12: Minor Metals

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12.1 Antimony

12.1.1 Introduction

In metallurgy, antimony was used in alloys for printer's type, in the preparation of anti-friction metals and for hardening lead. It was also used as an alloy, at from 5 to 10 per cent, with tin in the production of Britannia metal. Antimony compounds were also used as a de-oxidiser and colourant in glass, pottery, pigments and dyes. From an early period antimony compounds were also used in cosmetics and for medicinal purposes, and, as such, can turn up in the archaeological record (Watson 2013, 21). A small number of mines in the 19th century and earlier, primarily in Cornwall, produced antimony concentrates as a co-product and a few were promoted with antimony as their principal product.

12.1.2 Geological background

The principal ore of antimony is the sulphide stibnite (Sb_2S_3) although the antimony-lead sulphosalt ($PB_4FeSb_6S_{14}$) has been worked in some mines.

The antimony at the Louisa Mine, in Dumfries and Galloway, is associated with stratiform arsenopyrite-pyrite mineralisation in a Silurian greywacke sequence with similarities to that in the Clontibret area, County Monaghan (Gallagher *et al* 1983, 24). The latter is associated with gold, and antimony has been associated with gold mineralisation in the vicinity of Port Isaac, Cornwall. Work by Clayton and others (1990) links the antimony in that part of Cornwall to stratiform pre-granite mineralisation and whilst there has been little or no investigation of antimony mineralisation in south-east Cornwall it is probably of a similar origin (*see* Scrivener & Shepherd 1998 on stratiform mineralisation in general in Cornwall). In Cumbria, to the north-east of Bassenthwaite, work by Fortey and others (1984) again links the antimony to stratiform mineralisation similar to that in Dumfries and Galloway.

12.1.3 Historical background

Very few mines in Britain produced antimony ores in significant quantities and they appear to have been confined to Cornwall, Cumbria and parts of Scotland. Antimony minerals are reported elsewhere but with no known record of production. In Cornwall, at Wheal Leigh near Pillaton to the north-west of Saltash, antimony is said to have been worked from the late 16th century (Beer 1988, xxi). A mine or mines in the Pillaton area reportedly produced 25 tons of ore in the 1770s and over 130 tons of ore in the 1820s. Around Port Isaac in north Cornwall, and particularly in the parish of Endellion, antimony was being worked by the mid-18th century with production levels from Wheal Boys in the 1770s of around 95 tons (De La Beche 1839, 615-16). Lysons' (1814, 194-216, citing Pryce, Mineralogia Cornub.) noted that a works for producing *regulus* of antimony was set up by a Mr Reed at Feock, close to Falmouth, and De La Beche (1839, 616) gives a date of 1778 for the works. A small number of mines in both these areas of Cornwall continued to produce small amounts of antimony ore in the second half of the 19th century (Burt et al 1987, xxxii). Small amounts of ore were also produced from mines in Cumbria, to the north-east Bassenthwaite on the western edge of the Caldbeck Fells. These were worked prior to 1816 (Lysons 1816, cxi) and again in the 1840s but information on the extent of those workings is limited.

The best study of antimony mining and the processing of the ores in Britain comes from the south-west of Scotland and the working of the Louisa Mine at Glendining, in Dumfries and Galloway, and the work there can inform that which should be carried out in England. The history of the Louisa Mine, the antimony at which was first worked in 1793, was researched by McCracken (1965) at about the same period that it was examined by Charles Daniel in connection with other work in the area (Tylecote 1983, 43 n. 1). Slag from the smelting process on site was analysed by Tylecote (1983), and the site was subsequently surveyed and included in the RCAHMS publication on the historic landscape of eastern Dumfrieshire (RCAHMS 1997, 276-77).

12.1.4 Technological background

The mining and ore preparation methods employed in working antimony ores were little different to those used in the other hard rock non-ferrous metal mining sectors. Stibnite, the antimony sulphide, had a specific gravity well below that of galena, the lead sulphide with which it was commonly found in mixed ore deposits and could therefore be easily separated by conventional methods. Jamesonite, the antimony-lead sulphosalt, was a different matter with the lead and antimony in chemical combination, where the antimony would be separated after smelting. Smelting of antimony ores to a metallic regulus was a specialist liquation process, carried out on site at Glendining in the 1790s and described in detail in the contemporary Statistical Account of Scotland (Sinclair 1791-99, II, 525-27). The process was evidently also carried out on at least one mine in Cornwall, Pengenna, near Port Isaac, where ‘old smelting works remain at Watergate, near the adit mouth, where much slag, rich in antimony, still lies’ (Dewey 1920, 50). Processing was also carried out at Feock in Cornwall, albeit away from the mining sites (Lysons 1814, 194-216) but little detail is available and the site of the process has not been investigated.

Given that the presence of antimony could be a significant contaminant in lead, hardening it to the extent that it was brittle and no longer malleable; many producers were at pains to remove it. Softening hearths where antimony and other contaminants would be removed might be found at a number of lead smelters and Gill (2001, 95-96) describes such a hearth at Old Gang, Swaledale, confusingly known as the ‘Silver House’ although, as the process involved skimming contaminants from the surface of lead maintained in a molten state, it may have been confused with the Pattinson process for silver enrichment. There is, however, no evidence that the antimony was recovered as a marketable product.

12.1.5 Infrastructure associated with antimony production

There is no evidence of any elements within the infrastructure of mining in England which specifically supported the production of antimony. In Scotland, however, the settlement of Jamestown, in the parish of Westerkirk, Dumfries and Galloway, was built by the company operating the Louisa Mine in the 1790s along with an access road and bridges. The company also instituted a miners' library in Jamestown which still survives (McCracken 1965, 143-44 and Appendix).

12.1.6 Archaeological assessment

There has, as yet, been no archaeological investigation of antimony mines or the preparation and smelting of antimony ores in England. The limited amount of investigation done at Glendining, in Scotland, (RCAHMS 1997, 276-77) including analysis of the slag from the smelter carried out by Tylecote (1983), with the benefit of a contemporary account of operations in the 1790s (Sinclair 1791-99, II, 525-27), could provide information relevant to the investigation of sites in England.

12.2 Arsenic

Arsenic was one of a number of contaminants affecting copper and tin production in Cornwall and Devon. In the case of tin, where alluvial tin deposits were worked the arsenic had already been eliminated through weathering and leaching as part of the process of natural erosion and was not usually a problem. *In situ* tin lodes, however, were often contaminated with arsenic and as production from this source increased from about the 15th century the arsenic along with other contaminants (including iron pyrites, FeS^2 and zinc sulphide, ZnS) had to be removed by calcining the ore prior to smelting. A similar problem was attached to the exploitation of sulphide copper ores from the 18th century onwards, as mining progressed below the weathered secondary ores close to surface, and it became necessary also to roast the ores to remove these contaminants by burning them off as gases. Burning houses or reverberatory claciners used for this purpose were recorded by the anonymous writer of 1671; although no structures remain from this period, later examples from the 19th century survive at some mines in both Devon and Cornwall. Prior to the early 19th century this process was carried out without any attempt to recover the arsenic, which was lost to the atmosphere. Mine owners in Cornwall and West Devon were slow to recognise the economic potential in recovering arsenic in the form of the arsenious oxide (As_2O_3) but, once accepted, most large mines engaged in the practice and by the 1870s some mines were realising a significant income from arsenic sales.

The uses for arsenic compounds were, by the mid-19th century, manifold and the substance had a number of uses. It was added to molten lead in the manufacture of shot to produce a spherical shape and arsenical oxides were used in certain chemical processes as well as uses in the preparation of pigments for paint and wallpaper. It was also a powerful poison employed in the preparation of sheep dip and other insecticides, such as crop dusts and sprays. The most important application for the latter in the late 19th to early 20th century was the control of Colorado beetle in North American potato crops but the most well-known use, the control of boll weevil infestation in cotton plants in the 1920s, came too late to draw on English arsenic production (Burt 1988, 15-18).

Levels of arsenic contamination in copper ores from other mines in England was perhaps not as great as that in Devon and Cornwall but it was, never the less still a problem, which had to be eliminated. At Alderley Edge this was acheived as part of the acid leaching process and the arsenic was removed as waste along with the sand (Carlon & Dibben 2012, 74). Arsenic does not appear to have been recovered at these or any other copper mine in England outside Devon and Cornwall. A small quantity was recovered from tungsten-bearing ores at the Carrock Fell Mine, in what is now Cumbria, and it was worked as the primary produce in Scotland at the Talnotry Mine near Newton Stewart, in Dumfries and Galloway (Pickin 2013).

12.2.1 The geological background

In England the presence of significant amounts of arsenic in copper and tin is associated with mineralisation linked to the Cornubian granite emplacement in Devon and Cornwall. Although arsenic is present in some ores in Cheshire (Alderley Edge) and the north-west, in what is now known as Cumbria, it might have been regarded as a contaminant but it was not present in sufficient quantities to justify its recovery with the exception of a small quantity produced by the Carrock Mine in the early 20th century. The principal ore of arsenic is arsenopyrite or arsenical pyrites (FeAsS) also known as 'mispickel' or 'white mundic' found in close association with copper and tin ores (Scrivener *et al* 1997, 19). The geology of arsenic production is therefore firmly linked to that of tin and copper mining in Cornwall and Devon, addressed in the Resource Assessment for those metals.

12.2.2 Historical background

The first arsenic refinery in Cornwall was set up near Perranwell in 1817 to recover arsenic from mine waste. This was followed in 1835 by a second plant, again treating mine waste, near Bissoe-bridge after which mine owners realised that what they were burning off as a contaminant was of value, and some began to erect flues to condense and collect the arsenic from their roasting hearths (Earl 1983, 12).

By the late 1860s mines in Devon and Cornwall were working arsenopyrite specifically for the arsenic content, with sulphur (for sulphuric acid production) as a significant by-product. Within ten years production of arsenopyrite ores had risen to nearly 15 thousand tons per annum. Thereafter it fluctuated wildly but was still at over 12 thousand tons of ore per annum in the last years of the century (Burt et al 1984, xxv-xxvi).

The majority of the arsenic produced in Devon and Cornwall came, however, from the treatment of tin and copper ores. Its production provided a significant supplementary income for many mines but only in the case of Devon Great Consols, after 1884, did it become the dominant source of income (Burt 1988, 23, Table 5). Although some arsenic production continued into the mid-20th century it was a very much reduced levels (Earl 1983, 26).

12.2.3 The technology of arsenic production

Arsenical ores were seldom sold in their raw state and needed concentration at or near the source to convert them into a commercial product. Earl (1983) provides a detailed account of the processes used in arsenic recovery and refining, which might be used in the interpretation of surviving features, particularly those found on the later sites from the end of the third quarter of the 19th century.

The early calciners were simple structures, either reverberatory or shaft furnaces, sometimes a modification of existing 'burning houses', linked to long flue systems in which the arsenious oxides would condense as soot of varying purity. From the 1830s onwards mechanisation of the process was introduced with the Brunton calciner, which allowed for continuous operation. The Brunton, patented by William Brunton in 1828 (Stewart 2005, 10), had a rotating convex circular hearth, powered by a waterwheel, over which the flames from two fireboxes were drawn. Ore was fed into the centre of the hearth and was roasted as it slowly rotated below cast iron coulters, which ploughed it towards the outer edge where the fully calcined ore was discharged (Earl 1983, 15-17). Bruntons were usually associated with long flue systems or labyrinths in which the purified arsenic collected. Less successful and less common was the rotating tubular calciner developed by Oxland and Hocking in the 1870s, known as the 'Oxland Tube' and the adaptation of other mechanised hearths, which could allow pyritic ores to self-combust. However, the rolling motion of the ore in Oxland Tubes created too much dust and this system was less successful; the Brunton was therefore the foremost process used. The last Brunton calciners were in use up until the 1950s but, by then, the separation of arsenic from tin and copper ores was effected by froth flotation (Earl 1983, 24-27). Devon Great Consols had both Bruntons (by at least 1866) and Oxland (by 1878) in use (Stewart 2005, 10-11).

Refineries, to which the arsenic-rich soot from the calciners was sent, were established either at the larger mines or as separate concerns, initially part of the works recovering arsenic from mine waste. The earlier refineries employed cast iron retorts, or 'kettles', to separate out the arsenious oxide from the soot (Earl 1983, 13-14) but these were later replaced by flat-bed reverberatory furnaces, using high grade fuel such as anthracite, again linked to long flues and labyrinths or condensing chambers (Earl 1983, 19). Refined arsenic was then ground to a powder and packed in barrels for transport. The grinding mill from the 1920s refinery at Devon Great Consols still survives.

12.2.4 The archaeology of arsenic production

The presence of arsenic in copper ores worked in Britain in prehistory may or may not be relevant to the production of arsenical copper and bronze, and there is some evidence to suggest it may have been a factor in the selection of copper ores from the south-west of England (Ixer & Pattrick nd), but it was not until the 19th century that arsenic bearing minerals were worked in their own right. It is therefore to the modern period, and to Cornwall and West Devon, that we look for the archaeological evidence for arsenic production.

Among the best preserved burning houses in Devon or Cornwall is at the Atlas (or Albion) Mine, near Ilsington in Devon, Richardson (1992, 63). This has two burning chambers and an externally mounted stack, but it is unlikely to have produced arsenic commercially. A calciner of similar design, though with a single burning chamber survives at South Devon United mines at Mary Tavy and this example has had a long flue added as a means of deliberately collecting the arsenic (P Newman *pers comm*).

The flues, labyrinths or condensing chambers, and associated chimneys of arsenic calciners are dominant features on a number of tin and copper mines in Cornwall and West Devon, and some of the sites identified by Earl (1983) have been stabilised and conserved but some have been lost through neglect or deliberate clearance. The Brunton calciners and associated labyrinth and flues at Levant, in west Cornwall, were recorded prior to remedial work which resulted in the heavily contaminated site being covered over and the features are no longer accessible (Sharpe 1994). The similar surviving features at the nearby Botallack Mine in west Cornwall have, however, been conserved. They comprise the hearth for a Brunton calciner, flues, condensing chambers along with the remains of the stack, and these have been surveyed and interpreted by Pete Joseph (2010, 179-91, and 2012). Joseph had earlier prepared a survey and assessment of the calciner at Tolgus, in central Cornwall (2004).

In the Tamar Valley consolidation work on the surviving chimney at the Coombe Arsenic Works in East Cornwall was accompanied by a report on the watching brief (Buck 2006b). The arsenic works at Okel Tor, Calstock, were included in the assessment of that mine (Buck 1999). Archaeological assessments have also been carried out at Devon Great Consols (Buck 2002), including the arsenic works, and on the Gawton works (Buck 2006a), both on the Devon bank of the Tamar; the latter being carried out as part of the Tamar Valley Mining Heritage Project. The arsenic works at both Devon Great Consols and Gawton had been the subjects of earlier archaeological survey work (Dixon et al 1989; Pye & Dixon 1989; Pye & Weddell 1992).

Although the processes for the production of arsenic are well known for many individual calciners have been recorded in Devon and Cornwall, no overview, analysis or inventory of the surviving buildings is known, and a comprehensive study is overdue.

12.3 Manganese

12.3.1 Introduction

From the late 19th century onwards manganese was used extensively in steel production as an additive to assist with removing both sulphur and oxygen during the Bessemer process and as an alloy that toughened the steel. Its deoxidising properties were, however, also in demand for a number of other processes which predate its use in the steel industry. The addition of small amounts of manganese dioxide or calcium manganate to glass, only a few kilogrammes per 1000 tonnes, removed residual iron oxides found in some glass sands which discoloured the glass. When used in larger quantities the manganese could provide colour to the glass, from purple through to black. Other applications included its addition to oil based paints as a drying agent, as an oxidising agent in the manufacture of bleaches and dyes, and its use as a colorant in pottery glazes (Wilkie & Burt 1984, 19-20).

By far, the majority of the manganese ores mined in England came from the county of Devon but there are numerous other, lesser sources in Derbyshire and Warwickshire, which have contributed to production (for recorded production levels in the second half of the 19th and the early 20th centuries, see Burt et al 1984, xxvii). After the late 1880s production from English mines was eclipsed by that from mines in Merioneth and Carnarvonshire, in north-west Wales. The latter are, however, outside the remit of this project but details can be found on-line (Linton nd.).

12.3.2 Geological background

There are a number of manganese minerals which have been worked economically in England. Pyrolusite (MnO_2), manganese dioxide at around 63% manganese, and rhodonite ($MnSiO_3$), a manganese silicate with around 42% manganese, along with psilomelane, a basic oxide of barium with manganese $(Ba,H_2O)_2Mn_5O_{10}$ having a manganese content of 70-80%, have been worked in Devon. Rhodochrosite, also known as dialogite, ($MnCO_3$), the manganese carbonate, was the principal ore worked in north-west Wales but was not of economic importance in England (Dewey & Dines 1923). An impure mixture of hydrous manganese oxides, known as 'wad', has also been worked in Derbyshire and at Hartshill in Warwickshire. Manganese oxides are also found in combination with cobalt and other minerals in the sandstones on the rim of the Cheshire Basin, where they were also known as 'wad', but worked primarily for their cobalt content (see assessment for cobalt). Manganese oxides are also found in combination with iron oxides as umber, the earth mineral pigment, worked in a number of locations in Devon, and across England (Beer & Scrivener 1982, 144-45; also see the assessment for gangue minerals and pigments).

The manganese minerals described above are all secondary deposits and their origins in Devon are 'a matter of speculation'. They are much earlier than the Cornubian granite emplacement and found as replacement deposits in chert beds and as cement in sandstones (Beer & Scrivener 1982, 143-44). The origins of the 'wad', impure deposits of manganese oxides mixed with iron oxides, worked in limestone of the Elton - Winster area, and the area north of Brassington, in Derbyshire are also unclear. They are discussed in detail by Ford (2006, 200-01; and 2001, 43-44) but appear to be secondary deposits derived from adjacent strata.

12.3.3 Historical background

The properties of manganese minerals as colorants and oxidising agents appear to have been known since antiquity and they were probably first worked in Britain during the Roman occupation (Burt & Wilkie 1984, 20, citing Down 1980). From the Roman period through to the post-Medieval the use of manganese minerals is primarily linked to glass production but it is not until the late Medieval period that there is clear evidence for glass production in England (Crossley 2012; English Heritage 2011, 29). Prior to that glass was largely imported from continental Europe, with some examples of manganese glass from the Near East turning up in the south-east of England (Williams 1983).

There is, as yet, no evidence that English sources of manganese were used prior to the late 18th century and the development of mines at Upton Pyne, near Exeter in Devon (Russell 1968-70). There is also documentary evidence to suggest that manganese was being worked in Warwickshire at the same period (Cook 2013, 2). The Upton Pyne mines had probably closed by the mid-1820s but new workings had already been opened up a short distance to the north at Newton St Cyres and those were to continue in operation into mid-century. By that date, however, the focus of manganese mining in Devon, the only production area of any significance in England, had shifted to the Teign Valley and West Devon. Burt and Wilkie (1984) provide a comprehensive account of the development of manganese mining in the south-west of England which identifies the numerous small mines around Milton Abbot as being the principal source of manganese ores well into the mid-1880s, with the Chillaton Mine being by far the largest producer. A scatter of small mines in Cornwall, North Devon and Somerset also made a much lesser contribution to production (*see* Hamilton Jenkin 1969 and Claughton 1975 for detail on those lesser producers). Thereafter they were quickly eclipsed by production from mines in North Wales, in the counties of Carnarvon and Merioneth (Burt & Wilkie 1984, 34; see also Linton nd and Down 1980 for more detail on the North Wales mines).

The requirement for manganese as a deoxidising and toughening agent in steel production from the late 1860s onwards resulted in a wide search for suitable ores. The North Wales mines made a significant contribution in that respect and, although there was little expansion of manganese production in England as a result of the new demand, the south-west did contribute significant amounts of manganese-rich iron ores, particularly from the Brendon Hills in West Somerset, used in the preparation of speigeleisen (containing 15-25% manganese) used in the deoxidising process (Burt & Wilkie 1984, 19; see, also, the assessment for iron).

12.3.4 Infrastructure and technology

The mining of manganese was very small scale when compared with other mining operations in England and it placed no great demands on the country's industrial infrastructure. Short tramways were built to serve individual mines, as at Greystones Mine in East Cornwall, but the bulk of its transport needs were met by river and coastal shipping. Quays on the rivers Tamar and Exe were the shipping points with Exeter the principal port used in the late 18th and early 19th centuries.

In much the same manner, the techniques of manganese mining drew on the wider technology of mining and ore dressing. One element which does, however, stand out in treatment of the ore is the establishment of preparation sites close to the shipping points, particularly on the River Tamar at Morwellham Quay (Waterhouse *forthcoming*) and Slimeford, in Calstock parish. There the ore would be crushed and concentrated using gravity separation in water. In other parts of the south-west of England that preparation was carried out on the mine and dressing floors can be a significant feature, even on small mines like Fullabrook, near Braunton, in North Devon.

12.3.5 Archaeological recording

Little attention has been paid to the archaeology of manganese mining and its associated infrastructure. It features in the Rapid Identification Survey (RIS) for the parishes on the Cornish bank of the Tamar Valley where a number of small mines, including Greystones and Wheal Leigh, were noted along with some elements of the transport infrastructure at the former (Thomas & Buck 1994, 17, 22). Although surveys were recommended none appear to have been carried out.

Surveys have, however, recently been carried out on the sites of the manganese dressing mills at Morwellham Quay and at Shillamill near Tavistock (Waterhouse 2008a & 2008b). The manganese quarry at Hartshill Hayes, in Warwickshire, was included in a survey of the castle and its environs (Brown 1997) and underground workings close by, at Purley Chase, have been explored and mapped by Cook (2013).

12.4 Tungsten/Wolfram

12.4.1 Introduction

The presence of tungsten/wolfram in tin ores in the south-west of England (Cornwall and West Devon) was, like arsenic, a major contaminant which, if it was not removed prior to smelting, seriously degraded the value of the metal. Its German name 'wolfram' is even derived from reference to its unwanted status - wolf's spit or froth (Young *pers comm*[1]). It was not until the second half of the 19th century that the value of the metal as a hardening alloy in steel was realised and at that period methods of effectively separating tungsten ores from the tin were being developed. The processing of tungsten ores was never-the-less a complex procedure and the British metal industries showed little interest in it, preferring to send the concentrates to Germany for processing and re-importing the metal for use in the steel industry. With the advent of the First World War this reliance on German processing was curtailed, British industry had to quickly develop its own facilities and tungsten ores were in considerable demand for armament production. The rise and fall of production in Cornwall, West Devon and Cumberland (the only other source of tungsten ores in Britain) was governed thereafter by periods of conflict.

12.4.2 Geological background

The principal economic ores of tungsten or wolfram (the two names are interchangeable for the metal although the latter is frequently used to refer to the ores) are wolframite ($[Fe, Mn] WO_4$), a mixture of the tungstates of iron and manganese, and scheelite ($CaWO_4$), calcium tungstate. They are found in the south-west of England in association with tin as stockworks in greisen mineralisation linked to the Cornubian granite emplacement (Scrivener & Shepherd 1998, 149-50; Beer & Scrivener 1982, 134-35). In the north-west, on the southern slopes of Carrock Fell in what is now Cumbria, the mineralisation is associated with a granite-greisen outcrop of the Skiddaw Granite Cupola (Moore 1977, 7-8).

12.4.3 Historical background

Although a number of mines in Cornwall, including East Pool, South Crofty, Carn Brea, Tincroft and Clitters United, along with Bedford United in Devon (Brooks 2001, 107-30), produced tungsten concentrates as a bi-product of tin production (some 4857 tons from Cornwall up to 1913 - Burt *et al* 1987, xxxii), only a few mines in the south-west of England have been developed primarily as tungsten producers; Cligga Head, Castle-an-Dinas, in Cornwall, and Hemerdon, in west Devon. The latter, although sitting on one of the largest tungsten deposits in Europe, has a recorded production of only 31 tons since being opened up late in the First World War (Dines 1969, 688-89). Despite having significant investment in milling facilities in the 1940s and again in the 1970s it has been kept on 'care and maintenance' for the majority of its life. There is, however, active development currently underway on the site by a new company, Wolf Minerals. Cligga Head was re-opened in 1938, having been worked in a small way prior to that date, and worked until 1945 in response to the high demand created by the Second World War, producing 300 tons of tungsten concentrates (Dines 1969, 457-59).

Castle-an-Dinas was by far the most important tungsten mine in Britain, with a total production of over 2483 tons of concentrates over its 40 year life (Brooks 2001, 137). Tony Brooks (2001) provides a comprehensive account of the mine which was opened up in 1917 in response to war time demand. Apart from a brief period on care and maintenance in the 1920s the mine operated until the decline in the price of tungsten price after the end of the Korean War, with its most productive period in the late 1930s.

Carrock Mine, the only tungsten producer outside of Devon and Cornwall, was probably the first to be worked primarily for tungsten. It was tried initially as a lead/copper prospect in the 1850s and 1870s but soon failed and then re-opened for tungsten in 1902, being taken over by the German run Cumbrian Mining Company in 1906. In 1913 British interests took over and the mine was worked for the duration of the First World War, after which it was closed and only re-opened in 1942 as renewed conflict increased demand for the metal. Despite government sponsored exploratory work, the mine did not go into production and was abandoned the following year. Further exploratory work was carried out in the early 1970s and a new mill erected, but the mine closed more or less immediately. Renewed interest in the late 1970s led to further exploratory work and the mill was reactivated but only operated for a short period before it was closed in 1981 and dismantled in 1985 (Moore 1977; Cooper & Stanley 1990, 43-47).

12.4.4 Technology

The separation of tungsten ores from the tin ore cassiterite was difficult, the similarity in their specific gravities (wolframite 7.1 - 7.5, and cassiterite 6.8 - 7.1) limited the effectiveness of gravity separation although controlled crushing using stamps could result in the more friable wolfram ores being removed as slimes, along with a portion of the tin. Tin ore associated with tungsten ores was therefore avoided if at all possible (Brooks 2001, 5).

In 1844 the Oxland process was introduced as an effective method of removing unwanted tungsten from tin concentrates - the soda process. The concentrates were first roasted with sodium carbonate as a result of which sodium tungstate was produced and, as that is soluble in water, the tungsten could be removed by leaching. This process was replaced at the turn of the century by magnetic separation which first separated out any iron oxides from the concentrate using low power magnets and then removed tungsten minerals with high power magnets, leaving a clean tin concentrate. The tungsten ores thus separated were pickled in acid to remove any remaining iron, dried then passed through another magnetic separator to produce a clean tungsten concentrate (Brooks 2001, 5-6). The mill at Castle-an-Dinas used a combination of crushing, gravity separation and magnetic separation, and is described in detail, illustrated with a flow sheet, in Brooks 2001 (38-44).

The mill erected at Carrock Mine in the 1970s and the trial plant at Hemerdon in the 1980s were probably the most advanced ore preparation plants erected in Britain which did not rely on flotation.

12.4.5. Infrastructure

Prior to the first decade of the 20th century the production of tungsten concentrates came as a bi-product of tin production and was, thereafter, a relatively small scale specialist operation only viable during periods of conflict. It placed no new demands on transport systems or settlement patterns.

12.4.6 Archaeology

Until recently, there have been no archaeological investigations embracing the physical evidence for tungsten mining. The Castle-an-Dinas mine site was included in the Archaeological Survey Report (Bishop 2011) but only where it impacted on the Iron Age hill fort and the mine itself was not surveyed.

Two factors in recent years have focused attention on the archaeology of tungsten mining in Devon and in Cumbria. In the first instance, the renewed interest in exploiting the deposits at Hemerdon has initiated an assessment of the surviving features, including the mill buildings, but the results of that work have yet to be published. At the Carrock Mine, concerns over the environmental impact of mine water discharges have resulted in remedial work, including stabilisation of one of the mine entrances and on-going management of the scheduled ancient monument by the Cumbria Amenities Trust Mining History Society, supported by an archaeological survey carried out by Archaeo-Environment Ltd (2012). In its turn, that has highlighted the condition of the early 20th century mill buildings which are to be surveyed prior to conservation work (John Hodgson, LDNPA archaeologist, *pers comm*[2]).

12.5 The Archaeology of Cobalt Mining

12.5.1 Introduction

Cobalt is found as a component in mineralisation across the British Isles (Andrews 1962, 64; Tindle 2008). However, it has only been recovered at a few localities, principally in Cornwall, Cumbria and Cheshire, but also in north Shropshire, and the Ochil Hills, Scotland (Andrews 1962, 65). Once separated, cobalt minerals were used primarily in the manufacture of smalt, a pulverised glass produced by fusing cobalt oxide with powdered flint and potash, which was used for colouring in china and glass manufacture, and as a 'blue whitener' in paper making and in the linen industry. Ores could be smelted to produce the metal; this was usually carried out by specialist smelters remote from the mines but in one case, in Cumbria, it appears to have been attempted on site.

12.5.2 Geology

In Cornwall cobalt minerals include smaltite (a variety of the arsenide skutterudite), the hydrated arsenate erythrite, the sulpharsenide cobaltite, and the oxyhydroxide asbolane (Tindle 2008), and are found in association with nickel and bismuth ores (Dines 1956, 30). The association in Cumbria is with copper-lead-zinc mineralization and barite, with the former mineral grouping being linked to the Borrowdale granite intrusion (Stanley & Vaughan 1982). In Triassic sandstones of the Cheshire Basin cobalt is associated with barite mineralisation and localised occurrences of low grade, copper-dominated, sediment-hosted ore deposits, of which those in the Alderley Edge Geological Site of Special Scientific Interest are cited as a classic example (Warrington 2010).

12.5.3 Historical Context

Saxony was, from at least the 17th century, a principal European source of cobalt but export of the ore was prohibited and it was roasted there to produce *zaffre* for export; the Duke of Saxony thus monopolised the source material and that product, from which *smalt* was prepared. The cost of importing smalt into England in the mid-18th century stimulated a search for indigenous sources of cobalt ore. Some was already known from Cornish mines, and smalt production had been attempted there. In 1754 the Royal Society of Arts offered a premium of £30 for the best English ore sample and this was awarded in 1755 for ore from a mine near Truro. In the same year the Society offered a premium of £30 for the manufacture of zaffre and smalt from indigenous ore; this was not awarded until 1764 (Watney 1963). The Napoleonic Wars resulted in further impetus to the discovery of indigenous supplies amongst which were those in Cheshire (Warrington 1981, in press).

Only a few mines in England produced cobalt ores or concentrates. In Cornwall, East Pool, Great Dowgas, and St Austell Consols have recorded outputs, in the latter case mixed with nickel ore (Dines 1956, 333, 545-46). Ore was raised from Trugo (Beer 1988, x) and parts of South Crofty (Dines 1956, 318), and possibly also from Dolcoath (Dines 1956, 30). Wheal Sparnon in Redruth was an important source of cobalt ore from at least 1808. Work there ceased in late 1810 but had resumed by 1814 when ‘superior quality’ ore was being produced; two tons, valued at £1200, were sent to London. Later, around 80 tons were raised in about one year from a ‘large and valuable cobalt lode’. Mining at the ‘Wheal Sparnon and Corner Stone Cobalt Mines’ stopped while accumulated ore was smelted to produce pure oxide. A separate company was formed for that purpose and about £4000 worth of oxide was sold to potters between mid-1816 and mid-1817. In 1819 the ‘cobalt lode’ was worked down to 60 fathoms, and eventually down to 70 fathoms (below adit). In 1826 a ‘cobalt works’ was completed at the mine which was then unique in Cornwall in being worked *solely* for cobalt ore. Sales of the product to Staffordshire were anticipated and £600 worth of cobalt was prepared by January 1827, but the mine closed soon afterwards (Hamilton Jenkin 1962b, 19-23). Before 1817 some ore from this mine was apparently refined by the British Cobalt Smelting Company at Hanley (Watney 1963, 8). Cobalt ore was evidently worked at the Wherry Mine in Mounts Bay (Russell 1949; Hamilton Jenkin 1962c) in the late 18th century; Williams (1810, 488 cited by Timberlake 2010) referred to the mineral worked as ‘pure cobalt ore’; erythrite and skutterudite have been recorded (Tindle 2008, 200). Some ore was produced at Wheal Owles and Boscawen before 1893, and at Polgooth, Wheal Huckworthy and Wheal Unity (Andrews 1962, 65). Cobalt ores were recorded from the Botallack, Levant, Hawkes Point, Rosewarne and Herland, and South Terras mines (Dines 1956), and cobalt minerals are recorded from many others in Cornwall (Tindle 2008).

In the Lake District cobalt ore was obtained from mines near Coniston (Andrews 1962, 65) and near Borrowdale. From about 1848 the Keswick Mining Company attempted to work cobalt at a mine high on the fells between Sail and Scar Crags, to the west of Borrowdale. The intention appears to have been to produce metallic cobalt. Dressing floors were erected and a smelt mill adapted for the purpose but the working failed without producing anything of value (LDNPA HER 11654; Postlethwaite 1987, 109; Adams 1988, 47-48).

In Cheshire, mines at Alderley Edge were leased to the Alderley Mine Company in 1805. Cobalt minerals, predominantly asbolane (a mineral of variable composition but usually including nickel, cobalt and manganese or 'wad'), were recognised there in 1806, after probably being first identified at nearby Mottram St Andrew. In 1808 the Alderley cobalt ore was let to Tomlinson, Plowes & Co. of the Ferrybridge Pottery, in Yorkshire. However, this agreement was terminated after little more than one year although ore continued to be produced at Alderley and a treatment works was established at Wallasey, operated by the Seacombe Cobalt Company. That was dissolved around 1814 and succeeded by the Seacombe Smalt Company. However, the Alderley Mine Company had been dissolved before 1812 and the source of ore treated at Wallasey following that date is unknown. The Seacombe Smalt Company was dissolved in 1817 in the face of competition following resumption of imports from Europe after the Napoleonic Wars (Warrington 1981, in press). Cobalt was recovered at Alderley Edge later in the 19th century as a by-product of an acid-leaching process introduced there in 1857 to treat copper ore. It was also mentioned as having been sold from the nearby Mottram St Andrew mine between 1860 and 1865 (Warrington 1981, 65).

Cobalt minerals have also been recorded from Bickerton, west Cheshire (Carlon 1981) and from mines in north Shropshire, at Eardiston, Pim Hill and Clive; some ore was produced from the last (Dewey & Eastwood 1925; Shaw 2009). These occurrences are in deposits similar to but smaller than those at Alderley.

12.5.4 Techniques and Technology

There are few techniques or any technology specific to the extraction and production of cobalt minerals or the metal. During exploration of the Cobalt Mine at Alderley Edge tools were found which had evidently designed for extracting asoblane from joints in the sandstone (Timberlake & Mills 2003). The ore, described as blue-black grains, similar to gunpowder, disseminated in red sandstone or lying in thin seams, was 'got out in thin pieces, and separated afterwards as much as possible from the stone; it is then packed into tubs and sent near Pontefract, where it is manufactured into smalt' (Bakewell 1911). Otherwise the techniques of mining were no different from other mining activity of the period. Ore preparation would have relied initially on manual separation and grinding, with gravity separation employed in the large dressing floors treating polymetallic deposits, as in Cornwall. Unfortunately little is known regarding the attempt to smelt cobalt on site in Cumbria.

Later in the 19th century the Alderley Edge Mining Company Limited produced cobalt-rich residues between 1857 and 1864 as a by-product of an acid leaching process for the extraction of copper. Solutions remaining after precipitation of the copper by scrap iron were concentrated by boiling in wrought iron pans, then sprayed over sand-covered tiles heated from below, in a furnace at dull red heat. Metallic oxides accumulated in the sand, and acid vapour and steam were conducted to a condensing tower. The resulting acid was recycled, but to little financial advantage and this procedure was suspended until cobalt present in the sand could be recovered profitably. According to Timberlake and Prag (2005, 140) a cobalt and nickel precipitate was subsequently partially smelted in reverberatory furnaces. A company report (*Mining Journal* 1864, 153) mentions furnaces at the 'cobalt works' being stopped after 357 tons of precipitate that yielded 10 tons 11 cwts and 2 qrs of 'speiss' with an estimated value of £650 to £700 had been processed (Warrington 1981, in press). There is no record of further production of those materials and the works referred to were clearly ancillary to that for recovering copper. 'Cobalt Treatment Works' and a 'Cobalt Tower' are alluded to in Timberlake & Prag (2005), suggesting the existence of a plant dedicated solely to cobalt production; these were a part of a much larger operation to recover copper ore.

12.5.5 Transport and infrastructure

The transport of cobalt ores presented little difficulty. They were relatively small in quantity and could be expected to utilise the existing infrastructure. For example, the quantity of 'cobalt-bearing wad' (i.e. asbolane) produced at Alderley in the early 19th century has been estimated as between 50 and 300 tons (Timberlake & Prag 2005, 144). This would have been carried by packhorse or horse-drawn cart to a suitable point for transfer by canal or river to the works at Ferrybridge or Wallasey. In the 1860's Alderley produce may have been transferred from carts to railway wagons in nearby sidings. Treatment was attempted on site in the Lake District, and was carried out at Wheal Sparnon from where, in the early 18th Century, transport of the product to customers in, for example, the Staffordshire Potteries, would have been largely water-borne, by sea to river and canal systems.

The extraction and processing of the minerals did not continue on any one site for sufficient time for the establishment of dedicated settlements.

12.5.6 The archaeology of cobalt mining

Workings connected with cobalt mineral extraction at Alderley Edge and in Cumbria have been explored and recorded (Johnson 1984; Adams 1988, 47-48; Timberlake & Mills 2003; DCC 2007; Norgate 2012; Carlon & Dibben 2012, 103-09). The Ferrybridge Pottery site was interpreted by Bidgood (1978).

At Alderley evidence for a 'Cobalt Treatment Works', particularly an interpretation of soil geochemistry, is alluded to in the work by Timberlake and Prag (2005). The site of the 'Wood Mine cobalt works and associated mines' is now a scheduled ancient monument (Number 1020181) and the description of this site alludes to 'buried remains of metal ore processing works' and states that features related to cobalt production that will survive include 'remains of wooden tanks, … the bases of furnaces for heating the cobalt bearing solutions, the foundations of the cooling tower for evaporating the heated mixture and the beds for the steam engines which powered the entire process'.

Traces of some structures have been noted in this area (in Timberlake & Prag, 2005) but none are unequivocally related to cobalt production which ended in 1864. Many, if not all, the structures erected by the Alderley Edge Mining Company Limited were removed after the company wound-up and its effects were auctioned in 1878 (Warrington 1981, in press). A small processing plant that would have overprinted vestiges of structures from earlier periods was erected on the site, and removed, in the early 20th Century

(Warrington 1981, in press). Some buildings contemporary with and possibly connected with the early 19th Century cobalt mining are extant (Warrington in press), but lie outside the area of the scheduled ancient monument.

12.5.7 Notes on associated minerals

Nickel - Mainly produced in Scotland, the only Cornish mines to market this mineral were Fowey Consols and St Austell Consols. During the 1850s and 1860s, they had a combined output of 17.6 tons of ore valued at £653. (Burt et al, in prep. Two tons of 50-60% nickel ore were raised from Pengelly mine (Beer 1988, xiii). Precipitates containing nickel were smelted at Alderley Edge for a short period (see above: Techniques and Technology).

[1] Tim Young, *Wolf's spit: new evidence for an old term*, presentation to the Historical Metallurgy Society meeting on Research in Progress, Newcastle University 6 November 2012.

[2] Based on discussion at the Lake District Mines Forum meeting, Kendal, 31 January 2013.

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