# THE ROLE OF POST-VARISCAN EXTENSIONAL TECTONICS AND MANTLE MELTING IN THE GENERATION OF THE LOWER PERMIAN GRANITES AND GIANT W-AS-SN-CU-ZN-PB OREFIELD OF SW ENGLAND

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**Introduction:** The Cornubian batholith of SW England is the largest in the British Isles and one of the most intensively investigated in the world. Production from the associated giant W-As-Sn-Cu-Zn-Pb orefield ceased with the closure of South Crofty Mine in 1998. Total historical output is estimated at ~1.75 Mt Sn, 1 Mt Cu and 0.13 Mt Zn, and the province played a major role in the development of early magmatic-hydrothermal mineralization models and the science of mining geology.

Many of the petrological, geochemical and geochronological characteristics of the batholith, and the distribution, parageneses and broad fluid characteristics of the associated hydrothermal mineralisation have been elucidated. However, published models do not satisfactorily explain: (1) the generation and emplacement of a very substantial volume of granite within a relatively external part of the European Variscides, and (2) the complementary factors that favoured the development of a giant orefield.

We present here the integrated results of tectonic/structural geological and helium/sulphur isotope studies. These data indicate that post-collisional lithospheric extension and mantle partial melting exerted a major control upon magmatism and associated mineralization. These processes are considered in the wider context of Permo-Carboniferous magmatism in Europe, and generic controls upon Sn-Cu mineralization.

**Tectonics/structural geology:** The metasedimentary and metavolcanic rocks that host the batholith accumulated in marine sedimentary basins along the northern flank of an ~E-W trending Devonian rift zone in which oceanic lithosphere had locally developed (Lizard ophiolite). The passive margin was subsequently overridden during Variscan convergence (Carboniferous) and the sedimentary basins were progressively incorporated into a northwards propagating thrust stack above a mid-crustal détachment.

Mesoscopic thrust-related deformation is represented by two generations of folds and cleavage that are generally compatible with a top sense of shear to the NNW (e.g. Shackleton et al. 1982). The crust underwent only moderate thickening and the associated regional metamorphism does not usually exceed epizone (Warr et al. 1991).

A third generation of folds and cleavage has previously been interpreted to have formed during forceful diapiric emplacement of the Cornubian batholith (e.g. Rattey and Sanderson 1984). Our data do not support this hypothesis and instead indicate that these structures formed during regional southerly-directed shear. We attribute this episode of deformation to the extensional reactivation of major thrust faults and crustal thinning *prior* to granite emplacement (Shail and Alexander, 1997).

**Granite magmatism:** The granites of the Cornubian batholith were generated and emplaced during a 25 Ma period between *c.* 295-270 Ma (Chen et al. 1993). Gravity modelling indicates the batholith has dimensions of ~200×50×13 km and a volume of 68,000 $km^3$ (Willis-Richards and Jackson 1989). Coarse-grained two mica peraluminous granite predominates and has initial $^{87}Sr/^{86}Sr$ ratios of 0.710-0.716 and $\varepsilon_{Nd}$ values of -4.7 to –7.1 (Darbyshire and Shepherd 1994). Although a dominant lower crustal source is implied, a mantle component has tentatively been inferred on the basis of wholerock geochemistry, Sm-Nd isotope systematics, enclave studies and a close spatial and temporal association with lamprophyres and basalts (e.g. Leat et al. 1987, Darbyshire and Shepherd 1994, Stimac et al. 1995). Magmatic fabrics developed within the granites are commonly compatible with NW-SE extension during emplacement (Mintsa Mi Nguema et al. 2002).

**Mineralization:** There is a clear spatial association between the granite batholith and W-As-Sn-Cu-Zn mineralization. Principal styles include pegmatites (W, As, Sn), greisen-bordered sheeted veins (W, As, Sn), tourmaline-quartz breccia veins (Sn) and chlorite-tourmaline-sulphide veins (Sn, Cu, As, Zn, Pb). The latter two styles accounted for the majority of production and, in most areas, are hosted by steeply dipping extensional faults and/or tensile fractures that formed in response to regional NW-SE to N-S extension (Moore 1975, Shail and Alexander 1997). The fracture network allowed variable mixing between magmatic-hydrothermal, meteoric and metamorphic fluids (Alderton and Harmon 1991, Wilkinson et al. 1995)

**Helium and sulphur isotope study:** In order to test whether a mantle-derived component can be recognized, we have analysed: (1) He isotopes in volatiles hosted by fluid inclusions in wolframite, arsenopyrite and fluorite separates from magmatic-hydrothermal veins, and (2) S isotopes in the arsenopyrite from the same veins. The specimens are from the Land's End, Carnmenellis, Cligga Head and Hingston Down granites.

*Application of He isotopes.* Where fluid inclusions are trapped by dense U- and Th-poor minerals, the outward diffusion rate of He is low and isotope ratios are essentially unmodified from the time of trapping (e.g. Stuart et al. 1995). Subcontinental lithospheric mantle is characterized by $^3He/^4He$ of ~7 R/Ra (atmospheric ratio), whereas crustal radiogenic He is characterized by $^3He/^4He$ of ~0.05 R/Ra. As a consequence, $^3He/^4He$ is a sensitive indicator of mantle-derived volatiles in crustal fluids.

*Results.* A mantle-derived component is recognized within the majority of specimens and from all the granites, including the oldest and youngest within the batholith. Analyses of sensibly coeval minerals from a paragentically early assemblage (CRXC6) indicate He retention in arsenopyrite>> wolframite> fluorite. The sulphur isotope data are consistent with a dominantly magmatic source. Collectively, the data provide the first unequivocal evidence for a mantle source of volatiles in the magmatic-hydrothermal fluids associated with the Permian granites of SW England.

**Discussion:** Variscan convergence in SW England brought about modest thrust-related thickening of a thermally young passive margin. Whilst this undoubtedly increased the transient geothermal gradient within the lower plate, Permian granite magmatism and associated magmatic-hydrothermal mineralization was ultimately initiated, and subsequently controlled, by *c.*30 Ma of post-collisional lithospheric extension. Mantle melts underplated and/or injected during this episode provided the additional heat necessary to generate a large volume of granite from the lower part of a relatively thin crust.

*Comparison with European Variscides.* HT-LP metamorphism and widespread granite magmatism across the Variscides of mainland Europe have been attributed to orogenic collapse (Ménard and Molnar 1988). In SW England, it is more likely that latest Carboniferous changes in plate boundary stresses (e.g. Henk 1999) permitted differential lithospheric extension west of the Bray Fault, although mantle melt generation may have been aided by anomalous temperatures established following the creation of Pangea (e.g. Doblas et al. 1998).

**Table 1.** Helium and sulphur isotope data

| Name | Mineral | $R/R_a$ | mantle He % | $\delta^{34}S$ ‰ |
|---|---|---|---|---|
| C95-1 | wolframite | 0.36 | 4.4 | |
| C95-2 | wolframite | 0.16 | 1.6 | |
| C95-3 | arsenopyrite | 0.75 | 10.0 | +3.1 |
| C95-4 | arsenopyrite | 2.22 | 31.2 | +3.2 |
| C95-5 | wolframite | 0.05 | 0.0 | |
| CRXC6 | wolframite | 0.23 | 2.5 | |
| CRXC6 | arsenopyrite | 1.01 | 13.9 | +4.7 |
| CRXC6 | fluorite | 0.06 | 0.2 | |
| RC1 | wolframite | 0.15 | 1.5 | |
| RC1 | fluorite | 0.11 | 0.8 | |
| RC1 | arsenopyrite | 0.99 | 13.5 | +1.5 |
| D54 | fluorite | 0.68 | 9.0 | |
| HD1 | arsenopyrite | 0.73 | 9.8 | +1.4 |

*Generic controls.* Post-collisional lithospheric extension provides a favourable regime for the generation of enhanced volumes of granite and so poten-facilitates greater accumulation of Sn during differentiation. Our work is compatible with earlier suggestions that the transfer of mantle-derived volatiles (+/-melts) into the magmatic system may be a prerequisite for the Cu and S enrichment of the sulphide-cassiterite association displayed by many giant tin deposits (Clark et al. 1993). Continued lithospheric extension during and after granite emplacement is critical for the creation of steeply dipping upper crustal fault systems in which magmatic-hydrothermal and other fluids can be efficiently transported and mixed.

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