REPORT

The relationship between magmatic activity, fault systems, mineralisation types and potential economic mineral deposits of south-west Cornwall

Cornwall has an extensive economic history that is inextricably tied to its well-chronicled and illustrious mining identity. The province is rich in a wide variety of economic metal and other mineral deposits, primarily motivated by orogenic activity and subsequent plutonic granite intrusions. The St Just mining district (SJMD) of south-west Cornwall, whilst extensively exploited, has seen little work documenting the relationships between the economic mineral deposits of the area and the overarching geological processes and systems that define the region. Research by the author has identified and chronologically defined fault and cleavage systems and their relationships to plutonic intrusions, in addition to determining which of these systems served as propagation pathways for associated hydrothermal fluids and resulting mineral formation, confirmed through electron microscopy analysis.

The geology of south-west England is characterised by the imprint of Palaeozoic tectonics, most markedly the Variscan Orogeny that occurred between the Early Devonian and Late Carboniferous (Leveridge and Hartley, 2006; Schulmann et al, 2014). The orogeny resulted from the closure of the Rheic Ocean and subsequent collision of the continents of Laurentia (Laurasia) and Gondwana to form Pangea (Hunter and Easterbrook, 2004; Leveridge and Hartley, 2006). South-west England existed within the Rhenohercynian passive margin, a tectonic boundary on the northern front of the Rheic Ocean. South-west England is believed to represent a marginal zone (Holder and Leveridge, 1986; Shail and Leveridge, 2009) formed after the closure of the Rheic, with the province consisting of multiple extensional basins caused by consequent sea floor spreading, and accretional wedge sedimentation driven by the convergence of the Variscan Orogeny (Leveridge and Hartley, 2006; Shail and Leveridge, 2009). The Devonian sediments were heavily deformed by the orogeny (Holder and Leveridge, 1986; Hunter and Easterbrook, 2004) and maintain systematic cleavages associated with the primary directions of collisional stress, and both Simons et al (2017) and Hunter and Easterbrook (2004) state the subduction or partial melting of the thickened crust as the leading source of the massive granitic bodies in the region. The Variscan Orogeny accentuated and reactivated existing local fault systems in addition to the production of its own fault and cleavage complexes (Clayton et al, 1990). The hydrothermal activity responsible for the production of mineral veins across Cornwall was encouraged and escalated by such tectonic structures (Gleeson et al, 2001). A predominantly NNW–SSE extensional regime (Shail and Leveridge, 2009) succeeded the Variscan Orogeny exploiting pre-existing thrust and transfer faults. The crust of south-west England was considerably thinned by extension, depressurising the underlying mantle, and motivating the generation of copious volumes of magma, including the granitic Cornubian batholith (Barton, 1964; Shail and Leveridge, 2009), and the formation of metalliferous ores (Hughes, 2018). Analysis of fluid inclusions within quartz crystals from previously exploited mineral veins hosting economic metal sulphides classifies their origin as both magmatic and oceanic fluid systems, believed by Gleeson et al (2001) to have been active simultaneously.

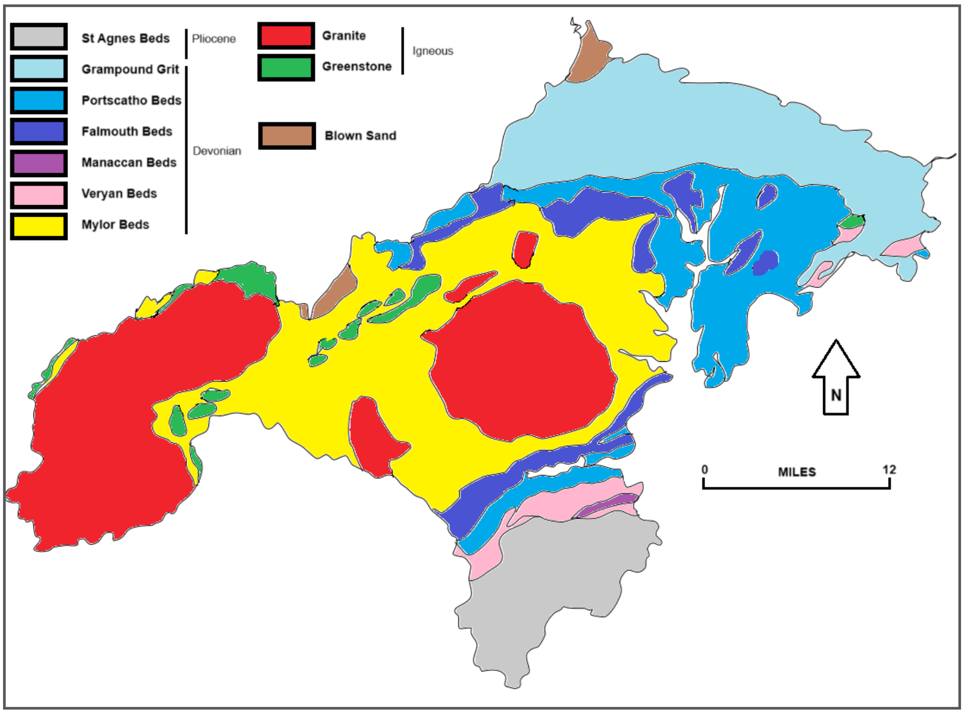

Figure 1: Overview of the lithology of the Gramscatho Basin (adapted from Barton, 1964). Note: this map employs old terminology.

The Gramscatho Basin, the southernmost geological basin of Cornwall (Fig. 1), comprises two major Devonian series: the eponymous Gramscatho Group (Devonian formations above Mylor Beds in Fig. 1) and the overlying Mylor Slate Formation (Mylor Beds in Fig. 1), in addition to the intrusive granite batholiths (Barton, 1964; Halliday, 1980). These batholiths, accompanied by complex porphyry dyke systems and widespread greisenisation caused by percolating hydrothermal fluids are acknowledged by Halliday (1980) as the primary sources of mineralisation within the region. The basin has historically been exploited for its abundant ore deposits (Rollinson et al, 2018), notably tin and copper ores, for which Cornwall gained global notoriety. The most prevalent and economic ores present in south-west Cornwall are principally cassiterite, chalcopyrite, malachite and azurite, with sulphides of iron, lead, zinc and silver also being exploited (Dines, 1956), whilst modern exploration has indicated the presence of lithium mineralisation and the potential for extracting lithium from geothermal brines (Shaw, 2022). The Cornubian batholith itself demonstrates significant mineralogical variation, attributed to a multitude of fractionation stages by Simons et al (2017), and by means of which it can be classified into five mineralogically distinct granites across Cornwall. Accessory phases within these larger periods of fractionation have resulted in further individualisation of the granites.

The Cornubian batholith is a heterogeneous, peraluminous plutonic body hosting five dominant mineralogical assemblages inherited from variation within lower continental crust source rocks, fluctuation of lamprophyre and mantle source involvement, in addition to magma differentiation and fractionation (Simons et al, 2017). The discordant batholith exists as a ridge-like intrusion along the length of Cornwall (Barton, 1964), with mineralogical variation expressed universally throughout, as visually demonstrated in Fig. 2. The granitic pluton emplaced in the SJMD, colloquially termed the Land's End Granite (LEG) (Barton, 1964), is further segregated into multiple petrological divisions, but is dominated by a coarse-grained, porphyritic tourmaline granite (Simons et al, 2017). The Cornubian batholith was emplaced over an estimated 30 Ma-period between 300 and 270 Ma (Chen et al, 1993; Chesley et al, 1993). The LEG is the youngest plutonic mass within the batholith, forming between 274 and 279 Ma (±2 Ma), after an interval of little to no intrusive activity after the genesis of older magmatic bodies such as the Carnmenellis and Bodmin Moor plutons (Chesley et al, 1993), with a cooling period for the entire batholith approximated at 80-100 Ma by Chen et al (1993). The Cornubian granites intrude low grade metamorphosed (syn-convergence epizone-anchizone facies), cleaved and highly folded Devonian and Carboniferous sediment and mafic igneous volcanics (Barton, 1964; Simons et al, 2017). This intrusion induced hornfels facies metamorphism and metasomatism within the country rock to produce hornfels, tourmaline slates and skarns (Chesley et al, 1993).

The principal form of mineralisation across Cornwall is granite-related and hydrothermal in nature, and Chesley et al (1993) categorised the process into four stages: exoskarns, sheeted greisenisation, polymetallic fissure veining, and late-stage, low temperature polymetallic fluorite veining. Granite-related mineralisation is assumed to occur over a geologically insignificant period (<10^6 years), and the bulk of Cornish mineralisation is stated by Hughes (2018) to have been active during plutonic emplacement at ±3 Ma. Mineralisation is regionally associated with steeply dipping fractures and cleavages that occur in both the granite and country rock (most notably NNW–SSE fault systems), or at contact planes between them. Repeated reactivation of fault pathways and associated fluid flow formed veins of multiple paragenetic sequences and layered mineralisation (Dines, 1956). Late-stage mineralisation in the Gramscatho Basin is colloquially

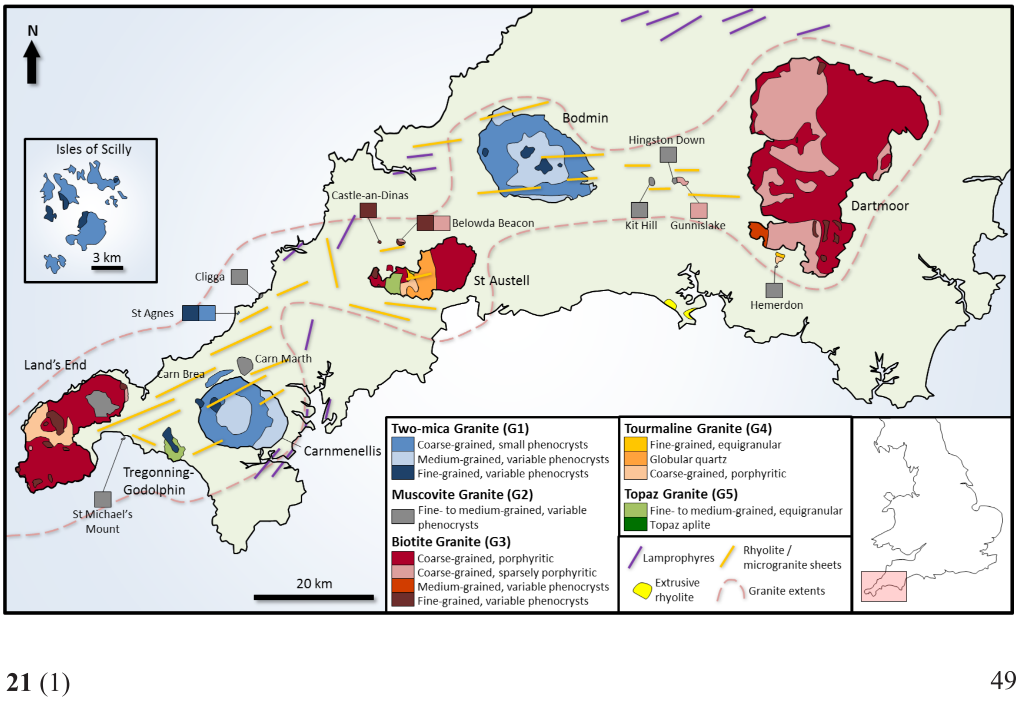

Figure 2: Mineralogical variation in the Cornubian batholith, showing the extent of the granites found in the SJMD, including a coarse-grained, porphyritic tourmaline granite, a fine-grained biotite granite and a topaz apatite granite (Hughes, 2018; reproduced with permission)

Table 1: Deformation events (D) and associated structural systems (F= folds; S= cleavage) listed chronologically from D1 to D5 (Hughes, 2018)

Relative chronology			Structures and orientations	Bulk kinematics and interpretation	Tectonic setting	Age
D1			F1 folds face and verge NNW, S1 dips gently SSE	NNW-SSE shortening during Variscan convergence, thrust nappe emplacement and continental collision	Ocean closure; Continental collision	DEV.
D2			F2 folds verge NNW, S2 dips moderately SSE			CARB.
Late / post-D2			NW-SE strike-slip faults and quartz veins			
D3	Distributed shear		F3 folds verge SSE, S3 dips moderately NNW	NNW-SSE post orogenic extension, possibly reactivating major thrust faults and pre-dating granite emplacement	Pangean intraplate tectonics (basin development)	PERMIAN
	Detachments		Synthetic extensional faults dip and displace SSE			
	Brittle listric faults		Extensional faults dip SSE, slickenlines plunge SSE			
LATE	Brittle listric faults		Extensional faults dip NNW, slickenlines plunge NNW	NNW-SSE extension coeval with granite emplacement		
	D4	Crenulation cleavage	Steep cleavage strikes NNW-SSE	ENE-WSW shortening		
		Steep faults and lodes	Steep, often mineralised, faults dip NNW or SSE	NNW-SSE extension and minor strike slip		
	D5		Steep cleavage strikes ENE-WSW, NNW-SSE striking tensile fractures	NNW-SSE shortening		
	Crosscourse		Steep faults, often mineralised strike NNW-SSE	ENE-WSW extension		TRIAS.

* Note that strike slip faults occur throughout each of the deformation events and reactivation of previous structures by later events is common

termed 'cross-course' due to its perpendicular relationship with earlier granite-related lodes (Hughes, 2018). Permo-Triassic E–W extension regimes were the primary tectonic driver behind the opening and mineralisation of typically NW–SE veins. These veins formed at much lower temperatures than granite-related mineralisation, and often appear texturally banded and vuggy (Shail and Alexander, 1997).

Convergence-related deformation has been resolved into two major phases, titled D1 and D2 by Shail and Alexander (1997). D1 is evidenced by SSE-dipping thrust faults, NNW isoclinal folds and gently dipping SSE cleavage (Hughes, 2018), whereas D2 relates to overturned folds that plunge E to NE, sometimes displaying an axial planar crenulation cleavage that dips moderately to SSE (Alexander and Shail, 1995). Table 1 orders all major deformation events recorded within the lithologies of the Gramscatho Basin and their associated structural tendencies.

Three separate fault systems and four distinct deformation events were recorded within SJMD lithologies through field investigations, but strike orientations of their associated cleavages are slightly shifted from values expected within other regions of the Gramscatho Basin observed in Hughes (2018). The relationships between the deformation events and their associated cleavage systems are visually demonstrated in Fig. 3. In addition, four major mineralisation types were identified: skarns, greisen sheets, polymetallic fissure veining, and polymetallic crosscourse veining. The most abundantly observable mineralisation was crosscourse, principally related to NW–SE striking faults and D3 and D4 post-orogenic deformation events (Fig. 4a). Earlier quartz veining is associated with D1 deformation and as such is commonly deformed by subsequent events (Fig. 4b). Scanning electron microscope (SEM) analysis of primary samples collected from the LEG and hydrothermally altered fault rock discovered identical Nd-monazites and Hf-zircons within both units, indicating a direct relationship between the LEG and the associated magmatic and hydrothermal fluids motivating polymetallic crosscourse and greisen mineralisation. The extensive fault and cleavage lattices produced by LEG emplacement provided multitudinous propagation pathways for magmatic and hydrothermal fluids, creating the district's comprehensive mineralisation networks.

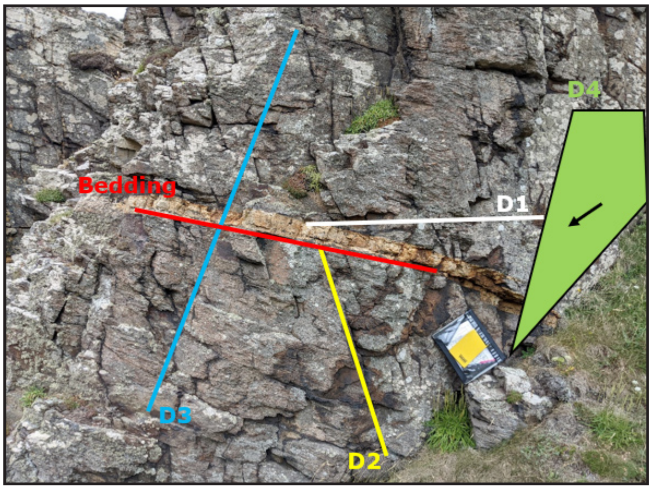

Figure 3: Cleavages and their temporal relationship to a granitic sill. Weather writer for scale (width=35cm)

Figure 4: *(a) Quartz vein within fault, finger for scale; (b) Thick quartz vein within D1 cleavage, hand for scale.*

An additional, later deformation event recorded within existing literature (D5 in Table 1) was unobserved across the SJMD, and the cleavage orientations of the foremost event (D1) diverged substantially from existing measurements. The SJMD also exhibited cleavage strikes and dips that deviated from those reported in the literature, a phenomenon also observed by Hughes (2018). The observed deviation of SJMD deformation cleavages may be the result of localised displacement caused by the emplacement of the LEG pluton (Clemens & Mawer, 1992; Petford et al, 2000).

Evidence presented in this paper indicates that the emplacement of the Land's End Granite pluton and the action of associated hydrothermal fluids are responsible for the widespread economic mineral network across the St Just mining district. The deposits are located along unique cleavage and fault lattices developed through Cornwall's Variscan and post-Variscan tectonic history that has allowed for relatively accessible lodes and veins to be exploited throughout the region. Despite the work of this project establishing links between St Just mining district mineralisation and the overarching geological history of the Gramscatho Basin, the regional disparities and apparent displacement remain a geological mystery.

References

Alexander, A. C. & Shail, R. K. 1995. Late Variscan structures on the coast between Perranporth and St Ives, Cornwall. *Proceedings of the Ussher Society*, **8** (4), 398–404.

Barton, R. M. 1964. *An introduction to the geology of Cornwall*. 2nd ed. Bath: Pitman Press.

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 mineralization in the Cornubian Batholith, southwest England. *Journal of the Geological Society, London*, **150** (6), 1183–1191.

Chesley, J. T. et al. 1993. Thermochronology of the Cornubian batholith in southwest England: implications for pluton emplacement and protracted hydrothermal mineralization. *Geochimica et Cosmochimica Acta*, **57** (8), 1817–1835.

Clayton, R. E., Scrivener, R. C. & Stanley, C. J. 1990. Mineralogical and preliminary fluid inclusion studies of lead-antimony mineralisation in north Cornwall. *Proceedings of the Ussher Society*, **7** (3), 258–262.

Clemens, J. D. & Mawer, C. K. 1992. Granitic magma transport by fracture propagation. *Tectonophysics*, **204** (3-4), 339–360.

Dines, H. G. 1956. *The metalliferous mining region of south-west England*. London: HMSO, Memoirs of the Geological Survey, vol. 1, 20–72.

Gleeson, S. A., Wilkinson, J. J., Stuart, F. M. & Banks, D. A. 2001. The origin and evolution of base metal mineralising brines and hydrothermal fluids, South Cornwall, UK. *Geochimica et Cosmochimica Acta*, **65** (13), 2067–2079.

Halliday, A. N. 1980. The timing of early and main stage ore mineralization in Southwest Cornwall. *Economic Geology*, **75** (5), 752–759.

Holder, M. T. & Leveridge, B. E. 1986. A model for the tectonic evolution of south Cornwall. *Journal of the Geological Society, London*, **143** (1), 125–134.

Hughes, S. P. 2018. *The tectomagnetic evolution of the Land's End Granite*. University of Exeter: unpublished PhD thesis.

Hunter, A. & Easterbrook, G. 2004. *The geological history of the British Isles*. First edition. Oxford: The Alden Group.

Leveridge, B. & Hartley, A. J. 2006. The Variscan Orogeny: the development and deformation of Devonian/Carboniferous basins in SW England and South Wales. In: *The geology of England and Wales* / edited by P. J. Brenchley & P. F. Rawson. London: Geological Society of London, pp 225–255.

Petford, N., Cruden, A. R., McCaffrey, K. J. W. & Vigneresse, J. L. 2000. Granite magma formation, transport and emplacement in the Earth's crust. *Nature*, **408** (6813), 669–673.

Rollinson, G., Le Boutillier, N. & Selley, R. 2018. Cobalt mineralisation in Cornwall—A new discovery at Porthtowan. *Geoscience in South-West England*, **14**, 176–187.

Schulmann, K., Catalán, J. R. M., Lardeaux, J. M., Janoušek, V. & Oggiano, G. 2014. The Variscan orogeny: extent, timescale and the formation of the European crust. *Geological Society Special Publication*, **405** (1), 1–6.

Shail, R. K. & Alexander, A. C. 1997. Late Carboniferous to Triassic reactivation of Variscan basement in the western English Channel: evidence from onshore exposures in south Cornwall. *Journal of the Geological Society, London*, **154**, 163.

Shail, R. K. & Leveridge, B. E. 2009. The Rhenohercynian passive margin of SW England: Development, inversion and extensional reactivation. *Comptes Rendus Geoscience*, **341** (2-3), 140–155.

Shaw, R. 2022. The potential for lithium in the UK. *British Geological Survey Commissioned Report* CR/22/123, 8pp.

Simons, B., Andersen, J. C., Shail, R. K. & Jenner, F. E. 2017. Fractionation of Li, Be, Ga, Nb, Ta, In, Sn, Sb, W and Bi in the peraluminous early Permian Variscan granites of the Cornubian Batholith: precursor processes to magmatic-hydrothermal mineralisation. *Lithos*, **278**, 491–512.

Michael Duggins, Derby University winner of the EMGS Beryl Whittaker Award for 2023.