slate Formation (thin greenstone sills occur in some of the drives) and, at this location, is ~100 m vertically above the contact with the Carn Brea Granite. Four main paragenetic assemblages have been recognised (LeBoutillier *et al.*, 2000, 2001) within the lode; Paragenesis 1 involves cassiterite and wolframite impregnation of the wallrock and is not associated with monazite, but parageneses 2-4 all include monazite.
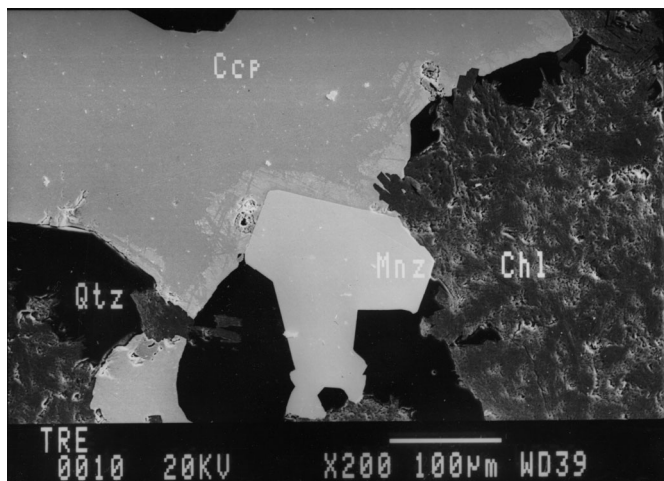
Paragenesis 2 comprises a complex polymetallic hydrothermal breccia (e.g. Halls 1987, 1994) in which angular clasts of slate are cemented by a schorl-chlorite-quartz-fluorite (± orthoclase) groundmass containing sphalerite, chalcopyrite, wolframite, cassiterite and arsenopyrite with minor lead and bismuth/silver sulphides (LeBoutillier *et al.*, 2000). Millimetre-scale quartz-schorl veins cut the breccia. Monazite was confirmed optically, but was not detected during SEM investigation, although its presence seems probable given high Ce values (17-955 ppm) obtained by XRF analysis (Table 1).

Paragenesis 3 is represented by impersistent veins of dark green chlorite, quartz and minor pale green fluorite that contain cassiterite, chalcopyrite, arsenopyrite, anatase, ilmenite, apatite and zircon. SEM analysis reveals that monazite is common and occurs in three main forms: (i) anhedral grains up to 200 μm in diameter that in some cases contain inclusions up to 1 μm of a thorium silicate, either thorite (primary) or the dimorph huttonite (a decay product from monazite), (ii) anhedral grains enclosed by chlorite, which display an 'interdigitating' texture with individual chlorite plates, and (iii) euhedral crystals enclosed by sulphides. XRF analyses of this material yielded Ce values of up to 2373 ppm, and La and Nd are also highly enriched relative to all other lode samples analysed in this study.

Paragenesis 4 reflects the formation of secondary minerals within 2-4 mm diameter vugs in the chlorite-quartz-fluorite

Figure 2. *SEM image of a lode sample from Trewavas Mine. Anhedral chlorite (Chl), intergrown with subhedral chalcopyrite (Ccp), monazite (Mnz) and quartz (Qtz)*

groundmass of Paragenesis 3. The vugs are often lined with an overgrowth of large chlorite crystals plus an extensive mineral suite, often as euhedral single crystals, twins and intergrowths, that includes: anatase (blue-colourless, transparent to opaque plates) and monazite (transparent to opaque, pyramidal, honey coloured crystals, which are often twinned). These are augmented by cassiterite (forming crystals of 'sparable' type), chalcocite, chalcopyrite, bornite, cuprite, ilmenite, goethite, langite, brochantite, marcasite, arsenopyrite, pyrrhotite, sphalerite and transparent apatite.

Wheal Gorland

Located on the eastern flanks of the Carn Marth Granite, Wheal Gorland (NGR SW 731 428) worked six ENE-WSW trending lodes, initially for copper and subsequently tin and tungsten. Samples were taken from *in situ* exposures of Davey's Lode at adit level (~150 feet or 46 m), where it forms the boundary between the Carn Marth Granite and the Mylor Slate Formation. The lode dips 75° NW and varies in width from 0.75-1.50 m. It is primarily composed of fluorite, earthy green chlorite and quartz, but the central 0.2-0.3 m is sulphide-rich, fine- to coarse-grained and black with iridescent crystals of chalcopyrite up to 10 mm in diameter. The black colour is due to a high sphalerite content; XRF analysis of the lode indicates 4% Cu, 14-18% Zn and 3.5-8% As (despite the high grades, sphalerite and arsenopyrite were gangue minerals when the mine was worked for copper). The complex polymetallic nature of the lode is confirmed by SEM analysis; wolframite, cassiterite, arsenopyrite, chalcopyrite and pyrite are present, together with a wide range of minor secondary copper minerals. Wolframite occurs as subhedral lath-like crystals, 100-300 μm in diameter, and occurs either free within the groundmass or intergrown with, or as inclusions within, arsenopyrite and sphalerite. However, one wolframite crystal carried an inclusion of sphalerite, indicating a complex paragenetic sequence. ZAF analyses (atomic number (Z) Absorption Fluorescence) of the wolframite revealed Fe:Mn ratios of ≥ 1. XRF analyses of lode material indicate Ce values up to 800 ppm and, although monazite was not found during SEM examination, its presence was confirmed optically in other samples.

Trewavas Mine

A lode specimen consisting of dense dark green chlorite, quartz and chalcopyrite was sampled from the dumps of Trewavas Mine (NGR SW 598 265), situated on the Tregonning Granite. SEM analysis confirmed chlorite (as large radiating, or anhedral masses), quartz, chalcopyrite (as large subhedral masses to >2 mm in diameter), rare anhedral cassiterite (20-150μm in diameter) and subhedral monazite (almost pure $CePO_4$, present as numerous

subhedral crystals, to 150μm in diameter) that is intergrown with all other phases (Figure 2). Uraninite (UO_2) occurs as subhedral to euhedral crystals up to 25 μm in diameter, together with anhedral to subhedral intergrowths of uraninite, xenotime and zircon.

South Terras Mine

A specimen consisting primarily of chlorite and arsenopyrite was sampled from the dumps of South Terras Mine (NGR SW 935 523), south of the St. Austell Granite. SEM analysis indicated a brecciated groundmass of chlorite (ferroan clinochlore), anhedral quartz and fluorite (to 2 mm in diameter) and minor tourmaline, hosting arsenopyrite, cassiterite, wolframite, chalcopyrite, bornite, chalcocite, hematite and siderite (these last two appear to be secondary). Chalcocite and bornite (subhedral, to 40 μm in diameter) often contain anhedral inclusions, up to 10 μm diameter, of bismuthinite (Bi_2S_3) and wittichenite (Cu_3BiS_3). In some cases bornite contains inclusions of galena (10 μm), that also occurs as scattered anhedral crystals (to 5 μm) in quartz. Monazite was also confirmed, optically, as subhedral to euhedral crystals (to 1 mm in diameter). Ti phases are absent. The breccia is cut by millimetric quartz-schorl veins.

Craddock Moor Mine

Craddock Moor Mine (NGR SX 258 702) is located on the southeastern margin of the Bodmin Moor Granite and worked seven ENE-WSW trending copper lodes. A lode specimen comprising dark green chlorite, quartz and arsenopyrite was sampled from the mine dumps. Optical examination revealed that anhedral quartz and fluorite infill sites between large, zoned, rosettes of chlorite (confirmed as Fe-rich chlorite by XRD). Parts of some of the chlorite rosettes are out of optical continuity, crowded with uraninite inclusions, display anomalous interference colours and appear to be chloritised biotite. Irregular masses of white mica (confirmed as muscovite by XRD) and angular broken fragments of orthoclase also occur within the chlorite groundmass. Anatase and the polymorphs brookite and rutile were all confirmed optically (anatase and brookite as isolated crystals, rutile as a vein infilling within the groundmass) along with large euhedral monazite crystals and small zircons (K. Tiltman, pers. comm., 2001). SEM analysis confirmed the optical examination and also indicated fluorite in the groundmass. Arsenopyrite contains inclusions (up to 200μm in diameter) and overgrowths of bismuthinite, plus, in some cases, inclusions and intergrowths of cassiterite and chalcopyrite.

South Caradon Mine

South Caradon Mine (NGR SX 272 697) is also located on the southeastern margin of the Bodmin Moor Granite, close to Craddock Moor Mine, and a lode sample from the shallow adit workings revealed a similar assemblage of dense green chlorite, quartz and arsenopyrite. Optical examination revealed a groundmass comprised of zoned chlorite rosettes, as at Craddock Moor Mine, but also relict granite clasts comprising chlorite (after biotite), muscovite, orthoclase and brown (dravite-rich) tourmaline; elsewhere isolated chloritised biotites contain clusters of uraninite inclusions. SEM examination reveals a brecciated texture, with rounded fluorite and monazite-rich clasts cemented by quartz and minor chlorite. Arsenopyrite occurs as anhedral to subhedral masses (reaching over 500 μm in diameter) with inclusions of bismuthinite (up to 10 μm); bismuthinite also occurs as anhedral grains (up to 100 μm) in the chlorite groundmass. Cassiterite is present as scattered subhedral crystals, up to 30-40 μm in diameter. Anhedral monazite, 10-150 μm in diameter, is scattered throughout the groundmass, with rare anhedral crystals (up to 20 μm) of an unidentified Th, Ca, U phosphate. Euhedral zircons (up to 10 μm) are also present, particularly within the chlorite groundmass. No Ti phases were found, but the presence of anatase and rutile were confirmed optically (K. Tiltman, pers. comm., 2001).

TOURMALINE-QUARTZ-CASSITERITE LODES

Tourmaline-quartz-cassiterite 'blue peach' lodes occur at depth on the flanks of the granite plutons (Garnett, 1962; Farmer, 1991; LeBoutillier, 1996) and at shallower elevations across the roof zones of the Land's End and Carnmenellis granites (Dines, 1956). Although Ce is present in these assemblages, typically 50-75 ppm (LeBoutillier, 2003), SEM examination of material from Nanjizal (NGR SW 356 237), Carnelloe Mine (NGR SW 442 387) and Giew Mine (NGR SW 500 367) within, and adjacent to, the Land's End Granite, and Wheal Roots (NGR SW 682 315) and South Crofty Mine (NGR SW 668 412) within the Carnmenellis/Carn Brea granites, failed to identify monazite or any other REE species. It is thought that the likely repositories for the detected levels of Ce, La and Nd are minerals such as apatite, fluorite (where present) and, to a lesser extent, tourmaline, which are known to be able to accommodate significant amounts of REE within their lattices (Alderton *et al.*, 1980; Collins and Strong, 1992; Morgan and Wandless, 1980; Gieré, 1996).

CHLORITE-QUARTZ-FLUORITE-CASSITERITE LODES

The complex polymetallic chlorite-dominated assemblages described above are typically exposed in relatively shallow workings. They contrast with those seen in the deeper workings (> 500 m) of South Crofty Mine, where chlorite mineralisation post-dates the main tourmaline-quartz-cassiterite 'blue peach' phase (Farmer, 1991; Farmer and Halls, 1993; LeBoutillier, 1996). These assemblages are often comparatively simple, consisting of chlorite ± quartz ± fluorite ± cassiterite and show a range of textures from hydrothermal breccias to open-space (banded) infilling (Taylor, 1965; Farmer, 1991). SEM examination of two samples from this paragenesis from the 3ABC Pegmatite Zone and the No.8 Lode on the 360 fm level (~600 m below surface) failed to detect monazite. However, Ce and La (oxides?) were detected as inclusions (1-2 mm) in quartz, and an unidentified Ce/La hydrated oxycarbonate species forming anhedral crystals up to 40 mm in length was present in minor amounts (see Figure 3) in the material from the Pegmatite Zone. Also, in contrast to the material from the shallow levels and elsewhere, the sample contained a number of small anhedral grains of cobaltite (CoAsS), while Ti-bearing species were absent in both samples.
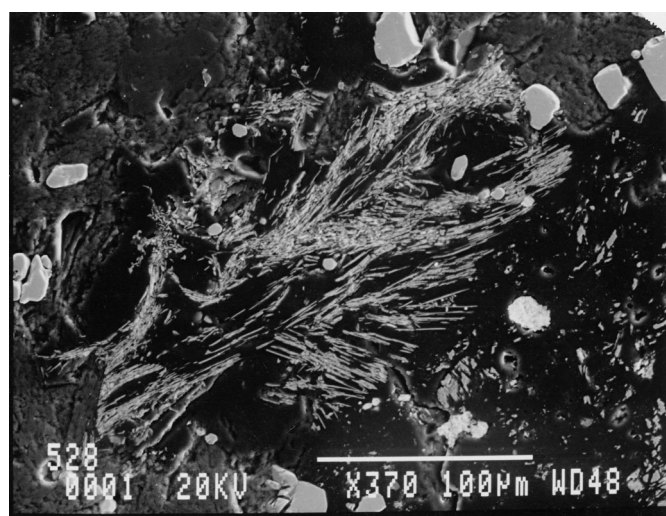
Figure 3. *SEM image of a lode sample from South Crofty Mine. A large platey crystal of a Ce/La hydrated oxycarbonate species (unidentified) occupies the centre of the image (REE), sited within a chlorite (Chl) and quartz (Qtz) groundmass. Cassiterite (Cst) is present, along with minor bismuthinite (BiS) and cobaltite (CoAsS). 3ABC Pegmatite Zone, 360 fathom level.*

DISCUSSION

Hydrothermal monazite in Cornish lodes

The occurrence of monazite in the lodes of the Cornubian Orefield has been underestimated. One explanation may be that over the last 40 years, the focus of most mineralisation research was the deeper workings of the recently active Geevor, Wheal Jane and South Crofty mines (e.g. Garnett, 1962; Taylor, 1965; Cotton, 1972; Jackson, 1977; Walters, 1988; Holl 1990; Farmer, 1991). Monazite may be absent from the tourmaline-quartz-cassiterite and chlorite-fluorite-cassiterite parageneses within many of these locations. In addition, without SEM analysis, it is possible that small crystals of monazite may have been overlooked.

In contrast, this preliminary work indicates that monazite is present in almost all samples of chlorite (± tourmaline)-quartz (± fluorite)-oxide-sulphide lodes hosted by both metasedimentary rocks and granite. These lodes are chlorite-dominated (typically ripidolite to clinochlore) and polymetallic (principally Sn, As, W, Cu, Zn, Bi, Ag and Pb). Sn, As and Zn are often highly enriched, with concentrations in some cases exceeding 10% (LeBoutillier *et al.*, 2000, 2001). Ti-bearing species (typically anatase, sometimes brookite and rutile) are also usually present. The samples exhibit textures compatible with formation, at least in part, as hydrothermal breccias (e.g. Halls, 1987, 1994; Halls and Allman-Ward, 1986; Taylor and Pollard, 1993). In locations where the lodes are granite-hosted, specimens contain variably altered and disaggregated granite clasts (that contribute chloritised uraninite-rich biotite, orthoclase, quartz, muscovite and tourmaline). Collectively, they represent essentially 'single pass' telescoped xenothermal assemblages, with interlocked species (and inclusions of lower temperature phases within higher temperature phases) from both the hypothermal and epithermal ends of the depositional spectrum (Hosking, 1964). Reactivation is typically minimal with later mineralisation confined to relatively rare millimetre-scale veinlets of quartz or rutile.

The vast majority of the monazite seen in this material appears to be of primary hydrothermal origin, contemporaneous with the other phases with which it is intergrown. Some rounded crystals may be of xenocrystic origin, but these are rare and easily identified; in any case where the origin of the crystal is in doubt it should be discounted from any dating of the lode material, similarly, free-growing vug-hosted crystals (often reaching >2 mm in size) must be treated similarly in view of the potential mobility of Ce in mesothermal fluids (Hole *et al.*, 1992; Wood, 1990). The high concentrations of cerium and the almost ubiquitous presence of titanium-bearing phases in these assemblages are also unusual, but not without parallel as a strong relationship between cerium, titanium and zirconium species has been recognised elsewhere (Gieré *et al.*, 1988; Gieré and Williams, 1992). The likely source of titanium is from the breakdown of biotite mica in the granite wall rocks adjacent to the lode fissures (Farmer, 1991; Taylor, 1965; Scrivener, 1982) initially releasing Fe, Mg, Al and Ti into the reacting hydrothermal fluids. Such reactions have been estimated to take place at around 400°C (Alderton, 1993), with fluids of magmatic origin dominating in the early stages. 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 hydrothermal fluids. Such an association of Ti minerals, monazite and, often, tourmaline, suggests that these phases were deposited from fluids of primarily magmatic origin. Studies of the hydrothermal transport of REE's (Haas *et al.*, 1995; Gieré, 1996) demonstrate that high temperature, high-salinity, low pH brines provide optimal conditions for transport (as fluoro- and, to a lesser extent, chloro-complexes), which match the profile of locally-derived magmatic fluids (Alderton, 1993). These brines may represent the 'first pass' of magmatic hydrothermal fluids into the upper parts of the lode systems now preserved in the outer parts of the granite and adjacent country rocks. Here they have interacted with meteoric and/or metamorphic fluids to produce

the Ce-Ti-polymetallic parageneses seen in this study. Mixing with fluids in the vicinity of the granite-country rock contact may explain why these assemblages are not observed at greater depth (e.g. the quartz-tourmaline-cassiterite and chlorite-quartz-fluorite-cassiterite assemblages of the deep levels of South Crofty Mine). These fluid conditions were sufficiently unique to ensure that later pulses of mineralisation that developed chlorite assemblages at depth (with Ce still present) do not carry monazite and Ti species are rare or absent.

Previous work on the geochronology of mineralisation in Cornwall

High precision U-Pb dating of magmatic monazite and xenotime, combined with Ar-Ar dating of magmatic micas, provided a major advance in understanding the chronology of granite emplacement and early cooling in SW England (Chen *et al.*, 1993; Chesley *et al.*, 1993; Clark *et al.*, 1993; Clark *et al.*, 1994). These studies indicate that magmatism was initiated at *c.* 295 Ma and persisted for approximately 25 Ma. The chronology of mineralisation is not as well constrained.

K-Ar, Ar-Ar and Rb-Sr dating methods have been widely applied to secondary micas and feldspars primarily sampled from greisen-bordered veins (Halliday, 1980; Jackson *et al.*, 1982; Bray and Spooner, 1983; Chen *et al.*, 1993; Chesley *et al.*, 1993). In the context of the recent magmatic U-Pb monazite/xenotime data, it appears that this style of mineralisation initiated within 2-3 Ma of the emplacement of the respective host granite (Chen *et al.*, 1993; Chesley *et al.*, 1993). Rb-Sr data appear reasonably robust, but K-Ar determinations on the same material commonly yield mean ages of 220-240 Ma (Halliday, 1980; Jackson *et al.*, 1982) and suggest Ar loss during a regional mid-Triassic rift-related hydrothermal event (e.g. Scrivener *et al.*, 1994). Chen *et al.* (1993) have therefore questioned the significance of Rb-Sr model ages.

Age determinations of the "main stage" tourmaline-quartz-cassiterite and polymetallic chlorite-(tourmaline)-quartz-(fluorite)-cassiterite-sulphide lodes that account for the majority of Sn-Cu production are sparse. Mean Rb-Sr ages of 270 ± 4 Ma and 279 ± 4 Ma for, respectively, polymetallic lodes at Geevor (Land's End Granite) and Wheal Reeth (Tregonning-Godolphin Granite) were obtained by Halliday (1980). Scrivener (1982) gives an Ar-Ar age of 278 ± 6 Ma for sericite bordering Wall's Lode (Sn) within the Birch Tor and Vitifer Mine in central Dartmoor; Shepherd and Darbyshire (1986) give (Rb-Sr) ages of 269 ± 4 Ma and 271 ± 15 Ma for fluid inclusions in quartz at South Crofty (No. 2 Lode) and Geevor Mine, respectively. The South Crofty date is much younger than that (~289 Ma, by ^{40}Ar-^{39}Ar, for hydrothermal muscovite) quoted by Chen *et al.* (1993) for the onset of mineralisation within the mine and therefore marks a later episode of lode development. Chesley *et al.* (1991), using Sm-Nd, obtained an age of 266 ± 3 Ma and 259 ± 7 Ma for fluorite within lodes at Wheal Jane Mine and South Crofty Mine, respectively, which are both much later than the onset of the main phase of cassiterite deposition (Clark *et al.*, 1993; Chen *et al.*, 1993).

A major problem with much of the available lode age data is the lack of paragenetic descriptions detailing the complexity, history and precise location (both geographical and physically within the specimen) of the exact phase being sampled. Such a lack of information leads to ambiguous results within complex lode systems, particularly if only one phase is sampled and fails to address the chronology of mineralisation within the lode assemblage.

The discovery of a rapidly increasing number of sites (comparatively) rich in hydrothermal monazite now raises the possibility of applying direct high precision U-Pb dating to the lodes of the Cornubian Orefield. Problems of access mean that much of this material will come from dumps, but a number of sites have already been identified where lode sections can be seen *in-situ* and sampling of individual paragenetic assemblages can take place. A combination of fine-scale lode mapping, structural and mineralogical studies (to ensure only primary, unaltered monazites are sampled; e.g. Poitrasson *et al.*, 2000) combined with monazite dating would allow a detailed chronology of individual lodes to be developed, with less well-constrained dates becoming available for large areas of the orefield at shallow elevations.

Conclusions

Monazite occurs far more widely within the magmatic hydrothermal lode systems of Cornwall than has been previously recognised. A primary hydrothermal monazite-chlorite ± anatase ± quartz ± fluorite ± schorl ± cassiterite ± sulphide assemblage is very common in lode specimens sampled from shallow (<60 m) levels of accessible mine workings and associated dumps. Collectively, these samples are from lode segments developed in the vicinity of the granite-country rock contact. The polymetallic assemblage is interpreted to represent an early lode paragenesis formed by mixing of magmatic hydrothermal fluids with meteoric and/or metamorphic fluids from the country rocks. Such a model may explain why these assemblages are not observed in mines that have worked at greater depths within the granite.

The widespread occurrence of hydrothermal monazite within these samples could allow a comprehensive program of sampling and U-Pb dating of Cornubian lode mineralisation to take place. In assessing the suitability of material for sampling, care must be taken to distinguish between what appears to be primary monazite and crystals which appear to be inherited xenocrysts (particularly in mines situated in granite) or of secondary (remobilised) origin.

The majority of the available sites are limited to mine dumps, which would allow a coarse resolution of the chronology of mineralisation to be ascertained for that particular locality; however, an increasing number of mine workings, at shallow elevations (above adit level) are being cleared and accessed by heritage and enthusiast groups (K. Tiltman, *pers. comm.*, 2003), where sections of lodes can be seen *in-situ*. Such exposures allow a detailed paragenetic framework to be established, with the potential for fine-scale resolution of the chronology of mineralisation, where monazite is present. The utilisation of these, and other sites, could make a major contribution to our understanding of the timing and duration of hydrothermal processes and of the Cornubian Orefield as a whole.

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