

COBALT MINERALISATION IN CORNWALL – A NEW DISCOVERY AT PORTHTOWAN



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Although cobalt mineralisation has been noted in Cornwall and Devon in the mining literature, there are limited details of its production and paragenesis; detailed mineral studies of cobalt are almost non-existent. This paper describes in detail previously unrecorded cobalt mineralisation discovered at Porthtowan, Cornwall, in the vicinity of old workings which are part of the Wheal Lushington group of mines, immediately west of the village. A small number of massive sulphide/gangue samples (taken from a larger sample suite) were chosen to be as representative as possible. Analysis was carried out using a QEMSCAN® automated mineral SEM-EDS system, which found that samples contained up to 50% cobaltite, along with chalcopyrite, bornite, galena, sphalerite, acanthite, erythrite, matildite, chlorargyrite and other primary and secondary mineral species. This assemblage is typical of a sub-type of crosscourse mineralisation, with secondary species a result of significant weathering and supergene alteration, complicated by seawater infiltration due to the coastal location. While the number of samples is limited, the detail of the mineralogical assemblage is significant, as it is the first time such an assemblage has been subjected to this level of scientific scrutiny in Cornwall.

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INTRODUCTION

Cobalt, atomic number 27, is a brittle, hard, silvery grey transition metal with an average crustal abundance of 26.6 ppm, occurring in nature as a series of sulphides and arsenides (and secondary species), in close association with silver, nickel and copper. Cobalt was first isolated in 1739 by Georg Brandt (<http://www.rsc.org/periodic-table/element/27/cobalt>) and is a dense metal (8.86 g/cm³) with a high melting point (1495°C) and ferromagnetic properties. It is used chiefly in the production of high-strength and heat-resistant alloys as well as in magnets, battery cathodes (with lithium), jewellery (alloyed with platinum) and medical implants. Its compounds have wide ranging uses as colourants and catalysts.

Cobalt does not occur naturally in native form, although it does form the very rare alloy wairauite (CoFe) found at one locality in New Zealand. It is known as an essential component in 59 mineral species (Mindat.org, 2017), the majority of which are sulphides, arsenides and secondary arsenates. The most common species, including those found in this study, are: cobaltite (CoAsS), skutterudite (CoAs₃), safflorite (CoAs₂) and, the secondary arsenate, erythrite (Co₃(AsO₄)·8H₂O). Cobalt has a strong affinity for nickel, silver and arsenic and compounds of these elements often form in close paragenetic association with cobalt species.

COBALT IN CORNWALL

Cobalt is a minor product of the Cornubian Orefield, with a total mined production (mostly from the mid-late 18th Century and early 19th Century; records of which are very incomplete) of a few hundred tons (Dines, 1956). In some cases it was mined in conjunction with nickel and bismuth ores and Alderton (1993) gives a combined production of 500 tons for these three metals, although the real figure is likely to be higher.

Cobalt mineral species were recognised in around thirty Cornish mines (Borlase, 1758; Pryce, 1778; Dines, 1956; Collins, 1912, 1892; Tindle, 2008; Le Boutillier, 1996, 2003). Cobaltite has been confirmed from Fowey Consols, St Blazey and South Terras Mine, St Stephen-in-Brannel. Earlier references to cobaltite at Dolcoath Mine, Wherry Mine and Botallack Mine, now appear to be dubious and are likely describing skutterudite (Tindle, 2008). Cobaltite was found as a minor constituent in the 3ABC Pegmatite Zone on the 360 fathom level of South Crofty Mine at Pool (Le Boutillier, 2003). Skutterudite is known from Botallack Mine; Levant Mine; Geevor Mine; Wherry Mine, Penzance; Hawkes Point Mine, St Ives; Wheal Herland, Gwinear (associated, in a crosscourse, with native silver and silver sulphides; Hamilton Jenkin, 1963a); Roscrow United Mine, Ponsanooth; Wheal Sparnon and Pednandrea Mine, Redruth; East Pool Mine, Illogan; Dolcoath Mine, Camborne (associated with U, Co, Ni-bearing crosscourses cutting Main Lode close to

the Great Crosscourse; Dines, 1956); St Austell Consols, Sticker (associated with U, Co, Ni-bearing crosscourses; Hamilton Jenkin, 1964a); Polgooth Mine, St Austell; Wheal Trugo, St Columb Major; South Terras Mine; Killifreth Mine, Gwennap and Fowey Consols (Golley and Williams, 1995; Tindle, 2008; Collins, 1892). Safflorite is known from Roscrow United Mine (Tindle, 2008) and Wheal Sparnon (Golley and Williams, 1995).

Erythrite is the pink-purple to deep rose pink secondary arsenate and is known from Pengreep Adit, Gwennap; Dudnace Mine, Pool (Borlase, 1758; Pryce, 1778); Botallack Mine; Roscommon Cliff, St Just; Carrick Du Mine and Wheal Trenwith, St Ives; Wheal Alfred, Phillack; Wheal Unity, St Day; Dolcoath Mine; East Pool Mine; Wheal Sparnon; Pednandrea Mine; Wheal Buller, Redruth; Wheal Unity and Wheal Huckworthy (Claughton, 2016); Cligga Mine, Perranporth; Polgooth Mine; South Terras Mine; Penberthy Croft Mine and Enys Wheal Virgin, St Hilary; St Austell Consols, Great Retallack Mine, St Agnes and Pentireglaze Mine, Wadebridge (Tindle, 2008; Golley & Williams, 1995; Collins, 1892); St Neot and St Cleer Consolidated Mines, Liskeard (Hamilton Jenkin, 1966); Treoil Mine, Lanivet; Wheal Trewolvas, near St Columb; and Pelyn Wood Mine, near Lostwithiel (Hamilton Jenkin, 1964b, 1966, 1967). In addition powdery coatings of erythrite on cobalt-rich arsenopyrite (Danaite, $(\text{Fe}_{0.90}\text{Co}_{0.10})\text{AsS}$ to $(\text{Fe}_{0.65}\text{Co}_{0.35})\text{AsS}$) were noted from 340 fathom Dolcoath South Lode and 360 fathom Roskear Complex of South Crofty Mine (Le Boutillier, 1996). Small amounts of erythrite were also found associated with tourmaline-quartz-chalcopyrite veins at Holman's Test Mine in the Carnmenellis Granite near Troon, south of Camborne (R. Shail, *pers comm.* 2015).

Cobalt was first noted in Cornwall in 1754 (only 15 years after being first identified as an element) in the form of erythrite. At Pengreep, Gwennap, a 3ft wide N-S 'cobalt lode' was found in an adit being driven through greenstone (dolerite). At the time, the lode was dubbed "the richest cobalt found in England" and the landowner, Mr Beauchamp, was awarded a £30 prize for the discovery by the Society for Encouraging Useful Arts. Shortly afterwards the adit was abandoned due to water influx (Borlase, 1758; Pryce 1778). In 1958, A. K. Hamilton Jenkin inspected the adit and found no trace of any mineralisation (Hamilton Jenkin, 1963b). At Trugo Mine, St Columb Major, a 4 to 6 inch wide vein of erythrite was found in an adit at a point where a crosscourse meets a copper vein (Pryce 1778). In 1798 "a rich vein of cobalt" was discovered at Wherry Mine (Joseph, 2012) just off Penzance. Samples of this material are highly prized by collectors, particularly the erythrite specimens; it is not known if any of this material was sold as the mine closed shortly afterwards (Joseph, 2012; Dines, 1956; Hamilton Jenkin, 1962b).

Production of cobalt ores took place at a very small number of mines and those production figures are far from complete. Pelyn Wood Mine, near Lostwithiel, produced 25 to 30 tons of mixed Ni/Co ores in 1860 (Hamilton Jenkin, 1967). Treoil Mine, near Lanivet, was producing cobalt and silver ores from the 14, 20 and 30 fm levels in 1844, but there are no details of tonnages produced (Hamilton Jenkin, 1966). Trugo Mine, near St Columb, was being worked for cobalt (erythrite) in 1813 and was selling cobalt ore for £200 per ton in 1825, though again no details of production tonnages are known. In an earlier working, from 1720, by German miners, the mine is reputed to have sold £10,000 worth of cobalt ore (Hamilton Jenkin, 1963c). In the St Austell district, Great Dowgas Mine produced 4 tons in 1857 (from a U, Co, Ni-bearing crosscourse) and St Austell Consols produced around 128 tons of mixed nickel and cobalt ores between 1854 and 1863 (Dines, 1956) also from a N-S crosscourse (Hamilton Jenkin, 1964a). Between 1845 and 1905 East Pool Mine, at Pool, near Camborne, produced 4.5 tons of cobalt ore (Dines, 1956). At Camborne, Dolcoath Mine sold 3 tons of cobalt ore in 1813 (Morrison, 1983); these ores, only found in the upper levels of the mine, came from lodes near the Great Crosscourse, from Main Lode, but primarily from crosscourses, associated with nickel and bismuth ores (Dines, 1956). Cobalt ores were also found on the dumps at Dolcoath

in 1838 (Morrison, 1983), though it is unknown what became of the material. Wheal Unity, near Gwennap, sold 1700lb of cobalt ore in 1820 (Collins, 1912).

The most significant cobalt producer was Wheal Sparnon at Redruth (Hamilton Jenkin, 1962a), which worked a sett bounded on the north by Raymond Road, and on the west by Falmouth Road. The mine was producing small amounts of cobalt in 1808 from the NNW-SSE trending 'Western Crosscourse', which parallels Falmouth Road and lies some 30-40 metres east of it (Hamilton Jenkin, 1962a), later renamed Cobalt Lode. Two tons of ore were sold in 1814 for £600 per ton. In 1817, 80 tons of cobalt ore had been stockpiled; much of this was roasted to produce cobalt oxides for the pottery industry and the mine sold oxides valued at £4000 that year as well as raw cobaltite/skutterudite ores for £240 per ton. By 1819 the workings on Cobalt Lode had reached 60 fms below adit (eventually reaching 70 fathoms) and the mine was being worked solely for cobalt – the only Cornish mine ever to do so. The mine appeared to be doing well in 1826 with regular sales of oxide, but it closed in late 1827 after making a loss of £200 a month for a few months (Hamilton Jenkin, 1962a). Although included in the sett of the neighbouring Pedn An Drea Mine that restarted in 1864, no further work was done at Wheal Sparnon and no further cobalt raised. There is no record of the total tonnage of cobalt ores raised (Dines, 1956) between 1808 and 1827. Gold was reputedly found in the crosscourse (Collins, 1892 and 1912) and on the dumps (Hill and MacAlister, 1906), but there are no further details.

COBALT MINERALISATION WITHIN THE CORNUBIAN OREFIELD

The Cornubian Orefield stretches from modern day Exmoor and Somerset to the Isles of Scilly (Dines, 1956). Mineralisation within the orefield is chiefly associated with the Lower Permian Cornubian Granite Batholith that runs down the spine of the SW Peninsula from Dartmoor to Land's End and continues west beyond the Scilly Isles (Alderton, 1993; Dines, 1956). However, mineralisation across the orefield can be seen to encompass a variety of tectonic settings and deposit types that also pre-date and post-date granite-related (chiefly tin and copper) mineralisation and span the period from the Carboniferous to Late Triassic, with low-temperature mineralisation and remobilisation taking place into the Tertiary (Alderton, 1993).

Although present in the main-stage lodes in trace amounts, rarely forming cobalt sulphides and arsenides (Le Boutillier, 2003), cobalt is mainly associated with structures known as *crosscourses*. These are mainly NNW-SSE to N-S trending faults that cut and often displace (hence the name) the earlier main stage lodes and post-date them, although the fractures themselves have a far longer history and have played a significant part in the tectonic history of Cornubia. The faults can be traced back to the early Silurian and the accretion of Avalonia (including southern Britain) and Baltica following the closure of the Tournquist Sea that formerly lay between them. This was accompanied by considerable transcurrent movements along a series of major NW-SE trending wrench faults (Durrance, 1998). Such faults often penetrate deep within the crust and may persist as planes of weakness long after accretion has been completed. They may be reactivated by later stress fields to give vertical and horizontal shear displacements. These wrench faults, many of which cut across the whole Cornubian Peninsula, played a major role in the development of Devonian/Carboniferous, and later, sedimentary basins across the region (Dearman, 1963; Selwood, 1990) and have also influenced granite emplacement; their reactivation before, during and after the Variscan Orogeny has had a profound influence on the structure of southwest England that continues to the present day (Turner, 1984).

The closure of the Rheic Ocean and the collision of Laurasia and Gondwanaland to form Pangaea at the end of the Carboniferous Period saw SW England thrown up into a massif

during Variscan convergence (Andrews *et al.*, 1998). Convergence was followed rapidly by orogenic collapse across the region (Alexander and Shail, 1995, 1996; Shail and Alexander, 1997, 2000), with the crust thinning by ~20%, decompressing hot mantle below the crust, resulting in mafic (lamprophyric) plutonism and volcanism, followed by crustal anatexis and the generation of huge volumes of granitic magma (Manning, 1998; Exley and Stone, 1982; Exley *et al.*, 1983; Floyd *et al.*, 1983; Floyd *et al.*, 1993), which was emplaced diachronously (Clark *et al.*, 1993; Chen *et al.*, 1993; Chesley *et al.*, 1993) in the Lower Permian (between 293 Ma and 274 Ma) to form the individual plutons, as seen today, of the Cornubian Batholith. This emplacement was aided, at higher structural levels, by pull-apart structures, between pairs of (crosscourse) NW–SE trending faults creating space for the magmas to flow into (Le Boutillier, 2003; Castro and Fernandez, 1998).

Pluton emplacement and inflation took place during continued orogenic collapse, resulting in extensive tensile extensional faulting through the upper crust (Le Boutillier, 2003) controlling pluton margins and the localisation of associated hydrothermal vein sets. Many of the main-stage lodes (outside of the Land's End District) trend ENE–WSW, between 050° and 070° (Dines, 1956) and display primarily dip-slip to oblique-slip movements. The typical lodes of the province are steeply dipping (most >70°) monolithic veins which are concentrated along the axis of the batholith and closely associated with quartz porphyry (elvan) dykes (Jackson *et al.*, 1989). The lode system as a whole has produced almost all the metallic output of the orefield and has produced not only tin and copper, but a range of metals including tungsten, iron, lead, zinc, silver, *etc.* (Dines, 1956). The origin of these metals is still in debate; the tin and tungsten is proposed to have been derived from a tin-rich protolith at the point of anatexis, though some authors point to the possibility of derivation from the mantle (Hutchison and Chakraborty, 1979). Though this seems less likely than a crustal source, Shail *et al.* (1998) have found traces of mantle helium in fluid inclusions from the orefield, attesting to some mantle involvement in mineralisation. The origin of the Cu–Zn–Pb mineralisation is thought to be due to a combination of xenolith assimilation and hydrothermal leaching of basic rocks (and pelites); it has been calculated that the volume of basic rocks and their copper content could easily supply the amount of copper extracted in the province (Jackson, 1979).

A second, later, sequence of lodes occur in many districts, which cut across and displace the earlier lodes. These later caunter lodes (Collins, 1912; Dines, 1956) generally carry a lower temperature, mesothermal, assemblage dominated by copper mineralisation and strike E–W (in the Camborne–Redruth District). Rotation of the stress field saw these lodes emplaced in a fracture set offset from the dominant lode trend by ~30°, associated with horizontal to sub-horizontal slickenlines formed by shear movements (Le Boutillier, 2003, 1996).

Mineralisation, like the associated plutonism, was diachronous across the orefield, with each pluton having its own discrete history (Chen *et al.*, 1993) of hydrothermal activity. Clark *et al.* (1993) give dates of 286 Ma for main stage lodes at South Crofty Mine, 272±4 Ma for the lodes of the St Just area and 278±6 Ma for the Sn lodes of central Dartmoor. This data indicates that mineralisation started in the Carnmenellis area some 3 million years after the emplacement of the early granites and was almost complete before the intrusion of the oldest (Zennor Lobe) of the Land's End granites at 274 Ma. The emplacement of the elvan dykes now appears to be related to later pulses of granite being tapped by extensional fractures, some of which were later utilised by ascending hydrothermal fluids. By 260 Ma plutonism and hydrothermal activity across the province had waned, but to the north and south of the uplifted Cornubian Massif extensional rift movements saw the development of subsiding sedimentary basins; the Bristol Channel Basin and Celtic Sea Basin to the north and Plymouth Bay Basin and Melville Basin to the South. These basins were

receiving sediments from the early Permian (Harvey *et al.*, 1994) and by mid-Triassic times contained several kilometres of infill, including evaporites (Evans, 1990).

Renewed tectonic activity and a rotation in the regional stress field in the Late Triassic saw the reactivation of the NNW–SSE fault system across the Cornubian Massif and beyond during ENE–WSW extension (Scrivener & Shepherd, 1998; Le Boutillier, 2003). Strike-slip and oblique-slip movements along the fracture network faulted the main-stage lodes to varying degrees (Collins, 1912). These fault structures are known by a variety of local names (fluccans, trawns, guides), but are commonly referred to as crosscourses. In mining circles only mineralised structures (usually chalcedony with quartz and minor haematite, *etc.*) are referred to as crosscourses (fluccans are gouge-filled structures), while those carrying economic mineralisation are called lodes (Pryce, 1778; Collins, 1912; Hill and MacAlister, 1906). They played an important part in mining as they represented 'easy ground' to work in and were selectively mined (being considerably easier to mine than granite or hornfelsed killas) as crosscuts into the workings on main-stage lodes (Collins, 1912).

The extension of this fracture network into the surrounding sedimentary basins tapped large brine reservoirs which had become charged with a variety of metals. The fluids associated with this phase have very different signatures to those responsible for earlier phases of mineralisation. They have a strong CaCl₂ component (NaCl:CaCl₂ wt% ratio of 1.2:1; 11–15 wt% NaCl; 9–13 wt% CaCl₂) and T_h of 110°C–170°C (Shepherd and Scrivener, 1987), they have many features in common with oilfield brines (Scrivener and Shepherd, 1998; Gleeson *et al.*, 2000). The fluids are envisaged to have moved into the orefield by tectonically controlled 'seismic pumping' (Bromley, 1989; Alderton, 1993). These fluids carried lead, zinc, silver, uranium, antimony, manganese, iron, bismuth, nickel and cobalt (though Co, Ni and Bi may have been scavenged from local basic intrusives during hydrothermal mixing and circulation of the basin brines and meteoric waters). In economic terms the deposits of this phase of mineralisation are often patchy, small and shallow. They reach greatest importance with the Tamar Valley and Menheniot (Wheal Mary Ann; mined to a depth of 600 metres) Pb–Ag–Zn ± fluorite and barite veins and the lead–silver mines around St Columb and Newquay, the most important of which was East Wheal Rose (Dines, 1956). Rb–Sr isotopic dating of fluorites from the Tamar Valley (Scrivener *et al.*, 1994) has demonstrated a Late Triassic (Carnian) age of 236 Ma for the mineralisation.

Away from the main Pb–Ag–Zn veins, a distinctive Co, Ni, As, U, Bi and Ag crosscourse assemblage can be recognised, both within the granites and the country rocks (Collins, 1892; Ball *et al.*, 1982; Alderton, 1993). They carry a range of sulphides and oxides, often in a gangue of quartz, fluorite, calcite, siderite, iron oxides/hydroxides and rare gold (Collins, 1892, 1912; Hill and MacAlister, 1906; Alderton, 1993) in a mesothermal (200°C to 300°C) assemblage (Hosking, 1964) deposited at slightly higher temperatures than the Pb–Ag–Zn assemblage veins. Wheal Spannon Cobalt Lode is the best (most productive) example of this type of vein.

Crosscourse structures were previously best exposed within South Crofty Mine. These were typically sub-vertical structures with a banded appearance, (due to repeated infilling and resealing over a protracted period) typically 0.5 metres in width, but commonly ranging from <1 cm to ~1 metre, and were infilled with chalcedony, quartz and occasional fluorite, siderite, earthy chlorite and soft haematite; kaolinite and bitumen were rare accessories. In the upper levels (260 fathom upwards) they also sometimes carried bismuthinite and other sulphides as a minor constituent (Le Boutillier, 1996). They ranged from compact to open vuggy structures, sometimes with brecciated segments. Wallrock alteration was typically absent or confined to minor kaolinisation, with the exception of the Great Crosscourse which was heavily kaolinised. Displacements were sometimes on the order of a few metres, but were generally <3 metres and often a few centimetres; both dextral and sinistral

displacements were recorded with horizontal or sub-horizontal slickenlines (Taylor, 1965; Le Boutillier, 1996). The Great Crosscourse (underlying the Red River Valley at Camborne) is one of the major NNW-SSE faults of the region and is over 100 metres in width with a displacement of ~100 metres or more (Taylor, 1965) with an infill of lenses of chalcedony within highly kaolinised country rock.

When crosscourses bisect main-stage lodes there is sometimes localised dilation within the lode where crosscourse mineral assemblages can be deposited, as at Dolcoath Mine, with regard to cobalt sulphides. It has also been noted, particularly in the case of cobalt, that these intersection points are places of cobalt deposition, especially if the main-stage lode carries copper (Collins, 1892; Hamilton Jenkin, 1962a). The reason for this localisation is not known; the copper may act as a catalyst or there may be a more direct reaction that fixes the cobalt sulphides in place.

WHEEL LUSHINGTON, PORTHTOWAN

Porthtowan [SW 695476] is a small, but dispersed, coastal village on the north coast of Cornwall, ~5 km north of Redruth. The local area was intensively mined for copper (and tin) during the 17th to 19th Centuries (Dines, 1956). The most important mine locally is Wheal Lushington [SW 690478], which is the over-arching name of a group of mines that worked the ground from the west side of the Porthtowan Valley, westwards 1.85 km to Kerriack Cove, by some 700m N–S back from the coastline. Wheal Sally, on the east side of Kerriack Cove is the furthest west, with Wheal West, Wheal Sterran, Wheal Tye, Metal Work Mine and Vincent Mine moving progressively towards Porthtowan. Wheal Clarence (comprising Wheal Fox, occupying the headland just west of Porthtowan, Wheal Mary, Cliff Down Mine and Wheal Sparrow) occupied the slopes and higher ground on the west side of the Porthtowan Valley (Dines, 1956). The workings here are ancient, with several of the small mines being in operation before 1750, when they were already described as “old mines” (Hamilton Jenkin, 1965). The mines, within metamorphosed slates and sandstones of the Devonian Porthtowan Formation (Leveridge *et al.*, 1990), worked a series of E–W to ENE–WSW lodes, dipping between 45° and 60° north or south, which carried copper ores with some sphalerite and cassiterite.

A number of lodes can be seen in the cliffs on either side of the main beach, particularly looking east. The structures are generally narrow (5–15 cm) and are composed of brecciated country rocks and quartz, cemented by quartz gangue. They pinch and swell a little down-dip, sometimes opening into long, narrow vughs, but appear weak and barren at exposure, following a series of prominent step-like faults both north and south dipping. Obviously within the mine workings the veins were locally wide enough and rich enough to warrant stoping.

A lead-bearing, N–S, crosscourse in Wheal Sparrow displaces the lodes with a downthrow to the east (Hill and MacAlister, 1906; Dines, 1956). There are several other references to lead production within the group of mines, that can be tied to N–S to NNW–SSE trending adits driven on crosscourses (Hamilton Jenkin, 1965). As with the main-stage lodes, a number of very narrow (2–10 cm) sub-vertical banded quartz veins representing crosscourse-stage mineralisation outcrop in the cliffs. Trending between 350° and 005°, these veins may also pinch and swell, and occasionally open out into long, narrow, open vughs, sometimes associated with secondary iron hydroxide mineralisation. Production details for the group are incomplete, but it is recorded that Wheal Lushington produced 518 tons of black tin between 1852 and 1858 and a further 1.5 tons in 1881. The group produced 2,610 tons of copper ore, 747 tons of lead ore and 13,709 ounces of silver up to the 1860's (Dines, 1956). No cobalt mineral species were previously recorded from any of the mine workings.

SAMPLE COLLECTION

Some 200m west of the headland on the west side of Porthtowan beach lies the portal of the Wheal Mary adit [SW 68886 47810], driven SSE on a very narrow (~1–2 cm) crosscourse that intersects Lushington Engine Shaft and Wheal Towan Lode (trending 065°, dipping 60°S) some 75 fathoms from the portal (Dines, 1956). Immediately to the east of the portal is a large landslip that appears to follow a major fault trending WNW (306°), which draws in material from the surrounding cliffs (see Figure 1). Between this landslip and the Wheal Fox Adit [SW 68919 47883] a number of sub-vertical veins and an excavation some 30m up in the cliffs can be seen.

One of these veins in the upper cliffs (along the line of the Wheal Fox Lead Lode, N. Pettett, *pers. comm.*, 2017) was associated with an area of secondary iron hydroxide mineralisation that caught the attention of local mineral collectors Rob Selley and Nic Pettett. When that section of the cliff collapsed in April 2011, the collapsed material was traced into the main landslip debris fan. Initially the presence of pyromorphite ($\text{Pb}_5(\text{PO}_4)_3\text{Cl}$) and minor amounts of copper carbonates were noted, but when scattered and abundant erythrite was discovered, it was obvious something unusual had been discovered. A protracted period of digging and sifting through material from the fall provided a number of massive samples rich in cobaltite (some of which were finally submitted for analysis in 2017) and a variety of complex secondary species. Several other samples, varying from small hand specimens to micro thumbnail pieces, contain crystallised sulphides and secondary species, including perfect erythrite spheres a number of mm across, and some have yet to be identified and might be new to science. These may form the basis of later non-destructive, investigations.

SAMPLE ANALYSIS

Samples were first examined in hand specimen both visually and with a x10 magnification hand lens. Next, five of the hand specimen samples were selected to be made into polished uncovered rock thin sections for further analysis by QEMSCAN®. This is a type of automated mineralogy that uses a scanning electron microscope with energy dispersive spectrometers (SEM-EDS), capable of providing detailed mineral data of a polished thin section or mount by comparing chemical EDS spectra against a customisable database (Gottlieb *et al.*, 2000, Goodall *et al.*, 2005, Goodall and Scales 2007, Pirrie *et al.* 2009, Haberlah *et al.* 2011). Samples were selected based on the presence and variability of mineralisation seen in the overall sample set collected from the Porthtowan site.

Samples were mapped using a QEMSCAN® 4300 system at the Camborne School of Mines, University of Exeter, at a 10 micron x-ray resolution producing both mineralogical data and mineral maps. Database (SIP) development was required due to the complex and unusual nature of the minerals present and followed guidance outlined by Rollinson *et al.* (2011). Specifically, cobaltite was added along with secondary and unusual minerals such as; bukovysite ($\text{Fe}^{2+}_2(\text{AsO}_4)(\text{SO}_4)(\text{OH})\cdot 7(\text{H}_2\text{O})$), realgar/orpiment ($\text{As}_4\text{S}_4/\text{As}_2\text{S}_3$), acanthite (Ag_2S), matildite (AgBiS_2), chlorargyrite (AgCl), cerussite/anglesite ($\text{PbCO}_3/\text{PbSO}_4$), gratonite ($\text{Pb}_9\text{As}_4\text{S}_{15}$), chrysocolla ($(\text{Cu},\text{Al})_2\text{H}_2\text{Si}_2\text{O}_5(\text{OH})_4\cdot n(\text{H}_2\text{O})$), auriacusite/olivenite(Fe) ($\text{Fe}^{3+}\text{Cu}^{2+}\text{AsO}_4\text{O}$), atacamite ($\text{Cu}_2\text{Cl}(\text{OH})_3$), clinoclase ($\text{Cu}_3(\text{AsO}_4)(\text{OH})_3$), erythrite, erythrite (Fe), scorodite ($\text{Fe}^{3+}(\text{AsO}_4)\cdot 2(\text{H}_2\text{O})$) and pharmacosiderite ($\text{KFe}_4(\text{AsO}_4)_3(\text{OH})_4\cdot 6.5\text{H}_2\text{O}$). All of these were checked using manual SEM-EDS, but validation by other methods such as X-ray diffraction (XRD) and optical microscopy was not possible, due to their low abundances being below XRD detection limits and small size making them difficult to verify by optical microscopy.

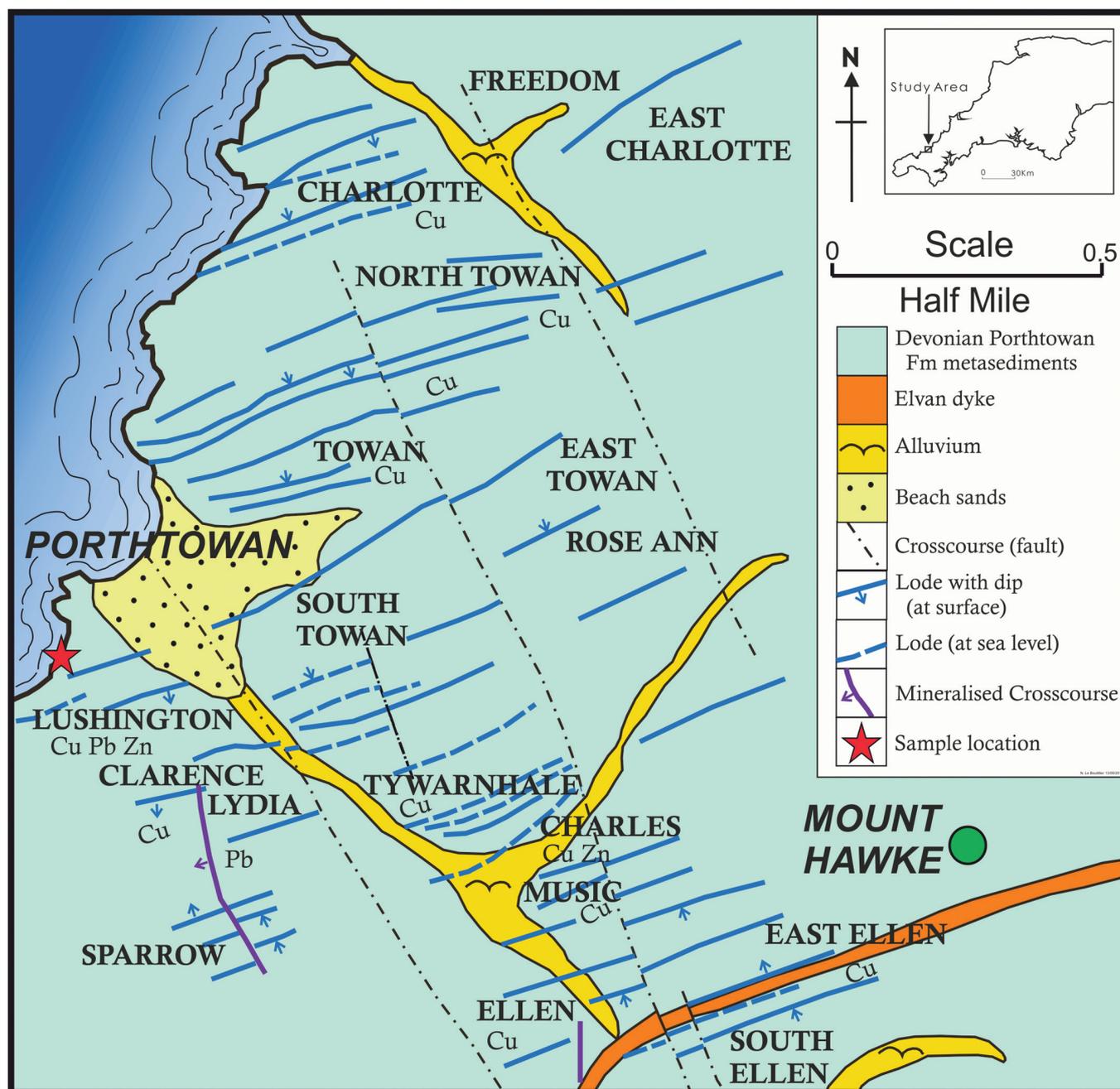


Figure 1. Map showing the location of sample collection in Porthtowan, Cornwall, with lodes and mines marked on (after Dines, 1956).

RESULTS

The hand specimen examination revealed chalcopyrite, erythrite, cobaltite, quartz and other silicate minerals. Analysis of the five samples by QEMSCAN® showed 44 mineral categories and the presence of primary and secondary cobalt minerals (Figure 2, 3), with a number of unusual minerals (Tables 1, 2). The primary sulphide minerals suggest crosscourse style mineralisation and the secondary minerals reflect alteration, weathering and the coastal location. Cobaltite varied from 0.41% to 50.05% with erythrite up to 5.9%. Chalcopyrite was the next most abundant mineral from 0.19% to 41.12%, with other sulphides such as bornite (up to 3.18%), chalcocite/covellite (up to 2.52%), galena (up to 0.17%), sphalerite (up to 1.8%), tennantite/enargite (up to 7.56%) arsenopyrite (up to 1.60%) and pyrite (up to 2.58%). The presence of chlorargyrite and atacamite/botallackite are a result of seawater percolation, and the presence of minerals such as bukovsyite (weathered arsenopyrite), scorodite, gratonite, chrysocolla, cerussite/anglesite reflect weathering and alteration

of primary copper, arsenic and lead minerals. From the QEMSCAN® data cobaltite shows dominant association with chalcopyrite, bukovsyite and erythrite, but this varies across the samples with other notable associations being gratonite, acanthite, bismuthinite/bismuth and auriacusite/olivenite(Fe). It should be noted that the association between cobaltite and erythrite is not exclusive, as erythrite does seem to occur in close association with bukovsyite and chalcopyrite. This suggests that the bukovsyite was likely to have originally been a cobaltian arsenopyrite (perhaps bordering on danaite) and that there is possibly some cobalt substitution within the chalcopyrite.

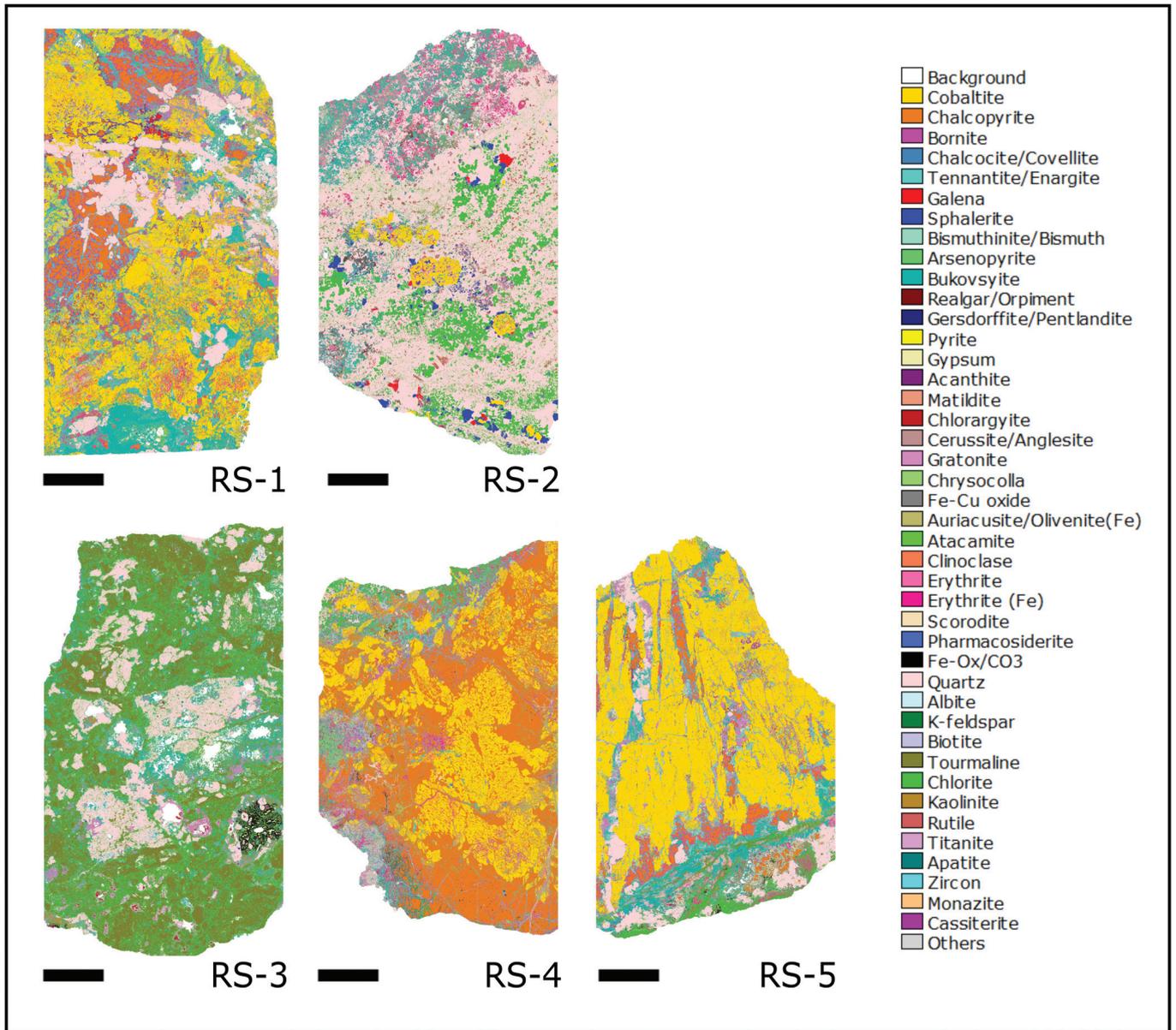


Figure 2. Mineral maps of the five samples, 10 microns x-ray resolution. Scale bar is 5mm approx.

DISCUSSION

The detailed mineralogy data was made possible by using QEMSCAN® and also a combination of scan resolution, meticulous checking, knowledge of the mineralogy of the study area and database development. Many of the minerals found would be impossible or difficult to detect by other techniques due to their low abundance and small size (Table 2). Therefore, as the mineral names are based on chemical spectra, the minerals listed are the most likely to occur. The amount of cobalt mineralisation is significant, but as these represent only five samples the scale of this is uncertain due to representivity. The data does however offer a detailed insight into the mineralogy of this location, showing diverse primary and secondary mineralogy and possibly the first detailed description of a cobalt mineral assemblage in Cornwall. The mineral assemblage encompasses the full suite of minerals from main stage to crosscourse mineralisation followed by secondary species due to weathering and later (to the present day) seawater interaction. The presence of high temperature (hypothermal, Hosking, 1964) mineral species such as cassiterite, schorl tourmaline, zircon, biotite, monazite, rutile, arsenopyrite, pyrite and chalcopyrite (\pm sphalerite), with

feldspar, is due to 'smearing' and incorporation of material from intersected main-stage lodes (and associated country rock) at the crosscourse margins. A typical mesothermal (Hosking, 1964) crosscourse assemblage is represented by galena, sphalerite, cobaltite, pentlandite/gersdorffite, native silver, acanthite, matildite and tetrahedrite/enargite, which will have accompanied the main chalcedonic silica (\pm chlorite, fluorite, siderite, *etc.*) crosscourse gangue infill (Le Boutillier, 1996) in a series of pulses. With the end of the mineralisation cycle, the in-situ assemblage would have been subject to supergene activity and weathering. Crosscourses are relatively porous structures (Le Boutillier, 1996) that concentrate water flow (Collins, 1912). A steady water supply and a complex polymetallic assemblage has facilitated the formation of a number of rare secondary minerals, particularly arsenates, which are known from only a small number of locations (Golley and Williams, 1995) across Cornwall; these include pharmacosiderite, auriacusite, clinoclase, gratonite, erythrite and scorodite. These are found with more common carbonates, sulphates (cerussite and anglesite), silicates (chrysocolla) and secondary sulphides such as orpiment, realgar, bornite,



Figure 3. Specific mineral maps of the five samples. Top: cobaltite, Middle: chalcopyrite, Bottom: erythrite(Fe).

Sample ID	RS-1	RS-2	RS-3	RS-4	RS-5
Measurement Area (mm)	19 x 33	20 x 34	19 x 35	19 x 30	19 x 35
No. X-ray Analysis Points	5,112,356	4,682,116	5,108,487	3,971,260	4,527,699
Cobaltite	33.34	3.40	0.41	26.80	50.05
Chalcopyrite	11.91	0.19	1.40	41.12	6.32
Bornite	3.18	0.01	<0.01	0.96	1.33
Chalcocite/Covellite	2.52	0.38	<0.01	0.05	1.26
Tennantite/Enargite	7.96	0.26	0.27	5.66	2.26
Galena	0.17	0.37	<0.01	0.01	0.06
Sphalerite	0.05	1.80	0.03	0.08	0.02
Bismuthinite/Bismuth	0.95	<0.01	0.32	0.05	4.70
Arsenopyrite	1.60	1.19	0.09	0.30	0.14
Bukovsyite	12.98	9.25	17.80	3.28	9.57
Realgar/Orpiment	0.84	1.68	0.17	0.01	1.15
Gersdorffite/Pentlandite	<0.01	<0.01	<0.01	<0.01	<0.01
Pyrite	0.16	0.38	2.58	0.13	0.50
Gypsum	0.05	0.13	<0.01	0.01	<0.01
Acanthite	1.79	0.08	0.11	0.02	1.55
Matildite	0.15	<0.01	0.02	0.01	0.23
Chlorargyrite	0.05	0.01	0.15	0.03	0.06
Cerussite/Anglesite	0.59	2.10	1.57	0.05	0.89
Gratonite	2.81	1.15	2.11	0.08	3.65
Chrysocolla	0.39	0.21	0.06	0.50	0.24
Fe-Cu oxide	<0.01	<0.01	0.14	1.30	0.01
Auriacusite/Olivenite(Fe)	0.16	0.01	<0.01	4.47	0.03
Atacamite	0.08	<0.01	<0.01	0.24	0.08
Clinoclase	0.02	<0.01	nd	0.07	<0.01
Erythrite	0.01	0.09	<0.01	<0.01	<0.01
Erythrite (Fe)	2.73	3.90	0.05	5.90	1.25
Scorodite	2.45	1.66	0.07	4.30	2.83
Pharmacosiderite	<0.01	0.01	<0.01	0.84	0.43
Fe-Ox/CO ₃	0.02	0.09	1.11	0.40	0.40
Quartz	12.23	54.31	17.34	0.48	7.21
Albite	0.02	0.95	0.80	<0.01	<0.01
K-feldspar	0.01	0.18	0.02	<0.01	<0.01
Biotite	<0.01	0.12	0.04	0.45	0.07
Tourmaline	0.36	0.94	36.36	0.02	0.76
Chlorite	0.32	13.53	16.66	2.13	2.89
Kaolinite	0.01	0.42	0.25	<0.01	<0.01
Rutile	0.08	1.01	0.04	0.14	0.02
Titanite	<0.01	0.03	<0.01	0.01	<0.01
Apatite	<0.01	0.05	<0.01	<0.01	<0.01
Zircon	<0.01	0.02	0.01	<0.01	<0.01
Monazite	<0.01	0.08	0.01	0.02	0.01
Cassiterite	0.01	0.01	<0.01	0.07	<0.01
Others	<0.01	0.01	0.01	<0.01	<0.01

Table 1. QEMSCAN® mineral data for the samples shown as volume/area %. Samples scanned at 10 microns x-ray resolution in fieldscan mode. Nd = not detected.

Sample ID	RS-1	RS-2	RS-3	RS-4	RS-5
Cobaltite	74.1	52.9	17.6	101.2	200.7
Chalcopyrite	44.4	17.3	20.7	94.1	49.2
Bornite	23.7	16.7	≤15	18.5	21.9
Chalcocite/Covellite	24.0	26.7	22.0	17.6	18.5
Tennantite/Enargite	26.7	18.9	15.5	20.2	20.0
Galena	45.7	60.0	23.1	21.8	18.8
Sphalerite	20.0	99.5	20.6	21.9	19.1
Bismuthinite/Bismuth	24.9	16.6	22.0	18.8	27.6
Arsenopyrite	16.5	18.0	15.2	16.2	16.2
Bukovsyite	37.3	31.7	29.0	23.9	39.3
Realgar/Orpiment	16.4	18.0	15.6	15.6	16.8
Gersdorffite/Pentlandite	≤15	≤15	≤15	≤15	19.3
Pyrite	16.3	16.1	16.4	16.9	17.3
Gypsum	21.2	55.7	15.8	19.1	16.8
Acanthite	23.0	21.6	23.6	17.1	20.0
Matildite	20.8	15.9	17.0	17.6	17.5
Chlorargyrite	15.5	15.3	34.4	17.3	22.7
Cerussite/Anglesite	16.8	19.2	16.7	17.3	16.7
Gratonite	23.1	21.0	28.4	18.5	27.0
Chrysocolla	17.0	17.2	16.0	27.4	18.1
Fe-Cu oxide	≤15	16.9	18.0	24.0	16.0
Auriacusite/Olivenite(Fe)	16.0	15.7	≤15	26.7	18.2
Atacamite	15.2	15.8	≤15	19.9	15.6
Clinoclase	16.4	15.8	nd	25.0	17.1
Erythrite	15.1	34.0	≤15	≤15	15.5
Erythrite (Fe)	20.8	30.6	15.1	21.1	21.9
Scorodite	26.0	20.8	15.3	24.2	30.8
Pharmacosiderite	15.2	16.6	≤15	18.5	17.6
Fe-Ox/CO ₃	17.1	16.3	32.6	17.4	21.1
Quartz	197.4	144.3	104.5	66.0	113.0
Albite	15.7	16.2	16.6	18.0	16.4
K-feldspar	20.8	19.6	15.1	17.0	21.7
Biotite	15.5	16.1	15.2	20.2	16.2
Tourmaline	21.9	23.9	61.8	20.1	28.4
Chlorite	18.4	71.1	27.5	39.1	41.3
Kaolinite	15.0	18.8	15.7	36.1	15.3
Rutile	48.8	37.4	24.4	45.4	28.8
Titanite	16.8	40.5	≤15	55.5	18.8
Apatite	21.4	24.0	21.9	25.5	19.3
Zircon	16.4	16.7	20.3	23.7	18.0
Monazite	21.7	21.3	18.5	23.7	23.5
Cassiterite	18.8	16.4	16.9	20.0	15.9
Others	17.4	15.5	15.5	16.7	15.4

Table 2. QEMSCAN® average mineral grain size data, in microns. Nd = not detected.

Time 				
Primary minerals		Secondary minerals		
Stage 1 Main stage	Stage 2 Crosscourse	Stage 3a Sulphide alteration	Stage 3b Clays/weathering	Stage 3c Salt stage
Chalcopyrite Pyrite Arsenopyrite Cassiterite Bismuthinite/Bismuth Quartz Albite K-feldspar Biotite Tourmaline Chlorite Rutile Titanite Apatite Zircon Monazite	Cobaltite Galena Sphalerite Acanthite Matildite Silver Pentlandite/Gersdorffite Tetrahedrite/Enargite	Bornite Chalcocite/covellite Cerussite /anglesite Bukovsyite Pharmacosiderite Gratonite Realgar/orpiment Auriacusite/olivenite(Fe) Clinoclase Erythrite Fe Ox/CO ₃	Scorodite Chrysocolla Fe-Cu Oxide Gypsum Kaolinite Chlorite	Atacamite Chlorargyrite

Table 3. Suggested paragenetic sequence for the samples.

chalcocite, covellite and bukovsyite. Finally, the coastal location of the sample site and direct connection of the debris pile to the sea facilitated the development of secondary chlorides and bromides such as atacamite/botallackite and chlorargyrite, including bromargyrite; while percolation downwards of calcium-charged meteoric waters has seen the small-scale development of gypsum. A suggested paragenetic sequence is shown in Table 3.

Looking wider in Cornwall, up to 92ppm of cobalt was recorded in Devonian sediments in the Perranporth area by Henley (1974), and up to 72ppm in the sediments of the Hayle Estuary and up to 23ppm in sediments of the Fal Estuary (Rollinson 2001). Notably, in the Hayle estuary cobalt varied from pre-mining levels of 19ppm to a maximum of 72ppm from mining related activity (Rollinson 2001). Cobalt up to 540ppm was recorded in bog iron ore from the Lizard by Scott *et al.* (2011), and trace amounts (18ppm) noted in the Teign Estuary by Simons *et al.* (2011). Andersen *et al.* (2016) itemised cobaltite in Gonamena and East Caradon mine (Bodmin Moor) and Buttspill mine (Cotehele). None of these outlined cobalt mineralogy and the cobalt levels recorded are low compared to the samples found at Porthtowan.

SUMMARY

This study has confirmed that hitherto unrecorded cobalt mineralisation occurs at Porthtowan in Cornwall, within the sett of Wheal Lushington, and provides detailed information on the mineral assemblage and its potential paragenesis formed during the late Triassic crosscourse phase of mineralisation within the Cornubian Orefield. This appears to be the first detailed study of cobalt minerals in this area and possibly Cornwall.

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