

THE CORNUBIAN SN-CU (-AS,W) METALLOGENETIC PROVINCE: PRODUCT OF A 30 M.Y. HISTORY OF DISCRETE AND CONCOMITANT ANATECTIC, INTRUSIVE AND HYDROTHERMAL EVENTS

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Emplacement of the Cornubian batholith and its associated giant Sn(-Cu, As) lode systems extended from the Pennsylvanian to the Early Permian, spanning an interval of 25-30 m.y. U-Pb dates for magmatic monazites range from 293.1 ± 1.3 Ma (2σ) in the Carnmenellis pluton, to 274.5 ± 1.5 Ma in the southern lobe of the Land's End pluton, and the smaller stocks were emplaced over a comparably extended period. Each pluton cooled through ca. 320°C (T_c argon, muscovite) within 4-5 m.y. at the existing exposure level, but insignificant cooling has taken place since the Late Triassic at present depths of 2-2.5 km. Greisen-bordered wolframite (\pm cassiterite) vein systems and lodes formed simultaneously with the cooling to ca. 320°C of the host intrusive rocks, lending support to an origin related to retrograde boiling of apical magmas. Major Sn-Cu lode development in the Carn Brea district was initiated 1-3 m.y. after emplacement of the local W-rich veins, and was broadly coeval with cooling of the Carnmenellis pluton — through T_c muscovite at 1-1.5 km below the greatest known depths of economic cassiterite deposition in the mineralized shear-zones. Both clans of lithophile-metal deposits formed diachronously across the province: thus, all cassiterite deposition in the lodes of the South Crofty mine took place prior to intrusion of the St. Austell and Land's End plutons. Microgranular, igneous-textured, tonalitic-togranodioritic enclaves, confirmed in all coarse-grained megacrystic biotite monzogranite bodies except for Cammenellis, are interpreted as hybridized 'pillows' of mafic melts, implying that crustal anatexis was directly stimulated by episodic incursion of magma(s) from the subjacent mantle.

The Cornubian petrographic and metallogenetic province undoubtedly comprises a large number of discrete magmatic/hydrothermal domains. Resolution of this collage and clarification of its implications for petrogenesis and ore formation will require more intensive geochronological and petrological research.

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INTRODUCTION

A quarter-century of modern research on the tectonic setting and petrogenesis of the Cornubian batholith and on its associated world-class tin, copper and kaolinite mineralization culminated in the later-1980's with several comprehensive syntheses (Stone and Exley, 1985; Bromley and Holl, 1986; Bromley, 1989; Willis-Richards and Jackson, 1989; Jackson *et al.*, 1989), coinciding with publication of a new series of B.G.S. 1:50,000 sheet memoirs (Goode and Taylor, 1988; Leveridge *et al.*, 1990). The consensual view is that crustal anatexis, probably caused by tectonic thickening of the Hercynian crust, was followed by emplacement of the greater part of the batholith at 280-290 Ma, and that a period of minor intrusion ensued at ca. 270-282 Ma. The two major classes of lithophile-metal deposit in the province, viz. the 'greisen-bordered' vein swarms and lodes, generally wolframite-rich, and the highly-productive cassiterite-chalcopyrite (-arsenopyrite-sphalerite) lodes, are considered to have developed in broad association with, respectively, the major and minor magmatic events. This model is based on an extensive body of conventional K-Ar (Miller and Mohr, 1964; Dodson and Rex, 1971; Halliday, 1980; Bray and Spooner, 1983) and, particularly, Rb-Sr (Harding and Hawkes, 1971; Darbyshire and Shepherd, 1985, 1987; Shepherd and Darbyshire, 1986) geochronological data,

although the ambiguities in the age relationships have been widely acknowledged. The hiatus of ca. 15-20 m.y. between batholith emplacement and 'main-stage' Sn-Cu mineralization has gained apparent support from an innovative programme of Sm-Nd isochron dating of hydrothermal fluorites (Chesley *et al.*, 1990, 1991).

Considerable doubt regarding several aspects of the above model is cast by new geochronological studies on the Cornubian granites employing the U-Pb and ^{40}Ar - ^{39}Ar incremental-heating techniques (Chen *et al.*, 1991, 1992; Chesley *et al.*, 1991, 1992), and by detailed ^{40}Ar - ^{39}Ar investigations of numerous carefully selected specimens of veins and lodes from the South Crofty mine (Chen *et al.*, 1991, 1992). In addition, a re-examination of the diverse enclaves occurring sparsely in the main granitic plutons (Stimac *et al.*, 1992) sheds new light on the petrogenesis of the batholith.

Salient data and conclusions of ongoing laboratory research at Queen's University, the Royal Ontario Museum and the Los Alamos National Laboratory are summarized herein, in the hope that they will be of interest to others undertaking research in Cornubia. Details of sampling, experimental methods and interpretation will be presented elsewhere (Chen *et al.*, in press and in prep; Chen, in prep; Stimac *et al.*, in prep.).

Errors in the U-Pb and ^{40}Ar - ^{39}Ar mineral dates are quoted at the 2σ , 95% confidence, level, calculated through numerical propagation of analytical uncertainties.

CHRONOLOGY OF INTRUSION

Early in the present research, it became evident that both ^{40}Ar - ^{39}Ar and Rb-Sr dates for the Cornubian granites record ages of cooling rather than initial magma emplacement. U-Pb dating of magmatic monazite, with a 'closure temperature' of $725 \pm 25^\circ\text{C}$ (Parrish, 1990), was selected as the most reliable method for the definition of intrusive events. As we discuss elsewhere (Chen *et al.*, in press), the rapid accumulation of ^{206}Pb through decay of ^{230}Th in this Th-rich mineral causes a slight upward bias of the $^{206}\text{Pb}/^{238}\text{U}$ ratio for several hundred m.y. after crystallization. These ages were therefore adjusted to take account of the Th/U ratios of the magmas and monazites (Schärer, 1984), rendering them concordant within is with the $^{207}\text{Pb}/^{235}\text{U}$ ages; $\text{Th}/\text{U}_{\text{magma}}$ values of 1.5 or 1.6 (Darbyshire and Shepherd, 1985) were employed in correcting the $^{206}\text{Pb}/^{238}\text{U}$ dates.

Our preferred $^{207}\text{Pb}/^{235}\text{U}$ ages for emplacement of the preponderant, coarse-grained, megacrystic monzogranitic (-syngranitic) facies in the major plutons are: Isles of Scilly (Peninnis Head), 290.3 ± 1.2 Ma; Land's End (Lamorna), 274.5 ± 1.4 Ma; Carnmenellis (Carnsew), 293.1 ± 1.3 Ma; St. Austell (Luxulyan), 280.6 ± 0.7 Ma; Bodmin Moor (De Lank), 281.1 ± 0.5 Ma; and Dartmoor, 281.0 ± 0.8 Ma (Pewtor) and 285.3 ± 0.8 Ma (Haytor, weakly-megacrystic facies). In addition, monazite from the Castle-an-Dinas (West) fine-grained granite in the core of the NE lobe of the Land's End pluton yields a monazite age of 277.1 ± 0.6 Ma; this is unexpectedly older than the coarse granite from Lamorna, but ongoing petrographic studies of the Land's End pluton suggest that several separate coarse-grained granitic intrusive foci are represented therein. This problem is being explored through more detailed U-Pb investigations.

The U-Pb data (see also Chesley *et al.*, 1992) clearly demonstrate that the Cornubian batholith was emplaced diachronously, from ca. 293.1 to ca. 274.5 Ma, i.e., over an interval of some 20 m.y. At least the Dartmoor and Land's End plutons comprise several intrusive units with significantly different ages. There is no systematic trend in the age of pluton emplacement along the axis of the batholith.

No U-Pb dates are available for the numerous small stocks in the province. However, minimum ages defined by $^{40}\text{Ar}/^{39}\text{Ar}$ muscovite plateaux (see below) are as follows: St. Michael's Mount, 281.4 ± 1.5 Ma; Boswyn (Carnmenellis), 276 ± 1.1 Ma; Cam Brea, 288.3 ± 1.0 Ma; Cam Marth, 284.1 ± 1.0 Ma; Cameron Quarry (St. Agnes), 278 Ma; Cligga Head, 279.9 ± 0.8 Ma; Castle-an-Dinas (East), 273 Ma; Kit Hill, 284.3 ± 1.0 Ma; and Hingston Down, 283.1 \pm 1.0 Ma. Finally, minimum intrusive ages of ca. 270 Ma are indicated by ^{40}Ar - ^{39}Ar muscovite dates for the Li-mica leucogranites of the western part of the St. Austell pluton.

IMPLICATIONS OF MICROGRANULAR ENCLAVES

The widespread recognition that mesocratic-melanocratic, igneous-textured enclaves in granitoid rocks commonly represent bodies of more mafic melt, recording its commingling and mixing with the host magma (e.g., Didier and Barbarin, 1991), has had a profound effect on interpretations of granitoid petrogenesis. Enclaves are not abundant (< 2% of outcrop) in the Cornubian batholith, but have received sporadic attention since the pioneering studies of Ghosh (1927) and Brammall and Harwood (1923; 1932). We concur with the latter authors that the enclaves reflect a diverse parentage, and distinguish those of metasedimentary origin, whether from the site of emplacement or from depth, from those of igneous origin. The former have a xenoblastic or foliated texture and consist dominantly of biotite, plagioclase, cordierite and quartz, with varying proportions of ndalusite, sillimanite, muscovite, hercynitic spinel, corundum and ilmenite. The igneous enclaves, in contrast, display a non-layered microgranular texture dominated by biotite

and plagioclase poikilitically enclosed in quartz and K-feldspar, and lack Al-rich minerals. Most such enclaves have a sub-rounded form and many exhibit crenulate margins. Unlike the non-igneous bodies, the microgranular enclaves widely incorporate megacrysts of K-feldspar, quartz and, rarely, plagioclase such as are characteristic of the enclosing granite, the megacrysts commonly lying athwart the enclave boundaries. The modal mineralogy of the enclaves extends from monzogranite to tonalite; Brammall and Harwood (1932) document examples as basic as gabbro ('diabase') and quartz diorite.

We interpret these bodies, corresponding to the 'Type A' granite of Exley and Stone (1964), not as xenoliths of older mafic igneous rocks but as 'pillows' of hybrid melts recording varying degrees of chemical interchange with the host monzogranitic magma. It is of interest to note that Brammall and Harwood (1932), although advocating an origin through incorporation of mafic rock fragments, considered the possibility that the microgranular enclaves represent bodies of basic magmas (see also Reid *et al.*, 1912). The incorporation of K-feldspar megacrysts, a feature nowhere shown by clearly metamorphic enclaves, is interpreted herein as resulting from mechanical mixing with the enclosing, partly-crystallized granitic magma, rather than from alkali-metasomatism (cf. Stone and Austin, 1961).

The precise nature of the commingling mafic magmas is problematic, owing to their hybridization. An extensive analytical database (Brammall and Harwood, 1932; Stimac *et al.*, 1992, and in prep.) clearly discriminates between the microgranular enclaves and those of metamorphic origin. The latter are markedly enriched in Al and depleted in Si, Ca, P, Sr and LREE relative to the former. In Harker-type variation diagrams, the microgranular enclaves define linear arrays connecting the host granites to the wide fields occupied by the Exeter Volcanics, but the data do not permit identification of a particular extrusive suite (e.g., basaltic or ultrapotassic) as the mafic end-member in the mixing system. The enclaves display an enrichment in Th, Rb, LREE, Sr and HFSE relative to the Exeter basalts, suggesting either the involvement of the lamprophyric magmas with or without basaltic contributions or the occurrence of fractionation or combined fractionation-assimilation of the mafic parent prior to, or in the earliest stages of, interaction with more silicic magmas.

Microgranular enclaves have been identified in all coarse-grained megacrystic granites in the province with the exception of those of the oldest, Carnmenellis, pluton. Although very sparsely represented (or preserved) at the present level of exposure (0.01-0.1%), the enclaves are strong evidence that mafic melt incursion from the mantle attended much of the history of batholith emplacement. Whereas it is possible that upper mantle melting may have been caused by crustal extension and decompression following an episode of crustal shortening and resulting anatexis, the close association of mafic and felsic melts over an interval of at least 15 m.y. implies that the former were directly responsible for lower-crustal melting.

EARLY COOLING HISTORY OF THE BATHOLITH

Although the textural relationships of the muscovite in the coarse-grained megacrystic granites suggest a range of crystallization conditions from magmatic to sub-solidus (southern Land's End), the ^{40}Ar - ^{39}Ar ages of this mineral provide good evidence of the time at which the several plutons cooled through ca. 320°C (T, muscovite: Snee, 1982; Snee *et al.*, 1988). Incremental-heating apparent age spectra obtained for numerous granitic muscovites exhibit consistent configurations with a few high ages for the lowest-temperature steps and well defined higher-temperature plateaux for ca. 75% of the argon released. The plateaux, accepted as cooling ages for the mica, are coeval within each coarse granite domain, and consistently 4-5 m.y. younger than the respective monazite dates. Representative ages are as follows: Isles of Scilly, 286.4 ± 0.8 Ma; Land's End, 270.1 ± 1.0 Ma; Carnmenellis,

289.7 ± 0.8 Ma; St. Austell (East), 276.8 ± 0.8 Ma; Dartmoor-Pewtor, 277.0 ± 1.4 Ma; and Dartmoor-Haytor, 280.8 ± 0.8 Ma. Muscovite from the Castle-an-Dinas (West) fine granite yields a plateau age of 272.4 ± 0.9 Ma, again 4-5 m.y. younger than the monazite date.

We have been unable to define muscovite cooling ages for the Bodmin Moor pluton. All analysed white micas from this body exhibit spectrum configurations indicative of the presence of considerable excess argon. However, we conclude that all of the other major intrusions cooled at very similar rates at the present level of exposure; thus, the Cammenellis pluton had cooled to below ca. 320°C prior to the emplacement of all of the other major intrusions other than the Isles of Scilly pluton.

Whereas the diachronous cooling of the batholith is clearly evident from the muscovite ⁴⁰Ar-³⁹Ar data, extensive ⁴⁰Ar-³⁹Ar step-heating dating of unaltered biotites from the Cornubian granites demonstrates that all incorporate significant volumes of excess argon. The cooling age of this mineral cannot therefore be precisely defined using this technique. Conventional K-Ar dates would be variably affected by this feature, accounting for the ambiguities in the K-Ar database for the granites.

LATE COOLING HISTORY OF THE BATHOLITH

The sub-320°C cooling of the granites may be broadly calibrated through ⁴⁰Ar-³⁹Ar incremental-heating dating of K-feldspar (*T_c* orthoclase or microcline 110°C for low temperature release: Harland *et al.* (1990) and our own calculations), and by fission-track dating of zircon and apatite (in progress). In particular, the Rosemanowas HDR geothermal project drill-core provides an opportunity to compare the cooling history of the central part of the Cammenellis pluton at the present exposure level and at depths of over 2 km (Chen *et al.*, 1991). Muscovite age plateaux for core samples from a depth of 2.3 km average 286.4 ± 0.9 Ma, only ca. 3 m.y. younger than those of surface samples, revealing the rapid cooling of this section of the pluton to ca. 320°C. In contrast, minima in the complex age spectra of K-feldspars (intermediate microcline) are interpreted as evidence that further cooling to below ca. 110°C did not occur until ca. 267 Ma at the present surface and 203 Ma at present depths of 2.3 km. Ambient temperatures at this level in the Rosemanowas core are as high as ca. 90°C (Camborne School of Mines, 1990), revealing a remarkable thermal stability within the Cammenellis pluton since the Late Triassic. These data necessitate reappraisal of the thermal history of the batholith (Willis-Richards and Jackson, 1989), while the cooling of the upper 3 km of the Cammenellis pluton to temperatures below those of initial main-stage lode development, i.e., 450°C (Jackson *et al.*, 1989), within a maximum of 8 m.y. places constraints on ore-genetic modelling.

AGE OF WOLFRAMITE-RICH VEIN SYSTEMS AND LODES

Although not highly productive, quartz vein swarms, commonly comprising sheeted series (e.g., Cligga Head) or stockworks (Hemerdon) and generally enriched in tungsten rather than tin or copper, constitute the earliest major facies of lithophile-metal mineralization in each pluton or stock (Jackson *et al.*, 1989; Bromley, 1989). These 'greisen-bordered' veins, and a small number of larger wolframite-quartz lodes, are considered to have been controlled by fracture systems closely related to granite intrusion and initial cooling, and are hence traditionally assigned to the 280-290 Ma episode of batholith emplacement. Thus, Halliday (1980) reported Rb-Sr model ages of 280-285 Ma for several vein systems of this type in west Cornwall. Bray and Spooner (1983), however, in a detailed K-Ar study of sheeted veins, albeit Sn-rich, from Goonbarrow, St. Austell, defined a mean age of 271.4 ± 4.5 Ma, slightly younger than that, 274.8 ± 2.1 Ma, yielded by muscovite and biotite in the host Li-mica leucogranite and biotite-muscovite monzogranite, strongly implying that this 'early' facies of mineralization was emplaced diachronously in the province.

This is confirmed by new ⁴⁰Ar-³⁹Ar step-heating dating of hydrothermal muscovites from several such centres. The mica, which crystallized at ca. 320-450°C (Jackson *et al.*, 1989), i.e., at or only slightly above its Ar-retention temperature, and at low pressure, characteristically yields excellent plateaux with little evidence of excess argon or thermal

resetting (cf. Halliday, 1980). Vein development at St. Michael's Mount took place at 281.9 ± 1.4 Ma, but occurred significantly later at Cligga Head, 279.9 ± 0.8 Ma, and much later at Castle-an-Dinas (East), 272.7 ± 0.8 Ma, and Bostraze (Land's End), 271.2 ± 0.8 Ma. Moreover, although several Ar-release spectra determined for muscovites from the wolframite-rich Roskear Complex lode on the 360 fathom level of the South Crofty mine exhibit evidence of diffusional Ar-loss at ca. 282-286 Ma, the higher-temperature segments of the patterns demonstrate that lode emplacement occurred prior to 289 Ma (Chen *et al.*, 1992, and unpubl. data).

In all examples for which correlative data are available for associated granites, the ages of the W-rich vein and lode systems are indistinguishable within error from the muscovite cooling ages of their host-rocks, broadly supporting an origin triggered by retrograde boiling of aliquots of magma in the upper parts of the intrusions (Jackson *et al.*, 1989). Both intrusion and greisen-bordered vein development, therefore, spanned intervals of ca. 20 m.y. in the province as a whole.

AGE OF MAIN-STAGE SN-CU LODE DEVELOPMENT

The timing of emplacement of the enormously productive cassiterite-chalcocopyrite ± tourmaline ± chlorite lodes which dominate the metallogenic fabric of Cornubia has received intensive study but remains controversial. Halliday (1980) concluded from Rb-Sr model ages of hydrothermal K-feldspars from several lodes in west Cornwall that they formed at ca. 265 ± 7 (isochron) - 272 ± 4 Ma (average age). Similarly, pioneering Rb-Sr isochron dating of fluid inclusions in lode quartz (Shepherd and Darbyshire, 1986) yielded ages of 269 ± 4 Ma (isochron; No.2 South Lode, South Crofty) and 271 ± 15 Ma (errorchron; various lodes in the Geevor Mine). Recently, Chesley *et al.*, (1990; 1991) have reported similarly young Sm-Nd isochron dates for fluorites assigned to the main stage of cassiterite deposition at Wheal Jane (266 ± 3 Ma) and South Crofty (259 ± 7 Ma), although there is some doubt regarding the paragenetic context of the latter samples (cf. Chesley *et al.*, 1990 and 1991). The above data have generated a consensus (Bromley, 1989; Jackson *et al.*, 1989; Chesley *et al.*, 1992) that the major Sn-Cu lodes were emplaced some 15-20 m.y. after batholith intrusion, and were the product of late-stage geothermal processes related to the extremely protracted cooling history inferred for the granitic rocks.

We have determined ⁴⁰Ar-³⁹Ar incremental-heating ages for hydrothermal muscovite which forms a component of wall-rock alteration envelopes to several of the tin-rich lodes exploited in the deeper workings of the South Crofty Mine, in particular Dolcoath South (360 fm.) and No.8 (380 fm.). At these levels, the lodes are dominated by polyphase tourmaline-quartz-cassiterite assemblages (Farmer and Halls, 1990, and in press) and are directly associated with quartz-muscovite (-chlorite) alteration zones (Chen, in prep.). Because the lodes are hosted by the muscovite-bearing Cam Brea granite and experienced numerous episodes of reopening, the age spectra are generally complex. In most cases, however, fine-grained muscovites (- 45 MESH) yield low apparent ages in the lowest steps, moderately well-developed plateaux 50% of the released Ar) at intermediate temperatures, and older ages at high temperatures. Coarse muscovite (+18 MESH) is less affected by the lower-temperature events: that from No.8 Lode gives a plateau (95.7% of gas) at 286.6 ± 1.2 Ma, and that from Dolcoath South yields a correlation (isochron) age of 286.2 ± 0.5 Ma. In comparison, unaltered magmatic muscovites from the Cam Brea granite yield plateau ages of ca. 288-289 Ma.

We interpret these spectra as evidence for initial lode development in this district at ca. 287 Ma, with renewed hydrothermal activity at ca. 283 Ma, and a final thermal event at 280 Ma. Both the No. 8 and Dolcoath South lodes in the sampled exposures are cut by fluorite-quartz veins lacking cassiterite. The intermediate event is clearly shown by muscovite from the No. 1 lode (Robinson's section, 260 fm. level), suggesting that the chlorite-rich Sn-Cu lodes which dominated the shallower levels of the mine may have developed at ca. 283 Ma.

On the basis of these data, we conclude that major Sn(-Cu) lode development in this, most productive, 'emanative centre' of the province commenced within 1-3 m.y. of the cooling of the host granite below ca. 320°C and the sensibly contemporaneous formation of the earlier wolframite-rich veins and lodes. It was, moreover, broadly coincident with the attainment of comparable temperatures (ca. 300-400°C) at depths of 1-1.5 km below the apparent lower limit of economic cassiterite deposition in the lodes, as indicated by the Sn grade decrease in the deepest levels (ca. 500 fm.) of the Dolcoath mine.

Elsewhere, $^{40}\text{Ar}/^{39}\text{Ar}$ dating of hydrothermal sericite from the Birch Tor-Vitifer lode system in the north-central part of the Dartmoor pluton yields corroborative evidence of the timing of Sn lode development. The dated mica, from the dumps of the major Wall Lode, extensively replaces fragments of wall-rock enclosed in a specular haematite-quartz veinstone, representative of the third, post-cassiterite, stage of lode development (Scrivener, 1982). The apparent age spectrum records incorporation of moderate excess argon in the low-temperature steps, but at higher temperature exhibits a good plateau at 278.0 ± 0.6 Ma (69% of released argon). This date is ca. 2-3 m.y. younger than the cooling age (280.8 ± 0.8 Ma) for muscovite in granite of this area and 7-8 m.y. younger than the monazite (emplacement) age of the granite in the Haytor area, thereby defining an hiatus between intrusion and major Sn lode mineralization similar to that inferred for the Cam Brea district.

We are carrying out further $^{40}\text{Ar}/^{39}\text{Ar}$ studies of alteration assemblages associated with Sn(-Cu) lodes in other parts of the province, but assume tentatively that lode development in the important St. Just district took place some 5-8 m.y. after emplacement of the Land's End megacrystic granites, i.e., at 262-265 Ma, perhaps 30 m.y. after initiation of plutonic activity in the region.

AGE OF FLUORITE-QUARTZ VEINS

Fluorite-quartz bodies with no significant Sn values constitute a well-defined late stage in the development of the deeper South Crofty lode systems. Muscovite occurring in vughs in a vein of this type from the North Pool Zones (370 fm. sub-level) yields an only weakly-disturbed spectrum with an integrated age of 269.2 ± 0.9 Ma, and a good plateau (78% of gas released) at 269.0 ± 0.8 Ma. This vein cuts tourmaline-cassiterite lode segments.

The $^{40}\text{Ar}/^{39}\text{Ar}$ date obtained for this post-main-stage vein is identical to the previously noted 269 ± 4 Ma Rb-Sr isochron age determined by Shepherd and Darbyshire (1986) for fluid inclusions in quartz from the No. 2 South Lode in the mine, and interpreted as recording the age of cassiterite mineralization. However, many exposures of this lode display post-cassiterite fluorite-quartz veinlet development and all lode quartz exhibits multiple generations of secondary fluid inclusions. We tentatively suggest, therefore, that the Rb-Sr date records the final event in the evolution of the lode system. The Sm-Nd fluorite date reported by Chesley *et al.* (1990, 1991) is more problematic: in their earlier abstract those authors assigned the fluorite to 'Paragenetic Stage 3', i.e., a post-cassiterite event, whereas they later interpreted it as contemporaneous with tin mineralization. Although there is a restricted paragenetic overlap between cassiterite and fluorite in the deep lodes at South Crofty, we consider it more likely that the Sm-Nd data pertain to the late fluorite-rich vein stage.

CONCLUSIONS AND IMPLICATIONS

The new geochronological data summarized herein, together with the reinterpretation of the microgranular enclaves as hybridized mafic melt bodies, form the basis for a reassessment of the origin of both the Cornubian batholith and its lithophile metal mineralization.

Intrusion of the major plutons and small stocks which constitute the present surface expression of the batholith persisted episodically from ca. 293 to 274 Ma, and therefore clearly straddled the Pennsylvanian-Early Permian boundary. Mafic melts coexisted with the granitic magmas at least from

290.3 ± 1.2 Ma (Isles of Scilly granite) to 274 Ma and, although their composition cannot be defined precisely, they are probably represented by the basaltic/lamprophyric Exeter Volcanics which are also of Pennsylvanian-Early Permian age. It is of interest that Tidmarsh (1932) presciently argued for the importance of mafic/felsic magma commingling and mixing in the evolution of the Exeter Volcanics. The most parsimonious interpretation of these relationships is that lower-crustal anatexis was stimulated at intervals by incursions of mantle-derived melts, possibly controlled by displacements along a major structure broadly paralleling the batholith axis. We therefore do not envisage the existence of a deep-seated and persistent batholithic continuum, which gave rise to late, more differentiated, shallow intrusions (Charoy, 1986). It is, moreover, implicit that each anatectic event affected essentially pristine lower-crustal lithologies, accounting for the absence of major changes in the composition of the dominant biotite (-muscovite) monzogranite with time. However, plutons emplaced over a significant interval, such as Dartmoor and Land's End, could reveal the involvement of progressively more refractory protoliths.

We further conclude that all important lithophile (Sn, W)- and all or much of the Cu mineralization in the province developed shortly after emplacement of the coarse-grained monzogranites, and was genetically related thereto. Each exposed intrusion underwent a similar history of vein development: the earlier W-rich quartz vein and lode systems formed within 4-6 m.y. of intrusion, contemporaneously with the cooling of their immediate host-rocks to ca. 320°C, whereas major, 'main-stage', cassiterite-chalcopyrite (-arsenopyrite, sphalerite) lode development began 1-3 m.y. later, at a stage when such temperatures had been attained at (present) depths of 2-3 km. within the cooling plutons. Each of these hydrothermal processes, however, was significantly diachronous in the province as a whole: thus, all significant W, Sn and Cu ore formation associated with the Cam Brea apophysis of the Cammenellis pluton had terminated prior to the intrusion of the contiguous Land's End and, even, St. Austell plutons.

Recognition of the existence in Cornubia of large numbers of magmatic/hydrothermal sub-provinces has direct implications for models of 'emanative centres' (Dines, 1956) and for the overall evolution of the metallogenetic province. Whereas we do not concur with the model of Chesley *et al.* (1992), which ascribes all significant lode development to a late, post-batholith, hydrothermal event, each intrusive centre is considered to have evolved essentially as proposed by Jackson *et al.* (1989), albeit far more rapidly than they envisaged. The broad homogeneity of granitic chemistry over an interval of 20 m.y. is paralleled by a consistency in the nature of the associated mineralization: thus, the oldest (Camborne-Redruth district) and, presumably, youngest (St. Just district) major Sn-Cu lode systems differ in only minor aspects. The processes that stimulated and focussed the lode systems were clearly mediated tectonically, but it is possible that enhanced interaction between predominantly crystalline granite and deeply circulating brine, and the partially explosive concomitant emplacement of the rhyolitic, 'elvan', dykes (Goode, 1973), could have been caused by renewed or continued injection of mafic melts into restricted portions of the plutons. The Cornubian Sn-Cu lodes are representatives of the 'sulphide-cassiterite' clan of Russian workers, who have persistently argued (e.g. Shcheglov, 1991) that mantle-derived magmas are the source of the Cu and other base metals in such deposits. In this context, it is of interest that mid-Tertiary cordierite-biotite monzogranites of the SE Peruvian segment of the Central Andean lithophile metal belt (Clark *et al.*, 1990), associated with enormously rich 'Cornish-type' cassiterite-chalcopyrite lodes such as San Rafael (fine Sn production to date, + 60,000 t; 1992 production, 10,600 t); display clear evidence of commingling and mixing with both K-rich basaltic (Kontak *et al.*, 1986) and minette (Sandeman and Clark, 1993) magmas.

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REFERENCES

- BRAMMALL, A. and HARWOOD, H.F. 1923. The Dartmoor granite: its mineralogy, structure, and petrology. *Mineralogical Magazine*, **20**, 39-53.
- BRAMMALL, A. and HARWOOD, H.F. 1932. The Dartmoor granites: their genetic relationships. *Quarterly Journal of the Geological Society, London*, **88**, 171-237.
- BRAY, C.J. and SPOONER E.T.C. 1983. Sheeted vein Sn-W mineralization and greisenization associated with economic kaolinization, Goonbarrow china clay pit, St. Austell, Cornwall, England: geologic relationships and geochronology. *Economic Geology*, **78**, 1064-1089.
- BROMLEY, A.V. 1989. The Cornubian Orefield. International Association of Geochemistry and Cosmochemistry, 6th International Symposium on Water-Rock Interaction, Malvern, U.K., Field Guide, Camborne School of Mines, Redruth, 111 pp.
- BROMLEY, A.V. and HOLL, J. 1986. Tin mineralization in southwest England. In: Mineral Processing at a Crossroads, *Proceedings of NATO ASI Conference No. 117*, United Kingdom, 195-262.
- CAMBORNE SCHOOL OF MINES. 1990. Progress in Hot Dry Rock Technology for Application in Southwest England (1987-1989). Report, U.K. Department of Energy, 131 pp.
- CHAROY, B. 1986. The genesis of the Cornubian batholith (southwest England): the example of the Carmenellis pluton. *Journal of Petrology*, **27**, 571-604.
- CHEN, Y., in prep. *Geochronological Relationships in the Cornubian Metallogenic Province*. Ph.D. thesis, Queen's University, Kingston, Ontario.
- CHEN, Y., CLARK, A.H., FARRAR, E., BROMLEY, A.V., HODGSON, M.J. and WILLIS-RICHARDS, J. 1991. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of granitic intrusion and Sn-Cu-(W) mineralization, Cam Brea-Cam Marth-Carmenellis area, Cornwall, U.K. (abstract). *Geological Society of America Abstracts with Programs*, **23**, A293.
- CHEN, Y., CLARK, A.H., FARRAR, E. and HODGSON, M.J. in preparation. $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology of magmatism and hydrothermal activity in the South Crofty tin (-copper-tungsten-arsenic) deposit, southwest England.
- CHEN, Y., CLARK, A.H., FARRAR, E., WASTENEYS, H.A.H.P., HODGSON, M.J. and BROMLEY, A.V. 1992. Geochronological evidence for diachronous and independent histories of intrusion, early-sub solidus cooling, and Sn-Cu-(W-fluorite) mineralisation in the major plutons of the Cornubian batholith, SW England (abstract). EOS, *Transactions of the American Geophysical Union*, **73**, 627.
- CHEN, Y., CLARK, A.H., FARRAR, E., WASTENEYS, H.A.H.P., HODGSON, M.J. and BROMLEY, A.V. in press. Diachronous and independent histories of plutonism and mineralisation in the Cornubian batholith, southwest England. *Journal of the Geological Society, London*.
- CHESLEY, J.T., HALLIDAY, A.N., MEZGER, K., SNEE, L.W., SHEPHERD, T.J. and SCRIVENER, R.C. 1991. High precision U-Pb, $^{40}\text{Ar}/^{39}\text{Ar}$, and Sm-Nd geochronology of the Cornubian Batholith and related mineralisation: a model for long-lived hydrothermal mineralisation (abstract). EOS, *Transactions of the American Geophysical Union*, **72**, 530-531.
- CHESLEY, J.T., HALLIDAY, A.N., MEZGER, K., SNEE, L.W., SHEPHERD, T.J. and SCRIVENER, R.C. 1992. Emplacement and cooling history of the Cornubian Batholith: implications for the effects of multiple pluton emplacement on hydrothermal circulation (abstract). EOS, *Transactions of the American Geophysical Union*, **73**, 283.
- CHESLEY, J.T., HALLIDAY, A.N., NAKAI, S., SHEPHERD, T.J. and SCRIVENER, R.C. 1990. Single mineral Sm-Nd dating of fluorite mineralisation in Cornwall, England. Geological Society of America Abstracts with Programs, **22**, A223.
- CHESLEY, J.T., HALLIDAY, A.N. and SCRIVENER, R.C. 1991. Samarium-neodymium direct dating of fluorite mineralization. *Science*, **252**, 249-251.
- CLARK, A.H., FARRAR, E., KONTAK, LANGRIDGE, R.L., FRANCE, 14., MCBRIDE, S.L., WOODMAN, P.L., WASTENEYS, H.A., SANDEMAN, H.A. and ARCHIBALD, D.A., 1990. Geologic and geochronologic constraints on the metallogenic evolution of the Andes of southeastern Peru. *Economic Geology*, **85**, 1520-1583.
- DARBYSHIRE, D.P.F. and SHEPHERD, T.J. 1985. Chronology of granite magmatism and associated mineralisation, SW England. *Journal of the Geological Society, London*, **142**, 1159-1177.
- DARBYSHIRE, D.P.F. and SHEPHERD, T.J. 1987. Chronology of granite magmatism in SW England: the minor intrusions. *Proceedings of the Ussher Society*, **4**, 431-438.
- DIDIER, J. and BARBARIN, B. 1991. Enclaves and Granite Petrology. Developments in Petrology, 13, Elsevier, Amsterdam, 625 pp.
- DINES, H.G. 1956. The Metalliferous Mining Region of South-West England. Memoir of the Geological Survey of Great Britain, 2 vols., 795 pp.
- DODSON, M.H. and REX, D.C. 1971. Potassium-argon ages of slates and phyllites from south-west England. *Quarterly Journal of the Geological Society, London*, **126**, 465-499.
- EXLEY, C.S. and STONE, M. 1964. The granite rocks of southwest England. In: *Present Views on Some Aspects of the Geology of Cornwall and Devon*, Eds: Hosking, K.F.G. and Shrimpton, G.J., 150th Anniv. Vol., Royal Geol. Soc. Cornwall, 131-184.
- GHOSH, P.K., 1927. Petrology of the Bodmin Moor granite (eastern part), Cornwall. *Mineralogical Magazine*, **21**, 285-309.
- GOODE, A.J.J. 1973. The Mode of Intrusion of Cornish Elvans. Institute of Geological Sciences Report **73/7**, 8 pp.
- GOODE, A.J.J. and TAYLOR, R.T. 1988. Geology of the Country around Penzance. Memoir of the British Geological Survey, 1:50,000 Geological Sheet 351/358 (England and Wales).
- HALLIDAY, A.N. 1980. The timing of early and main stage ore mineralisation in southwest Cornwall. *Economic Geology*, **75**, 752-759.
- HARDING, R.R. and HAWKES, J.R. 1971. The Rb:Sr age and K/Rb Ratios of Samples from the St. Austell Granite, Cornwall. *Institute of Geological Sciences Report*, **71/6**, 10 pp.
- JACKSON, N.J., WILLIS-RICHARDS, J., MANNING, M., and SAMS, M. 1989. Evolution of the Cornubian ore field: Part II. Ore deposits and mineralizing processes. *Economic Geology*, **84**, 1101-1133.
- KONTAK, DJ., CLARK, A.H., FARRAR, E., PEARCE, T.H., STRONG, D.F. and BAADSGAARD, H. 1986. Petrogenesis of a Neogene shoshonite suite, Cerro Moromoni, Puno, S.E. Peru. *Canadian Mineralogist*, **24**, 117-135.
- LEVERIDGE, B.E., HOLDER, M.T. and GOODE, A.J.J. 1990. Geology of the Country Around Falmouth. Memoir of the British Geological Survey, 1:50,000 Sheet 352 (England and Wales).
- MILLER, J.A. and MOHR, P.A. 1964. Potassium-argon measurements on the granites and some associated rocks from southwest England. *Journal of Geology*, **4**, 105-126.
- PARRISH, R.R. 1990. U-Pb dating of monazite and its application to geological problems. *Canadian Journal of Earth Sciences*, **27**, 1431-1450.
- REID, C., BARROW, G., SHERLOCK, R.L. MACALISTER, D.A. and DEWEY, H. 1912. The Geology of Dartmoor. Memoir of the Geological Survey of England and Wales, Sheet 338.
- SANDEMAN, H.A. and CLARK, A.H. 1993. Mingling and mixing of minette and 'S-type', anatectic, rhyodacitic magmas, Crucero Supergroup, Puno, SE Peru (abstract). Geological Association of Canada/Mineralogical Association of Canada, Program with Abstracts, 18, Edmonton, Alberta, May, 1993, A-92.
- SCHÄRER, U. 1984. The effect of initial ^{230}Th disequilibrium on young U-Pb ages: the Makalu case, Himalaya. *Earth and Planetary Science Letters*, **67**, 191-204.
- SCRIVENER, R.C. 1982. Tin and Related Mineralisation of the Dartmoor Granite. *Unpubl. PhD thesis*, University of Exeter.
- SHCHEGLOV, A.D. 1991. Tin deposits and the mantle. *Global Tectonics and Metallogeny*, **4**, 69-74.
- SHEPHERD, T.J. and DARBYSHIRE, D.P.F. 1986. Fluid inclusion Rb-Sr geochronology of mineral deposits. In: *Geology in the Real World*. Eds: R.W. Nesbit and I. Nichol, Institution of Mining and Metallurgy, Kingsley Dunham Volume, 403-412.
- SNEE, L.W. 1982. *Emplacement and Cooling of the Pioneer Batholith, Southwestern Montana*. Unpub. Ph.D. thesis, Ohio State Univ., 320 pp.
- SNEE, SUTTER, J.F. and KELLY, W.C. 1988. Thermochemistry of economic mineral deposits: dating the stages of mineralization at Panasqueira, Portugal, by high-precision $^{40}\text{Ar}/^{39}\text{Ar}$ age spectrum techniques on muscovite. *Economic Geology*, **83**, 335-354.
- STIMAC, J.A., CLARK, A.H. and CHEN, Y. 1992. Microgranular enclaves and their bearing on the origin of the Cornubian Batholith, southwest England (abstract). EOS, *Transactions of the American Geophysical Union*, **73**, 627.
- STIMAC, J.A., CLARK, A.H., CHEN, Y., and GARCIA, S. in preparation. Enclaves and their bearing on the origin of the Cornubian batholith, southwest England.
- STONE, M. and AUSTIN, W.G.C. 1961. The metasomatic origin of the potash feldspar megacrysts in the granites of south-west England. *Journal of Geology*, **69**, 464-472.
- STONE, M. and EXLEY, C.S. 1985. High heat production granites of SW England and their associated mineralisation: a review. In: *High Heat Production (HHP) Granites, Hydrothermal Circulation and Ore Genesis*, Institution of Mining and Metallurgy, 571-593.
- TIDMARSH, W.G. 1932. Permian lavas of Devon. *Quarterly Journal of the Geological Society, London*, **138**, 712-773.
- WILLIS-RICHARDS, J. and JACKSON, N.J. 1989. Evolution of the Cornubian ore field: Part I. Batholith modeling and ore distribution. *Economic Geology*, **84**, 1078-1100.