

# An early medieval lead-smelting bole from Banc Tynddol, Cwmystwyth, Ceredigion

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*ABSTRACT: Excavations in 2002 at Cwmystwyth, in Central Wales, found an ancient lead smelting site. There are remains of the medieval and the Roman periods. This paper describes in brief the excavation of the medieval lead bole (Timberlake 2002a) but also provides an archaeological reconstruction of this and details of an experimental lead smelt carried out at the site in 2003 (by ST). The analytical study (by LA) is of the medieval metallurgical debris excavated in 2002, mostly slag, but also ore and lead. The aim was to understand the raw material, the metal produced and the smelting process. The ore smelted was predominantly galena but with no detectable silver, showing it was probably exploited to produce lead. The extremely high sulphur content of the slag indicates that the ore was not roasted before smelting. It is argued that the medieval activity was small-scale, smelting a very rich ore. The furnaces apparently did not require much capital investment, enabling a short-lived and/or exploratory smelting operation.*

## Background

### Geology and mineralogy

The hydrothermal ore veins in the area of Cwmystwyth in Central Wales have intermittently sustained a metal production spanning thousands of years, from the Early Bronze Age up to the recent past. The whole area is intersected by a large system of faults; mineralization occurred along ENE-WSW trending normal faults and breccia zones that cut across folds of early Devonian age in Lower Silurian turbidites and sandstones. The normal faults have 10- to 30m-wide, laterally impersistent, breccia zones. Dating suggests that the mineralization occurred in the Upper Palaeozoic (Dobson 1995).

At the Cwmystwyth Mines the main Cwmystwyth Fault, which post-dates the emplacement of the mineral lodes, runs parallel to and along the floor of the Upper Ystwyth Valley, and most of the old workings are in the hillside to the north of the fault. The fault itself is a conspicuous and major feature of the landscape in that it has influenced the course of the River Ystwyth and its U-shaped glaciated valley. The mineral workings, which extend for more than a mile along the north side of the valley, consist of the Mitchells, Pugh's and Kingside

(Level Fawr) Mines, and Copa Hill. Smaller workings abound, such as the Penguelan Mine immediately to the north of Banc Tynddol and the valley road. The principal mineralization involves lead and zinc (galena and sphalerite) with some copper (chalcopyrite), but nickel and antimony are also present in trace amounts. The following minerals have been recorded: galena, sphalerite, chalcopyrite, malachite, marcasite, native copper, pyromorphite, cerussite, hemimorphite, brochantite, dolomite (ankerite), quartz and linarite (Dobson 1995).

### Prehistoric mining

The site is best known amongst archaeologists for its prehistoric copper mine, the Comet Lode Opencast, the latter exploiting a rich shoot of lead and copper (chalcopyrite) ore at the point where this vein outcrops at 426 metres OD on the side of Copa Hill (Timberlake 2003; Mighall *et al* 2000). Abundant stone hammers and massive spoil heaps containing some 5000 metric tonnes of prehistoric mine waste bear testimony to the large-scale nature of the operation, whilst archaeological excavations carried out here have proved the presence of wooden drainage launders, antler tools, withy handles, rope and basketry dating from the Early Bronze Age.

The ancient workings here extend to depths of over 10m. Very little, however, is known about the smelting of copper and lead sulphide ores in prehistory. As regards copper, the earliest miners at Cwmystwyth could have been separating and extracting the small amount of oxidized ores from the sulphides (Timberlake 2009).

### Early lead mining

Evidence for Roman and medieval mining for lead is beginning to emerge as a result of further archaeological work carried out at these mines and from the palaeo-pollution record preserved within the blanket peat covering the top of Copa Hill (Mighall *et al* 2002). An ancient mining leat carrying water from the headwaters of the Nant yr onnen stream to a reservoir within the infilled prehistoric opencast for the purposes of hushing appears to have been already abandoned by the 13th century AD, and may be a lot earlier still (Timberlake 2003, 13). There are also indications of medieval prospecting activity within the same area.

The re-discovery in 1990 of the ‘ancient smelting site’ first referred to by the geologist O T Jones in 1921 at Penguelan (Banc Tynddol) thus provides a link with both this and other circumstantial evidence for early lead mining at Cwmystwyth.

### Documentary and field evidence for medieval smelting

Prior to 1560, though poorly documented, lead and silver mining in north Ceredigion was most probably small-scale and quite underdeveloped compared with that of Flintshire, the majority of mines being little more than near-surface trials or opencast rakes exploited intermittently as local demand for lead rose and fell. Typically, lead would have been in demand for the upkeep of castles, an example being the repair of Cardigan Castle carried out using lead from the Strata Florida Mines in 1451 (Lewis 1967), and for the construction and repair of churches and abbeys such as the Cistercian house of Strata Florida (Hughes 1981) a little over 10km south of Cwmystwyth. The presence of two inspectors of silver at Cardigan in 1340 might suggest the mining of argentiferous ore and also some small-scale production of silver coinage (Lewis 1967) whilst at Strata Florida there are claims that the monks were practising cupellation (Williams 1889).

There are few references to lead smelting within the Upper Ystwyth Valley, yet this situation is not that different from that encountered elsewhere in the north Ceredigion mining field in the period leading up to 1500.

What evidence there is to be found within a number of brief reports which mention the following types of remains: the discovery of small spreads of lead-rich slag and charcoal such as those found at Pontrhydygroes (Maen Arthur), Bow Street and Ysbyty Ystwyth (Davies 1936, 305) and also at Cwm Bwa, Penrhyncoch (Davies 1937; Hughes 1990,13); the discovery of lead metal trapped within cracks or fissures in the rocks such as in the nearby Hafod Estate (Chambers 1858); the existence of rocky hearths without any upstanding structures at Hafod; and the discovery of traces of fused stone and gritty clay furnace lining alongside other refractory materials at Cwm Bwa (Davies 1937, 303). Such remains are all fairly typical of bole-smelting sites, the use of which is much more likely to have been medieval than post-medieval in date (Tylecote 1986; Willies and Cranstone 1992). Moreover, all of these sites are close to mines considered on other grounds to be ancient, Cwmystwyth being no exception (Fig 1).

The earliest clear documentary reference to mining at Cwmystwyth is that provided by John Leland, the King’s Antiquary under Henry VIII who passed along the valley while on his way from Strata Florida Abbey to Llanbadarn sometime between 1536 and 1539. He describes what would appear to be contemporary diggings on the Graig Fawr (Fig 2a) plus evidence of former smelting: ‘... I saw on the right hand on a Hill side Clothmoyne [Cloth or Clodd = mine, Moyne or Mwyn = lead, perhaps a reference to ‘Craggie-Moyne’, or Graig Fawr], where hath been greate digging for lead the melting whereof hath destroid the Woddes that sometime grew plentifull thereabout ...’ (Meyrick 1907, 140). Although the locations of these offending smelting hearths cannot be deduced from this account, the tree-loss he describes is most likely to have taken place on the lower, less steep slopes of the valley and valley floor, the slightly more elevated parts of which would have been suitable for the furnace sites.

Today most of the area along this part of the valley side is covered with either river gravel, mine spoil, scree, or else cuttings and embankments for the tramroads and leats, thus it is little surprise that no evidence for these hearths have (until now) come to light. However, one clue as to the possible location of one of these sites was to be found on a map of the mineral veins and workings on Copa Hill published by the geologist Professor O T Jones (1921) which refers to the ‘Remains of Ancient Lead Smelting Works’ at Penguelan (Fig 2a). However, the poor description of this plus the absence of any obvious surface evidence meant that all previous searches had failed to locate it (Hughes 1981).

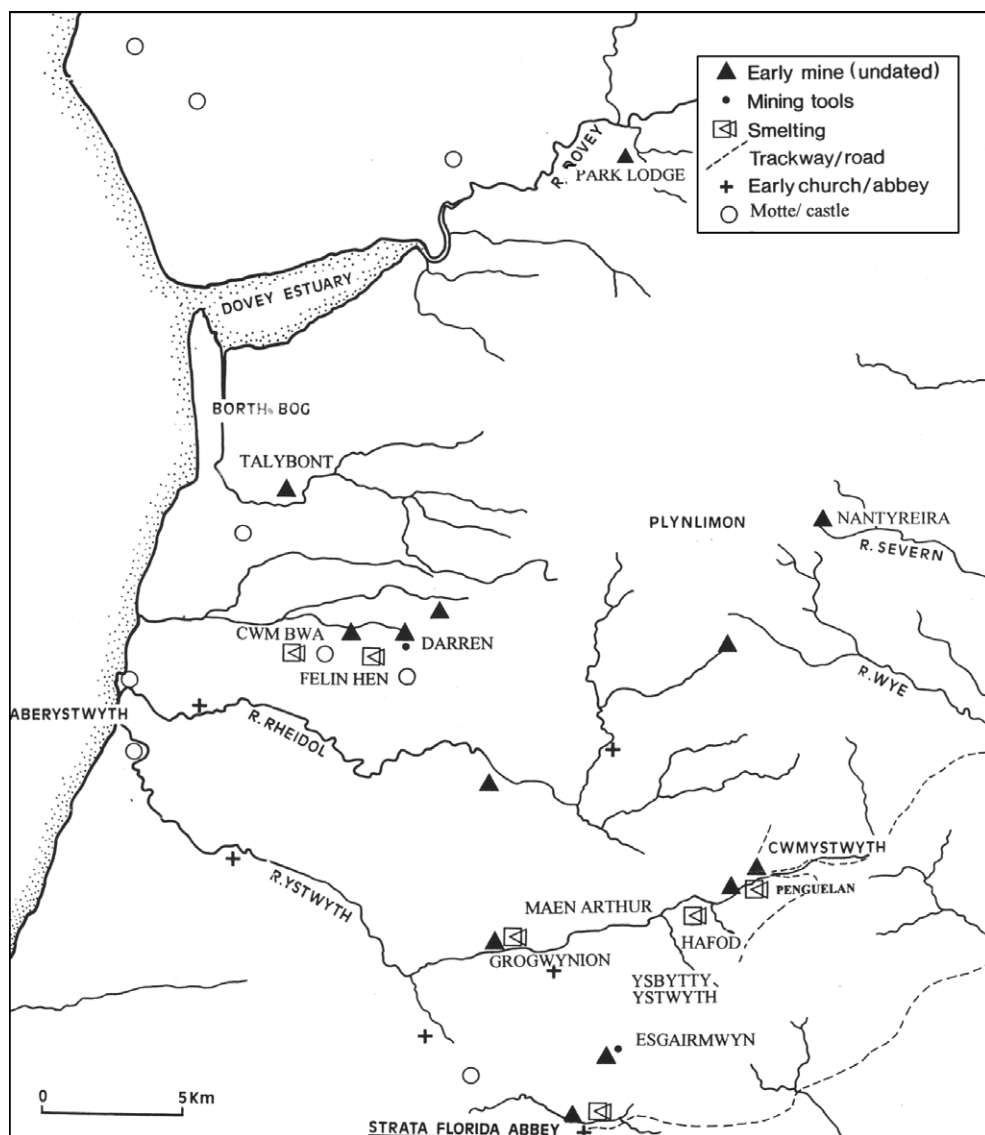


Figure 1: Suggested sites of medieval lead mining and smelting in north Ceredigion.

Our attention was first drawn to this site (SN 809748) during the course of a detailed landscape survey of Copa Hill carried out by the Early Mines Research Group in 1989–1990. An area of pronounced infertility amplified by the dry summer conditions could clearly be seen on the rough pastureland which covers a lobe of glacial outwash moraine at Banc Tynddol some 30–40m above the valley road. During fieldwalking, small fragments of burnt and pitted rock with the occasional fragment of fused galena attached were picked up from amongst the shallow sheep-disturbed soils, confirming the presence of one or more destroyed hearths (Timberlake 1990, 9).

### Excavation of the Banc Tynddol lead smelting site (ST)

Following geochemical and geophysical surveys, archaeological evaluation of the site took place in 1999, 2002 and 2003. Sample trenches (test pits) PSS1, 2 and 3 were dug in 1999, while trenches PSS4–6, 10

and 12 were dug during 2002/3 (Fig 2c). Trenches 10 and 12 uncovered the course of an 8m-long channel of lead spill downslope of the Roman hearth in PSS4. The latter was excavated in 2002 but is not discussed in any detail here as this paper focuses on the bole hearths found in Trench 6 and the smelting remains found in both Trenches 5 and 6.

### Geochemical and geophysical surveys

In 1996 a soils geochemical survey was undertaken of a 25m<sup>2</sup> plot within the area of presumed smelting activity using a portable XRF analyser (Spectrace 9000). This revealed a generally high level of contamination of around 5000ppm lead, but with hot-spot anomalies of up to 25,000ppm (2.5% Pb) (Fig 2d). Elevated levels of potassium here may be linked to the presence of charcoal and ash in the soil (Jenkins and Timberlake 1997, 29).

A larger area (625m<sup>2</sup>) including both the western and eastern ridges of the plateau was geophysically surveyed

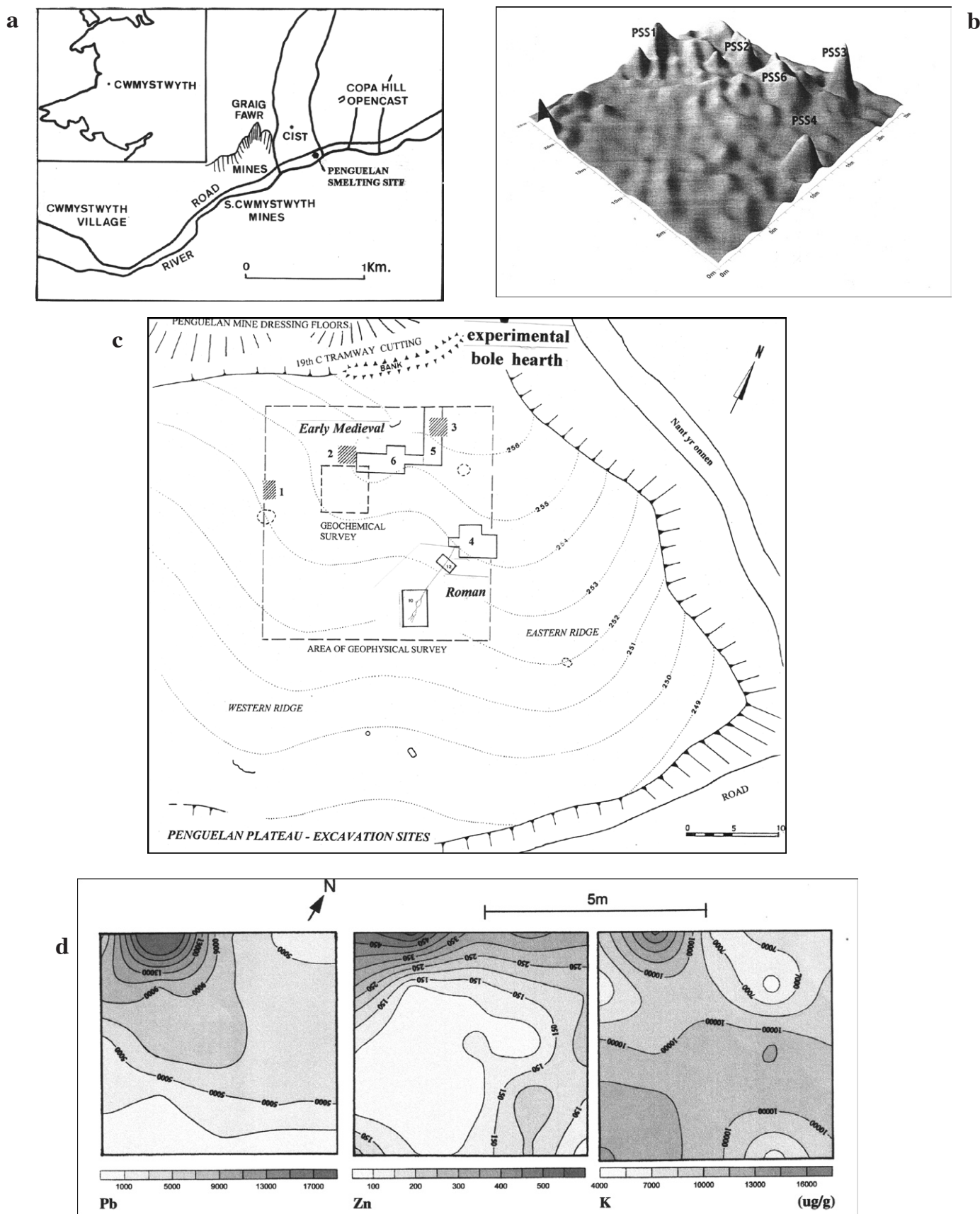


Figure 2: a) Location map of Cwmystwyth – mines and smelting site; b) geophysical survey of Banc Tynddol – magnetic susceptibility and electrical conductivity anomaly map (Archaeophysica Ltd 1999); c) Banc Tynddol plateau and Penguelan Mine, Cwmystwyth showing areas of excavation, survey and experiment; d) geochemical anomaly maps of soil contamination at Banc Tynddol (after Jenkins and Timberlake 1997).

by Archaeophysica Ltd in June 1999 prior to the first sample excavations. Volumetric magnetic susceptibility and electrical conductivity contour surveys revealed very similar positive anomaly patterns suggesting the presence of a number of well-localised areas of strong burning (or spreads of burnt rock and slag), perhaps equating to between five and seven hearths (Fig 2b). The east-west orientation of these anomalies, located along the crests of the two ridges, suggested to us that these might well be wind-blown furnaces.

### Archaeological evaluation

In 1999 three 4m<sup>2</sup> sample trenches were opened up within the above area to investigate some of the anomalies and possible hearth sites identified (Fig 2c). The westernmost trench (PSS1), located on the margins of the surveyed area, uncovered a patch of disturbed ground with burnt stone, slag and 18th–19th century bottle glass at a depth of between 100–200mm. However, beneath this lay a thick layer of charcoal and ash which appeared to be *in situ* and associated with localised burning of the underlying ground surface. The absence of any fused lead ore or slag here was considered to be significant, thus this was originally interpreted as being the remains of a possible charcoal clamp or oven, although on reflection this could just have been the raked out embers of a large hearth(s). A date of 820 ± 60 yrs BP (1030–1300 Cal AD at 95% probability; Beta-140992) was obtained from a bulk sample consisting of small pieces of *Quercus sp* (oak) charcoal (Timberlake 2002a, 49). This provided the first indication of the period of the site, suggesting that we were looking at a phase of smelting activity contemporary with the building and early occupation of the Cistercian Abbey of Strata Florida. This was a logical conclusion, given that we were well aware of the circumstantial and later documentary evidence that the monks had mining interests at Cwmystwyth (Meyrick 1907, 567; Hughes 1981, 7).

The two other trenches (PSS2 and PSS3) were located on the ridge crests, much closer to the area we now know to be the focus of bole hearth construction. No actual hearths were identified at the specific locations corresponding to the anomalies, but considerable spreads of raked-out burnt rock, part-fused ore and slag were recovered, along with small droplets and runnels of lead metal. This appeared to confirm that we were looking at the remains of lead-smelting hearths.

### Excavation of the bole hearth sites

In October 2002 larger excavation trenches (PSS5 and PSS6) were opened up in the area identified above as being the centre of the bole site. Meanwhile a separate

investigation focused on another geophysical anomaly (PSS4) located c15m downslope, on the west flank of the easternmost ridge of the plateau (Fig 2c).

### Early medieval bole hearths

In contrast with the pit bole hearth (in PSS4), the bole sites (in PSS5 and PSS6) showed almost no evidence for any sub-surface component, whether a trench, pit, post-holes or even any sort of credible stone foundation. Moreover, the archaeology here was thin, a maximum of 150–200mm above a natural (?) spread of boulders [007] (Fig 3b). The latter had been subjected to a fair degree of erosion as well as modern disturbance along its upper edge. Nevertheless, the record for the existence of these boles was clearly evident in the form of *in situ* burning, and overlying this a layer of charcoal and earth [006] and heat-decrepitated rock [006b]. An additional scatter of glassy slag, part-fused and unfused galena, melted masses of metal and sulphide (including lead ‘matte’), plus the occasional droplet of melted lead covered the site. At least some of these appeared to have been formed *in situ*, the metal having dropped or flowed down cracks in between the boulders. These suggest the presence of elevated bole sites constructed above ground, much of the stone fabric of which, such as the dry-stone (shale) walling surround, appears to have completely disintegrated on firing.

The bases of at least two boles (A and B) can be identified within trench PSS6 (Fig 3a), the centres of which appear to have been raked clean (in fact much of the burnt earth and charcoal may have been scraped away in the process of recovering any residual smelted lead metal and un-smelted/part-smelted ore and lead-rich slags for re-smelting). It appears that some of the upstanding earth-fast boulders here may also have been selected as foundations for the building of boles. Many of these are only very lightly burnt, suggesting the presence of a thick covering of turf at the time smelting commenced. Some evidence of the quarrying of the underlying boulder layer [007] for the purposes of bole construction is evident within a number of areas. Moreover there is some suggestion that the putative grave located beneath the find of the Beaker gold foil disc (Timberlake 2002b; 2004, 137) was disinterred, then heavily robbed of stone by the medieval smelters. For this reason it may now be very difficult to recognize the remains of any eroded or flat cairn once present at this spot.

Important information has, however, been forthcoming from the dating of charcoal linked to the use of these boles. A radiocarbon date of 1060 ± 40 yrs BP (880–1020 Cal AD at 95% probability; Beta-181060)

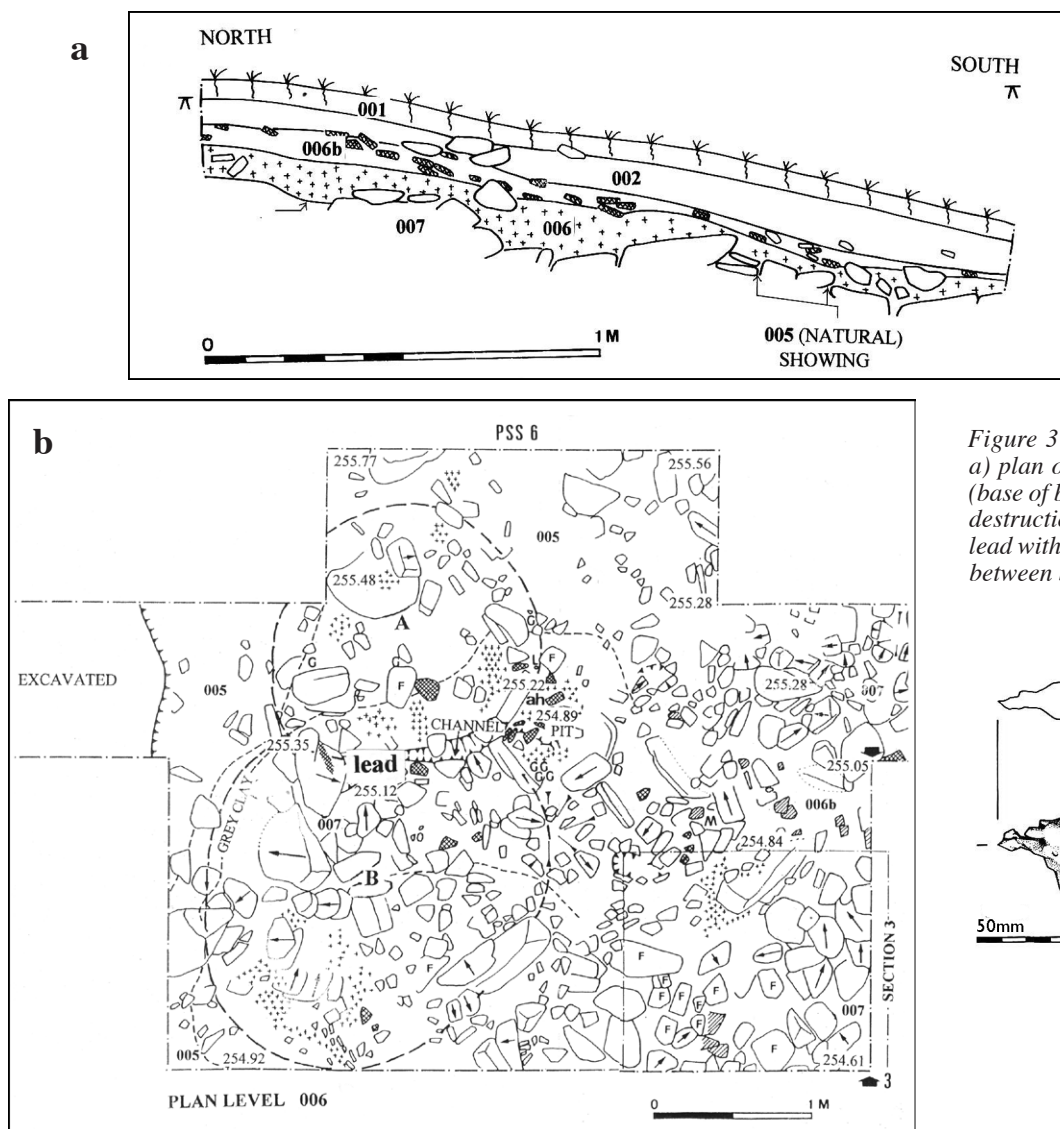


Figure 3: Banc Tynddol Site PSS6. a) plan of trench at the level of 006 (base of boles); b) Section 3, the bole destruction layers; c) lump of melted lead with adhering charcoal found in between boulders on edge of bole A.

was obtained from charcoal pieces associated with the lump of melted lead recovered from the ‘channel’ around the edge of bole A (Fig 3c). Given that this charcoal was of branchwood, the sample date provided above would realistically seem to suggest a date earlier than the Cistercian interest in the mine as the Abbey of Strata Florida was founded in 1164 AD (Hughes 1981, 5). Meanwhile, another radiocarbon date of 1264 ± 27 yrs BP (670–840 Cal AD at 95% probability; OxA-12956) was obtained from a single small piece of oak charcoal recovered during excavations carried out on the bole site and grave in 2003 (Timberlake 2004, 137). This adds weight to the suggestion that what we are in fact looking at is the repeated use of the same bole location for small-scale lead smelting over a 300–400 year period.

**Discussion**

The amount of surface disturbance and erosion here makes it quite difficult now to accurately locate the boles or else to quantify the scale of activity. Nevertheless,

a crude estimate of the total amount of lead smelting which has taken place can still be made. Somewhat less than 20 tonnes of slag, part-smelted ore and burnt rock waste probably cover the entire area of the Banc Tynddol plateau, whilst the geophysical evidence for areas of burning (within the surveyed area) suggests the presence of between 6–10 furnace sites over the whole site. Some of these, of course, may be earlier or later in date.

Even if this activity amounted to the smelting of 50–100 tonnes of ore, this would still represent only a very small part of the total production from medieval mining prior to AD 1500 (Hughes 1981, 6). The scale of activity here would also not account for the level of environmental destruction witnessed by Leland as being evident in 1539.

Other evidence to consider here are those rises in atmospheric lead pollution recorded within the ombrotrophic blanket peat on Copa Hill and ascribed to



Left to right, Figure 4: Slag sample from trench 5, width 60mm. Figure 5: Furnace wall associated with slag from trench 6, width 66mm. Figure 6: Galena sample from trench 6, width 46mm.

early medieval mining (Mighall *et al* 2002, 181). It is true that these tend to be small (typically less than 50ppm lead recorded at depths of between 400 and 200mm in cores CH1, 2 and 4), in particular when compared with the lead peaks of up to 60ppm lead linked to Roman working. Nevertheless, it should be remembered that the smelting sites at Banc Tynddol are some distance from the top of Copa Hill, also that the epicentres of Roman and early-medieval mining activity at Cwmystwyth may be quite different (this is something which could quite easily be established through the analysis of ores from the two different types of smelting hearth). Furthermore, the pollution peaks themselves need to be properly dated.

In conclusion, it seems that one of the areas of wind-powered lead smelting located on the valley floor has been identified, and some insight into the different types of bole constructed, the period(s) of their use, and the approximate number of furnaces/quantities of ore processed have been gained. The archaeological evidence so far supports what little is known from documentary accounts of mining and smelting, as well as from the environmental record (peat bog archive) as regards local lead pollution. However, there remain a number of important questions. Who was carrying out mining and smelting here prior to the peak demands for lead brought about by the creation of the Cistercian houses and lands? Were the small-scale smelting campaigns witnessed at Banc Tynddol representative of what were in effect little more than occasional bouts of mining, or were there more important bole sites located elsewhere upon the floor and sides of this valley? If so, was the smelting at Banc Tynddol simply 'experimental', carried out as a means to assay the ore and metal from a variety of different veins and workings?

### Analyses of medieval lead slag from the Banc Tynddol excavations (LA)

During the excavations, described above, various metallurgical materials were recovered, namely slag *sensu stricto*, furnace walls associated with slag, lead metal, galena (unreacted or semi-reacted) and a fragment of iron metal. All the materials of interest were found in two layers associated with a high concentration of ash and charcoal, close to where the sites of the bole hearths A and B were identified within the excavations (Fig 3a).

The material can be grouped into four different categories:

**Slag:** several kilograms of slag were excavated from an area of about 16m<sup>2</sup>. Most fragments are broken, with maximum dimension of 40–50mm. The slag pieces are covered by a white to red corrosion patina typically 1mm thick (Fig 4). The density of several pieces was found to be 5–6g/cm<sup>3</sup>, clearly higher than fayalitic copper or iron slag which is 3–4g/cm<sup>3</sup>.

**Furnace wall material:** burnt stone associated with slag; the surfaces are blackened by fire and covered by a brown-red patina (Fig 5). These are the majority of the metallurgical remains found at the site.

**Lead metal:** drops or fragments, some with the typical shape of runnels, and some associated with the excavation of a 'channel' (possibly a former animal hole) less than a metre from the furnace (Fig 3c).

**Galena:** several fragments of unreacted or semi-reacted galena, with a deep white alteration patina (Fig 6). The samples are often associated with quartz fragments.

### Analytical methods

The study involved the use of three analytical methods: optical microscopy (OM), energy dispersive X-ray fluorescence spectrometry (ED-XRF), and

Table 1: Composition of the glass matrix in the slag samples (wt%).

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	FeO	CaO	K <sub>2</sub> O	PbO	ZnO
5-4b	18.9	1.5	1.8	0.8	0.5	71.6	4.6
5-4c	33.9	2.9	1.7	1.2	1.5	54.6	4.3
5-4e	20.4	1.8	1.6	1.0	0.6	70.5	4.1
6B-2b-a	19.9	1.9	1.5	0.9	0.3	71.6	4.0
6B-2b-c	21.4	1.8	1.7	1.0	0.4	69.1	4.1
6B-2b-d	17.7	1.6	1.1	0.7	0.5	75.9	2.5

Table 2: Bulk slag composition (wt% XRF analysis).

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	CaO	BaO	Na <sub>2</sub> O	K <sub>2</sub> O	MnO	MgO	PbO	CuO	Sb	As <sub>2</sub> O <sub>3</sub>	Ag	S	ZnO
	%	%	%	%	ppm	%	%	%	%	%	ppm	ppm	ppm	ppm	%	%
5-4a	16.8	1.34	1.03	0.64	103	nd	0.12	0.02	nd	74.8	207	1051	528	16	3.11	2.12
5-4b	16.5	1.00	1.17	0.62	79	nd	0.16	0.02	nd	75.1	61	704	480	11	3.32	2.12
5-4c	20.6	1.50	1.24	0.74	158	nd	0.27	0.02	0.07	70.4	116	1028	669	13	2.38	2.77
5-4e	16.9	1.78	1.16	0.58	105	nd	0.13	0.01	nd	74.8	221	1114	350	19	2.47	2.12
6b-2b-a	13.8	0.96	0.72	0.52	95	1.40	0.07	0.01	nd	76.7	136	1381	375	nd	4.50	1.24
6b-2b-b	17.9	1.25	1.31	0.59	112	nd	0.25	0.02	0.09	72.7	131	617	533	nd	2.71	3.17
6b-2b-d	16.4	1.48	1.07	0.59	114	nd	0.14	0.02	nd	75.4	224	1022	390	14	2.86	2.04
6b-2b-f	17.0	1.08	1.32	0.29	91	nd	0.11	0.02	nd	73.6	133	592	198	9	2.94	3.63
6b-2b-o	14.0	1.11	0.93	0.62	98	nd	0.12	0.02	nd	77.6	147	1391	548	14	4.13	1.40
6b-2b-q	15.2	1.31	1.00	0.70	101	0.86	0.10	0.02	nd	76.0	146	1523	678	21	3.40	1.40

Note: Sample numbers starting 5- are from trench PSS5 and those starting 6b- are from trench PSS6.

scanning electron microscopy with energy dispersive spectrometry (SEM-EDS).

Lead is a challenging element for energy dispersive instruments as the high lead concentration in the samples results in a high absorption of characteristic X-rays of lighter elements due to high mass attenuation. For the XRF analyses a generic calibration curve set up for oxides was used; a calibration curve for lead-rich materials is under development, but was not yet available for this research. The SEM-EDS analyses are based on a ZAF correction procedure and were tested for their accuracy by analysing known lead-rich phases; the results for lead sulphide were within a few percent relative to the ideal stoichiometric composition, indicating that there are no major analytical problems with the major components in these compositionally relatively simple systems. However, minor and trace element data may be less accurate for both instruments.

The samples were prepared for the microscopes follow-

ing standard metallographic procedures. For ED-XRF the samples were prepared as powder pellets after grinding to less than 1.25 $\mu$ m in a rotation mill with an agate set. The SEM-EDS analyses were either spot analyses of the crystals (sulphides and silicates) to establish their composition, or area analyses of the glassy matrix, avoiding the sulphide inclusions, in order to selectively determine the composition of the liquid phase. Five area analyses were performed on different areas of the sample to show their chemical homogeneity/non-homogeneity. The data is given in Table 1 and graphically presented in Figures 13 and 14 (see below).

## Results

Thirteen samples were analysed, including eleven slags (see Tables 1 and 2), one ore sample (6B-2b-g) and one furnace wall fragment (4-3/04a).

The furnace wall stones with slag adhering to them (eg Fig 5) show no alteration by the smelting process, such as traces of burning or newly-formed high-temperature

Table 3: Major element composition of the furnace wall (wt% XRF analysis).

Sample	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	Na <sub>2</sub> O	K <sub>2</sub> O	PbO	CaO	TiO <sub>2</sub>	MgO	ZnO
4-3/04a	64.5	12.3	5.3	2.0	1.5	4.0	0.2	0.7	0.7	0.3

Note: Values quoted are the average of five area analyses by SEM-EDS on different areas of the sample.



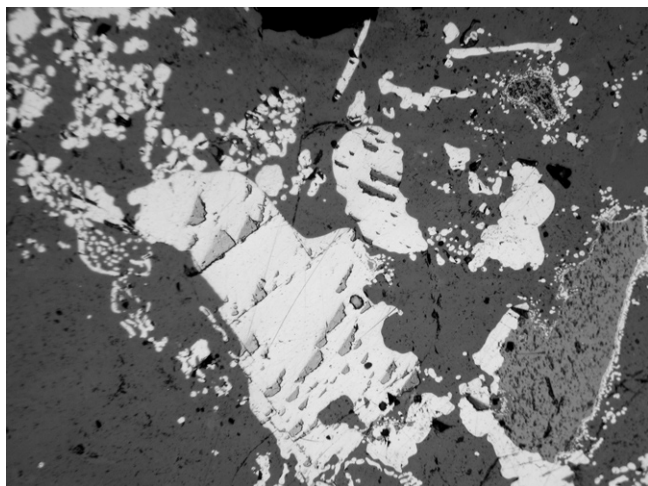


Figure 7: Optical image of slag sample 5-4a showing glassy matrix (dark) and residual galena (light grey) with typical triangular cleavage pattern. Image width 500 $\mu$ m.

minerals: the only trace of high temperature processes are erosion bays where the slag is in direct contact with the rock. The bulk composition of one sample of furnace wall had been determined by XRF (Table 3). The silica:alumina ratio is 5:1, calcium and magnesium oxide are less than 1% and the sum of sodium and potassium oxides is less than 4%. The lead oxide content of 4% indicates some contamination by adhering slag in this sample.

The three unreacted ore samples (eg Fig 6) are mineralogical associations of galena with quartz in different concentrations (from thirty to just a few percent of quartz) and they present the typical triangular cleavage pattern of galena. At least one of the galena samples is also associated with glassy slag, indicating that these ore samples were directly exposed to the smelting process although they obviously did not react fully. Conversely, it is possible to see re-crystallized galena within the glass, and reaction bays between galena and glass (Fig 7) representing more advanced but still incomplete stages of the reaction.

Only some of the micro-analyses of the galena sample (6B-2b-g) showed a local concentration of silver around 0.2wt%, others failed to detect silver altogether (the silver detection limit in EDS is 0.1%) agreeing with the bulk concentration of silver of around 10ppm measured by XRF (Table 2). No silver was detected in the SEM-EDS area analysis of the metallic lead associated with the slag sample 6B-2b-c, and only less than c470ppm during the bulk analyses of either galena or lead metal by ED-XRF.

The slag samples are petrographically all rather homogeneous (Fig 8). The matrix is completely glassy with a

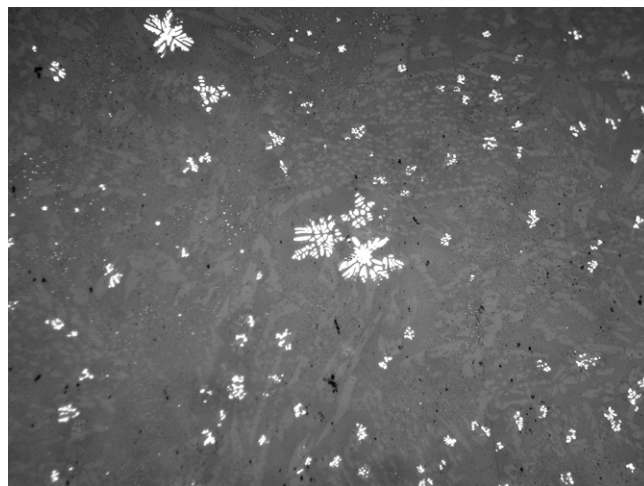


Figure 8: Optical image of slag sample 6B-2b-f showing the glassy matrix (darker grey), silicates (paler grey) and crystalline sulphides (white). Image width 200 $\mu$ m.

scatter of newly-formed opaque crystals with a spherical or dendritic shape, tentatively identified as lead sulphide. The volume proportion of lead sulphide varies within and between samples from a few percent to eight or ten percent. In some of the samples, long needle-like or skeletal silicate crystals were identified. There was no intergrowth between sulphides and silicates, both of them formed separately in the glassy matrix.

The main oxide concentrations in the slag samples as analysed by ED-XRF are shown in Table 2. The slag is dominated by lead oxide (c70wt%) and silica (c15–20wt%) with minor amounts of alumina, zinc and iron oxides. Remarkable is the high sulphur content of c3–4wt%. The bulk analyses confirm the overall homogeneous composition of the slags. The ‘metallic’ component of the slag is dominated by the association lead-zinc with rather low iron oxide, suggesting an ore association of galena-sphalerite with only a minor amount of pyrite. The almost complete absence of copper (below c0.01% in all analyses) suggests the absence of chalcopyrite from the smelting charge. Noteworthy is the low concentration of typical rock components other than silica, which suggests a charge comprising almost exclusively of galena plus quartz.

To further test the possible contribution of furnace wall material to slag formation, the ratio of SiO<sub>2</sub>:Al<sub>2</sub>O<sub>3</sub> in the two materials were compared. In the slag it is between 10:1 and 15:1, while in the furnace wall it is only about 5:1. Obviously there is only a limited contribution of alumina to the slag, resulting from the aggressiveness of lead oxide during the smelting against the wall. The most likely origin of this concentration of silica in the slag is the presence of quartz with the galena during the

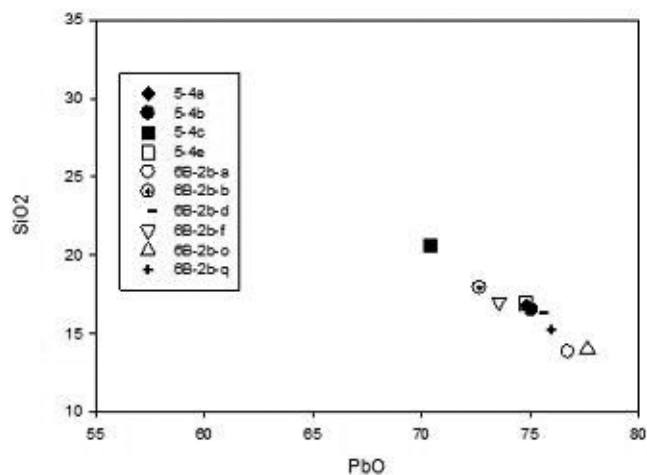


Figure 9: Silica (SiO<sub>2</sub>) and lead oxide (PbO) content of the slag samples from Banc Tynddol (XRF analyses).

smelting. It has to be discussed whether the quartz was added on purpose as a flux, or whether it represents unintentional gangue from the ore. Noteworthy also is the very low concentration of calcium and barium oxide in the slag, in stark contrast to the majority of bale slags from medieval Yorkshire (Smith and Murphy, this volume) reflecting the very different gangue composition of the ores from the two regions.

The SEM-EDS analyses of the glassy or microcrystalline part of the slag (Table 1) confirmed in principle the XRF data. However, sulphur is below the detection limit, the lead levels are slightly lower and the other oxides accordingly increased, reflecting the exclusion of the lead sulphide crystals from the analyses (Figs 9 and 10). The differences may also reflect different calibration and evaluation procedures for the two different instruments, as mentioned above.



Figure 11: Secondary electron image of sample 5-4c showing the glassy matrix (light grey) and associated alumina-silicates (dark grey) and sulphides (white). Image width 200µm.

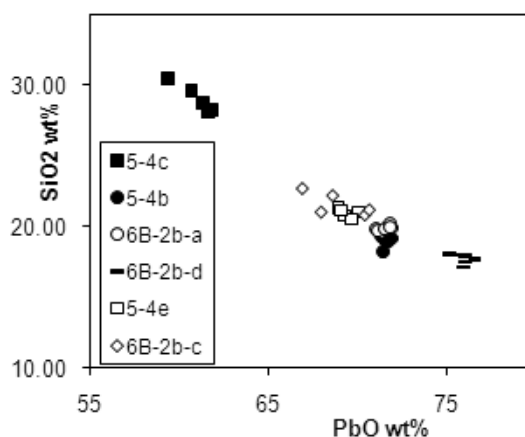


Figure 10: Silica (SiO<sub>2</sub>) and lead oxide (PbO) content of the glassy matrix of the slag samples from Banc Tynddol (SEM-EDX analyses).

During the SEM-EDS analyses different types of slag were identified based on their population of silicate crystals. Some had a fully-glassy matrix, some showed a scatter of silicate crystals seemingly floating freely in the predominantly glassy matrix, and one sample was completely crystalline. The latter sample showed a characteristic spinifex texture; the crystals are thin and skeletal with growth orientation perpendicular to the cooling surface. A further distinction within the crystal-containing slags is based on the different types of silicates present. One type can be described as Pb<sub>4</sub>(Al<sub>6</sub>Si<sub>20</sub>)O<sub>53</sub> (sample 5-4c; Fig 11), another as PbZnSiO<sub>4</sub>, (samples 6B-2b-a and 6B 5-4e ), and the third one (6B-2b-d), showing the spinifex texture and forming a fully crystalline matrix (Fig 12), has a formula similar to PbSiO<sub>3</sub>.

The fully crystalline sample is compositionally no different from the majority of the other samples; its

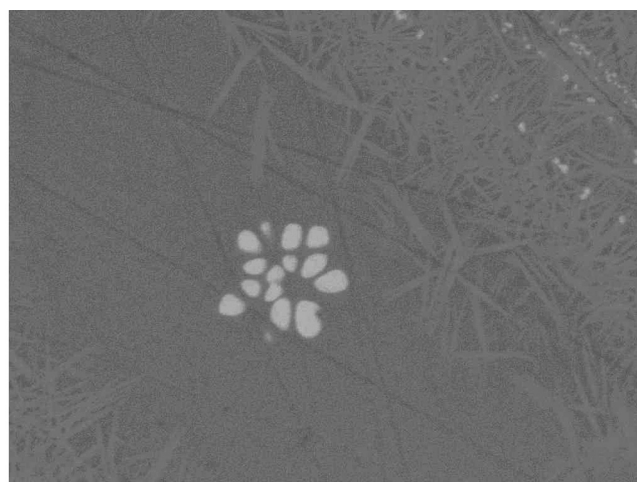


Figure 12: Secondary electron image of sample 6B-2b-d showing sulphides (light) associated with fully crystalline spinifex matrix (two tones of mid grey). Image width 100µm.

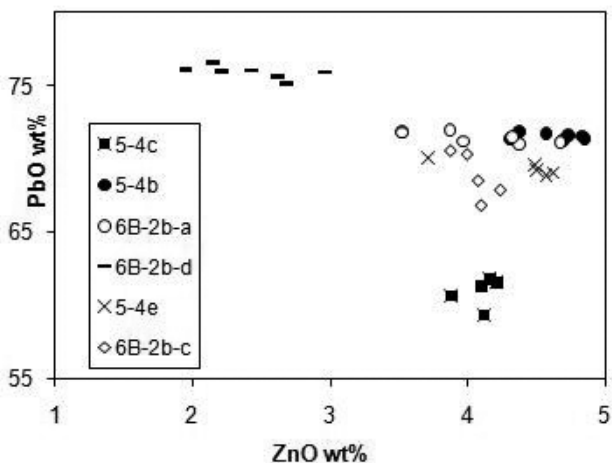


Figure 13: Zinc oxide (ZnO) and lead oxide (PbO) content of the glassy matrix of the slag samples from Banc Tyddol (SEM-EDX analyses).

different structure probably reflects a slightly slower cooling history, with more time enabling crystal nucleation and growth. However, the cooling still took place relatively rapidly as indicated by the spinifex structure. The sample comprising the aluminosilicate crystals has overall higher alumina and silica levels in the glass phase than the other slag samples, and accordingly a lower lead oxide concentration. However, it is not fundamentally different from the other slags, and may simply represent a composition with a slightly higher contribution of absorbed furnace wall material and a richer concentration of residual quartz. Similarly, the two samples with lead-zinc silicates show no apparent compositional peculiarity which would explain the presence of these crystals, so we assume that only slight variations in nucleation and cooling history resulted in the growth of these crystals here.

Figure 13 shows the ratios between ZnO and PbO in the glass matrix, in particular the distinction of the sample 6B-2b-d which has the lowest concentration of zinc in the glass matrix but is also the only one that contains zinc in the sulphides. Sample 5-4c contains zinc only in the glass matrix and is the lowest in PbO. The peculiarity of sample 5-4c is mainly linked to the high silica (and alumina) content (Fig 10); this high concentration affects the concentration of PbO, which is therefore lower in this sample. Sample 6B-2b-d does not have complete decomposition of the sulphides, so we can still note some zinc in them, while the liquidus phase (the glass) is not as enriched in zinc as the other analysed samples. These small differences between the samples, discussed below, are probably connected to the heterogeneity of the system in the furnace, regarding both the chemical

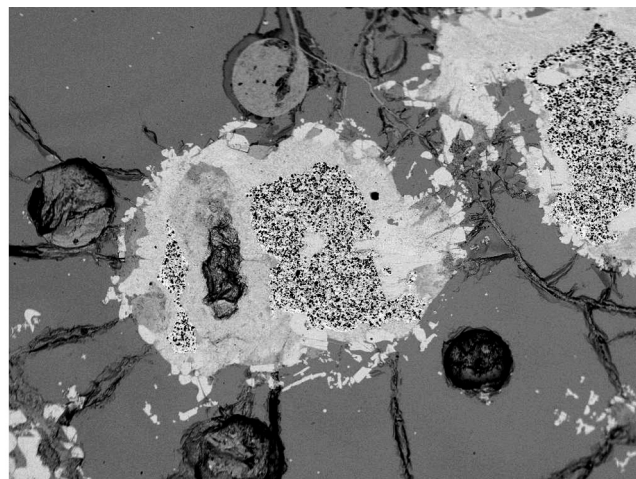


Figure 14: BSE image of slag sample 6B-2b-c showing lead metal (pale grey with black spots) segregating from lead sulphide (light grey). Image width 200µm.

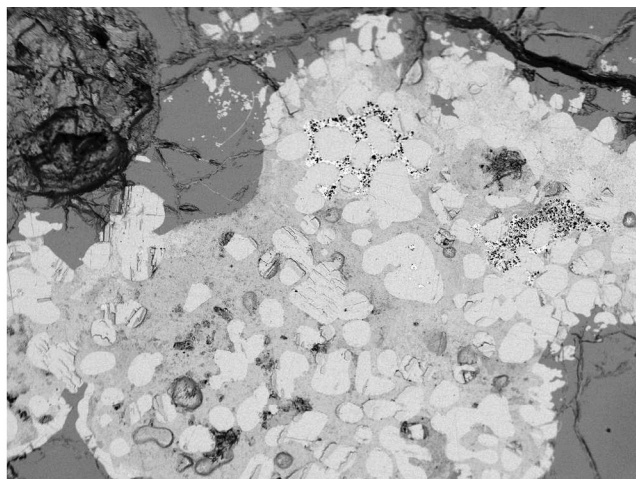


Figure 15: BSE image of slag sample 6B-2b-c showing lead metal (with grey with black spots) segregating from lead sulphide (light grey). Image width 200µm.

diffusion of the elements and the temperature. SEM-EDS analyses of the sulphides invariably confirmed their optical identification as lead sulphide (PbS) with an almost stoichiometric composition of *c*13wt% S and *c*86wt% Pb.

In all the samples larger areas of lead sulphide are visible, forming matte inclusions with segregation of lead metal (Figs 14 and 15); these are apparently formed from the melt rather than being residual or re-crystallized galena. They indicate that the system, even when at a sufficiently high temperature to be fully liquid, was still so rich in sulphur to allow only part of the lead to be present as metal, while some was still forming a separate lead sulphide phase due to incomplete reaction of the charge.

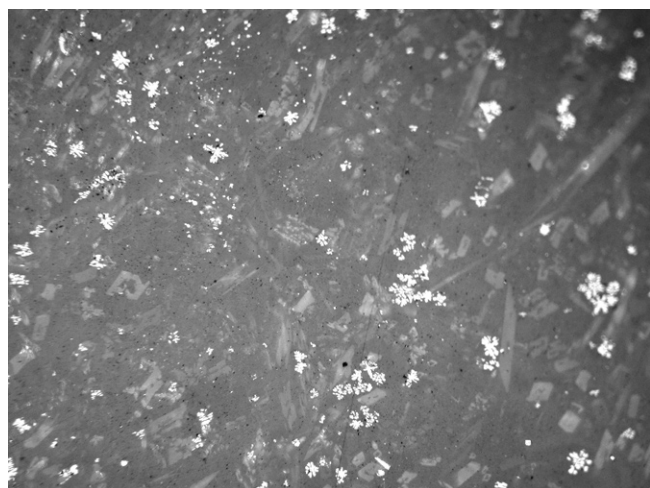


Figure 16: Optical image of slag sample 6B-2b-f showing the glassy matrix (darker grey) and crystalline silicates (pale grey) and sulphides (white). Image width 500 $\mu$ m.

### Interpretation and discussion

The ore smelted was predominantly galena with quartz gangue; some sphalerite and minor pyrite were also present, as indicated by small concentrations of zinc and iron in the slags. The complete absence of carbonate gangue and chalcopyrite would seem to reduce the likelihood that the ore was obtained nearby, either from the Comet or Penguelan mineral lodes at the foot of Copa Hill (Hughes 1981; Timberlake 2003). Instead the most probable near-surface source is the Kingside Lode on the Graig Fawr or where this has been worked by old surface rakes on the northwest slopes of Copa Hill (ST).

Noteworthy are the rather low overall silver levels found in ore, slag and metal. They do not exceed a few hundred ppm, and would therefore not have been economically viable to extract during the Middle Ages. Rehren and Prange (1998) discussed economic cut-off grades for silver levels in Late Bronze Age and Roman lead, and found that silver extraction in these periods is not economical below about 600–1000ppm. No comparable data exist for the medieval period; however, it is unlikely that the cut-off grades would have been significantly lower as early-medieval technology was no more advanced than Roman technology, and large amounts of silver from Central Asia flowed into northern Europe via the Viking trade prior to the 10th century AD.

The very high sulphur content of the slag (around 3wt% compared to the 0.05wt% average indicated for fayalitic slags of the same period by Tylecote (1987, 302)) indicates that the ore was not roasted before smelting, resulting in only partial reduction of some of the metal, and the abundant precipitation of lead sulphide crystals

from the melt. The relatively low level of other ore-related oxides, such as zinc, iron or copper, indicates that the ore was almost pure galena.

The high silica:alumina ratio in the slag, of about 15:1, shows that contamination of the slag from the furnace wall played only a very minor role, otherwise higher alumina levels would be expected in the slag. This indicates that the silica in the slag originates predominantly from the quartz gangue of the charge. The analyses of the glass matrix show the composition of the liquid phase during the process. It is interesting to compare the SiO<sub>2</sub>-PbO data in the glass (Fig 16), which are consistent with the bulk data, with the SiO<sub>2</sub>-PbO phase diagram (Geller *et al* 1934). The data show firstly that the minimum temperature of the process was around 750°C. The composition is mainly at the top of the cotectic curve (~760°C) joining the eutectics at 15 and 30% SiO<sub>2</sub>, except for sample 5-4c whose composition is close to the eutectic richer in SiO<sub>2</sub> (~740°C). These temperatures are for the pure system SiO<sub>2</sub>-PbO but the presence of several minor oxides is likely to reduce these temperatures further. The peculiarities of sample 5-4c are an example of the heterogeneity of the conditions inside the furnace, for the composition of the charge, the role of the furnace lining for the material closer to the furnace wall, and for the temperature inside the furnace. The other point is that at this temperature (~750°C) the slag could have absorbed more silica than it did solidifying following the cotectic line and ending up with a solid at the eutectic at 30% silica. This could indicate that the addition of quartz was not deliberate, the material smelted was simply the ore including the average of gangue already associated with it; and that the medieval lead smelters knew that their raw material was pure enough not to need a further addition of quartz. On the other hand, this makes the slag aggressive against the siliceous stones from which the furnace was built, as can be seen in the erosion cavities at the interface between slag and furnace wall, and the limited uptake of alumina into the slag.

The combination of limited silica in the charge, the highly sulphuric conditions in the furnace and the relatively low temperatures make this an interesting model for a well-balanced furnace operation. This can be considered a technical choice in order to limit the production of slags while maintaining a non-oxidizing atmosphere, which limits the formation of lead silicates. Pre-roasting of the ore could have resulted in higher formation of lead oxide, which would be more aggressive towards the furnace wall rather than increasing the yield through reduction to lead metal. Allowing lead sulphide to form as an excess phase is in contrast less deleterious, and any matte recovered

from the slag could easily have been reprocessed with the next smelt, together with fresh galena. This choice could also be connected with the need for saving fuel for the process in one area where the easy availability of the pure raw material allows the waste of part of the metal as matte.

How does this slag compare with lead slag from other sites? The overall composition of the slag differs significantly from the other known medieval lead smelting sites, indicating a different smelting technology. Murphy (1992) identified three different types of remains from ore hearths: white-coated material, dark-grey black slag and vitreous black slag. The content of lead in those slags varies from 12wt% in the glassy black slag to 17wt% in the dark-grey slag. Both of these are far lower than the concentration of lead in Banc Tynddol slag ( $\approx 65\text{--}70\text{wt}\%$  PbO, Table 3). Other lead-rich slags mentioned in the literature are from Pentre Ffwrndan (Wales) with around 30wt% lead oxide (Atkinson *et al.* 1924–5) and the Pennines, with around 50wt% (Tylecote 1987); still much less than the 65–70wt% found in the slags from Banc Tynddol. The slags from the Pennines are identified as remains of a bole smelting process needing a further step in a slag hearth, while the slags from Banc Tynddol are the result of a one-step process in a hearth furnace. For Banc Tynddol, one can further discuss the slag composition in view of the quantities found during the excavation, and the nature of the furnace installations unearthed. The amount of slag is rather low, so that even if it is lead rich, it will still not represent a major loss in metal. Furthermore, the furnace excavated is a simple and low-cost structure, made of local stones, and most probably wind-blown, compatible with a low-key operation.

## Conclusions

It is argued that the medieval activity at the site was small-scale, smelting a very rich lead ore under conditions which limited the amount of slag produced while at the same time tolerating a rather lead-rich slag.

Considering the remains analysed, the results obtained and the description of a lead smelting process by Tylecote (1987, 112) we get the image of a hearth furnace, with a footprint of about one square metre, completely filled with wood, maybe mixed with charcoal, with different layers of charge in it, but mainly on the surface. When the temperature is high enough (around 300°C) the oxidation reaction (the roasting) would start and the semi-reacted material would begin sinking into the furnace, where the temperature would easily reach 800°C in around two hours with a wind speed of between 4 to 5m/s (based on an experiment carried out by LA on Banc Tynddol

in 2005). At 800°C the reaction between lead oxide and lead sulphide is possible (Tylecote 1987, 112) without the need of a more complex furnace. In the case of Banc Tynddol, in this central area of the furnace the reaction between the oxidized lead and the residual galena or the new-formed matte might have happened at a temperature as high as 1200°C, depending on the size of the furnace. Of course we have to bear in mind that this furnace is an open structure completely dominated by the wind action. In the same experiment carried out in 2005, a difference in temperature in the furnace of 200°C was noticed with a change of only 1m/s in the wind's speed.

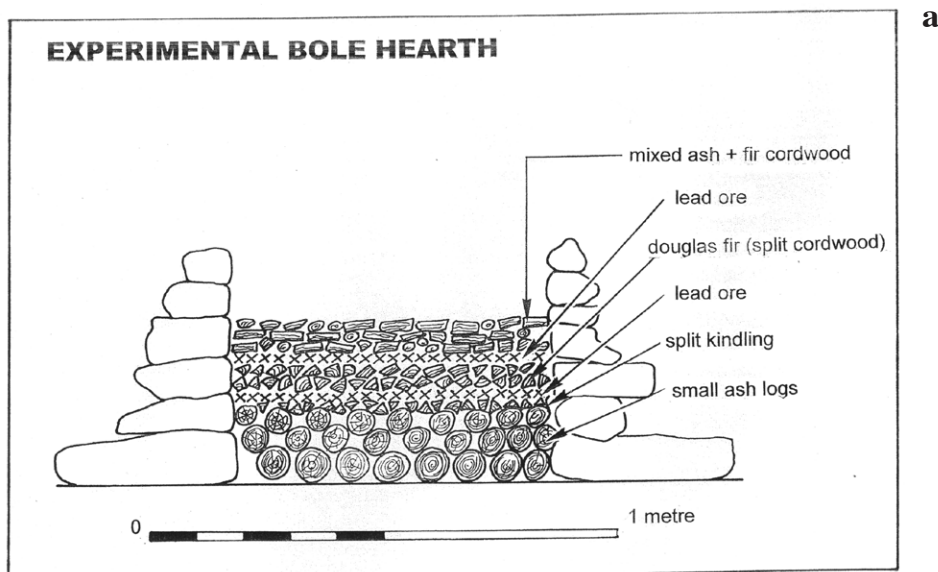
With very pure raw materials, the only slags formed are the ones connected with the presence of quartz and the other few impurities (as Zn and Fe) coming from the charge, and the impurities coming from the degradation of the furnace walls due to the aggressiveness of lead oxide. It looks as if a small amount of quartz was left in the charge, possibly consciously, in order to help purify completely the already fairly pure and massive galena ore, accepting some waste of part of the lead in order to absorb the minor amounts of zinc and iron present within the ore.

The furnaces used apparently did not require much capital investment, enabling a short-lived and/or exploratory-like smelting operation to be conducted. The absence of silver within the lead sample analysed suggests to us that the galena was not exploited to process the lead in order to obtain silver, but only to obtain lead itself. However, we still cannot say with confidence whether smelting was carried out here on a regular basis to produce small quantities of lead metal, or whether these were just test smelts in order to assess the quality of the ore and to assay it as a potential source of silver.

## The experimental reconstruction and operation of a medieval bole hearth at Penguelan, Cwmystwyth (ST)

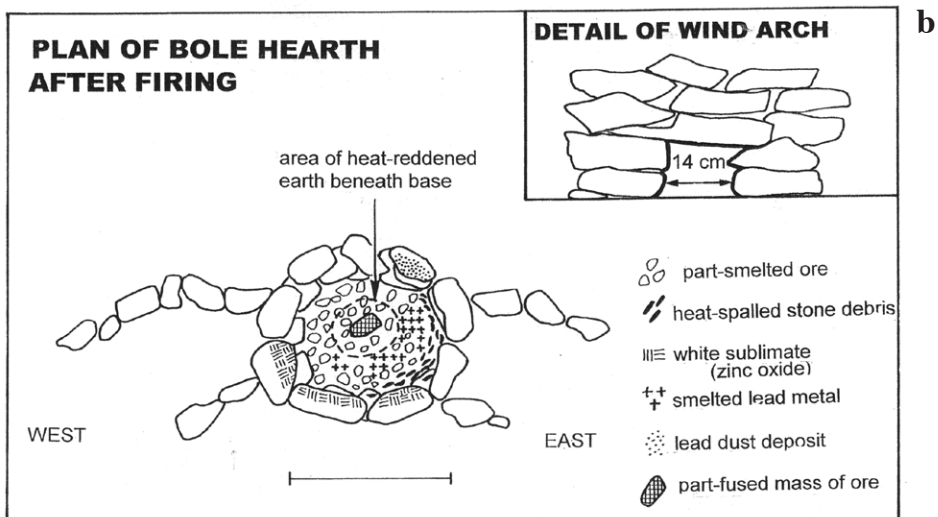
In May 2003, one of the authors (ST) carried out an experimental lead smelt within a dry stone-walled bole hearth constructed on a patch of high ground located on the flattened tips of the old Penguelan Mine, just above the Banc Tynddol meadow and some 25m north of the excavated medieval hearth in PSS 6 (Fig 2c). The experiment tried to reconstruct the sort of hearth which might have been in use at the latter site during the early-medieval period. The intention was to observe the progress and conditions of the smelt and to collect and analyse the smelt products.

Although detailed analysis of these smelt products has



a

Figure 17: The experimental bole hearth. a) diagrammatic cross-section before burning; b) plan after smelting.



b

not yet been undertaken, much information could be gleaned from recording the process in action and also from a visual inspection of the partially-smelted ore and lead metal afterwards. These findings were something of a revelation to our understanding of the process.

The smelt was carried out over a period of three hours on the evening of the 15th May, the significant limiting factor here being the amount of dry, chopped firewood which could be contained within a much scaled-down walled hearth, and also the small amount of hand-picked galena available to us, all of the latter collected within a 500m radius of the site.

The design of the sub-circular dry stone-walled bole structure was loosely based upon the evidence uncovered during the excavation of PSS6, as well as from historical record and field remains of post-medieval

Derbyshire boles such as the Topley Bole Hill (Kiernan and Van de Noort 1992) and from the excavation record of the medieval bole dug at Beeley, Derbyshire in 1967. The latter had been built into the structure of a triple Bronze Age cairn (Radley 1970).

The walls of the Penguelan bole were constructed of flat riverine boulders plus shale and quartz mine waste, and as with the hearth sites found in the excavations in area PSS6 this was constructed directly on top of the turf, without any sort of scooped-out base or hollow underneath. The external dimensions were about 1.5m by 1.2m wide and 0.7m tall, but internally this was no more than 0.65m by 0.45m wide, a space which was compactly stacked to a height of only about 0.35m with split wood (cord wood) and layers of crushed ore (Fig 17a). Built into the base of the walling surround on both east and west sides of the hearth were small openings or ‘wind

arches' and in addition funnel-like projections beyond in the form of two pairs of low stone walls some 1–2m long converging on each of the openings. The latter would act as funnels or wind-tunnels to concentrate the action of the prevailing winds and help raise the smelting temperature within the hearth (these winds were mostly westerly channelled up the Ystwyth Valley from the coast some 20km away). Such a careful arrangement of 'wind gathering' is recorded at Beeley (Radley 1970) although of course nothing at all has survived of any of these above-ground walled structures within the Banc Tynddol excavations. Thus while the use of wind funnels is known about, the actual lay-out of the bole construction at Penguelan was little more than calculated guesswork based on the excavator's own judgement of the topography and wind dynamics of the site.

The experimental hearth was tightly packed with some 74kg of wood composed of alternate cross-wise layers of split 200–300mm by 60–80mm logs of ash and Douglas fir (chosen because of its hot-burning properties) plus brushwood kindling, with all of the thicker and more tightly-packed and un-split large logs stacked at the base, an arrangement similar to that found within the excavated hearth at Beeley, and believed there to have been an attempt to prevent the heavy ore sinking too quickly into the base before being oxidized (Blanchard 1992, 11). Interleaved, in amongst the wood, were some 2–3 layers of crushed galena, most of this in 'hazel nut' to 'walnut-sized' pieces (of a similar size fraction to that recovered from Banc Tynddol (Fig 18)), hand-picked and wherever possible separated from most of the adhering blende and larger pieces of quartz and carbonate gangue. In total the ore charge amounted to some 8.5kg of galena, a ratio of about 1:10 of ore to fuel.

The experimental smelt commenced about 6pm (see front cover for its progress) the bole being lit from the base, with the bulk of the wood quickly catching fire and burning strongly fanned by a variable but strong breeze. At the end of the first 20–25 minutes yellow sulphurous fumes (sulphur dioxide) within the smoke plume indicated an effective roasting of the ore, and some of these gases were collected for analysis. After 6.30pm the breeze increased to small gusts, predominantly from the west, but thereafter this changed to intermittently west and east squalls, resulting in some swirling effect of the fire around the base of the bole site, but not diminishing the rate of combustion. By 6.55pm the wind had died down considerably, but by this time much of the wood had already burnt down. On approaching the bole, a white-blue sublimate deposit (zinc oxide) was noticed on the side of some of the boulders in the walling sur-

round, whilst a yellowish deposit (lead oxide) could be seen on some of the burnt wood around the edges of the fire. Although no accurate record of the temperatures reached inside of the hearth was taken, at this point it was estimated to be around 750–800°C based on visual colorimetry of the still-burning embers and mass of fused/molten ore lying within the base of the bole. One and half hours later these embers were still burning, fanned by a light, steady breeze, but by 9pm this had died down and nearly ceased altogether; the smelting process was probably now at a halt, frozen as the light patter of rain increased, and the wind died.

The results of the smelting were examined the following morning, the overnight rain having washed out the tops of the embers, exposing part-fused galena lumps lying above the burnt clay ground surface (Figs 17b and front cover). The formerly soot-blackened rock of the stone-walled hearth surround was now fire-reddened, and the white deposit visible the day before coating the surfaces of the stones more or less invisible, the latter perhaps washed away or else still further altered. On the northeast side of the hearth a deposit of metallic dust (lead?) had formed on one of the stones on top of the walled surround, while small amounts of galena dust 'blown out' by the force of the combustion or else by the squalls of wind lay scattered over the ground outside the hearth. Flakes of rock 'spalled-off' by the heat of the fire from the stones lining the inside of the hearth wall covered much of the interior of the bole. In both size and appearance these matched well the type of burnt rock fragments found in layer 006b within area PSS6 of the Banc Tynddol excavations. The latter had been found covering the charcoal and ancient burnt turf horizon exposed within the area of the medieval smelting hearth. Many of the rock fragments from the experimental smelt showed some evidence of surface vitrification in the form of brown-green slaggy glazing (lead silicate), some of this being fused together in the fire. Immediately beneath the centre of the hearth a patch of burnt earth indicated the area of greatest heat penetration, whilst just above this was found a large mass of partly fused and smelted lead ore. However, the largest single concentration of lead metal droplets, some joined with pieces of incompletely smelted galena in a network of lead metal runnel, was to be found outside of this central zone, closer to the hearth wall and in particular to the eastern 'wind arch' situated on one side of the furnace.

Effectively the smelting process we had witnessed here was incomplete. The smelt seems to have been frozen in mid-flight, perhaps due to the exhaustion of the fuel,

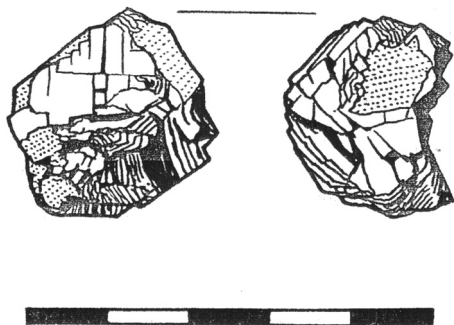


Figure 18: Typical ore charge, a crushed fragment of rich hand-picked galena. Scale 50mm.

a cessation of the breeze and consequent plummeting in the furnace temperature, but also to changes in the oxidizing/reducing conditions prevalent within the hearth. However, what we can see on close study of those part-smelted galena lumps examined (Fig 18) is that there is some evidence for localized oxidation and reduction and then melting and coalescence of the metal into droplets on the external surfaces of the ore pieces. This could also be seen happening in real time as the fire died down, and is recorded in some of the photographs taken looking down into the centre of the hearth. These show lead metal forming like beads of silvery solder on the outside of the red-hot glowing lumps of ore. As the smelting progressed these drops appear to have been gathering into incipient runnels prior to any proper pooling of the metal. The latter does not appear to have taken place, probably on account of the fire having burnt down and the resultant temperature drop. The external texture of many of the ore pieces re-

covered appears similar in some ways to that of melted chocolate (Fig 19), whilst in some pieces this process was rather more advanced, as can be seen in the fragment drawn in Figure 20. Here the original lump of ore appears, literally, to have shrunk and collapsed, leaving the gangue impurities on the exterior with a long runnel of lead metal emanating from it.

All of these fragments of lead metal and part-smelted and un-smelted ore were collected, examined and weighed. Some 150g of the total mass appear to be discreet identifiable droplets, runnels and amorphous lumps of pure lead metal, the remaining 8kg being incompletely smelted ore with minor amounts of lead metal attached alongside adhering lead 'slag' and charcoal. No lead-rich glassy slags similar to those recovered from the medieval hearths in area PSS6 appear to be present, not surprising in view of the much lower temperatures and only poorly-reducing conditions achieved. However, some interesting insights into the process had been achieved, and some useful parallels could now be drawn.

**Conclusions**

The achievement of an 'unsuccessful' smelt has in some ways been much more useful to us than if it had all gone well and we had been left with a separated pool of lead metal and 'slags'. Being able to observe the process 'frozen' in mid-smelt afforded us a rare insight into the way the metal forms and the way it is liberated from the ore (at least under these poorly-reducing and relatively uncontrolled smelting conditions). In effect the smelting appears as a one-step process of virtually simultaneous oxidation and reduction from sulphide to metal without any oxide stage being visible. This con-

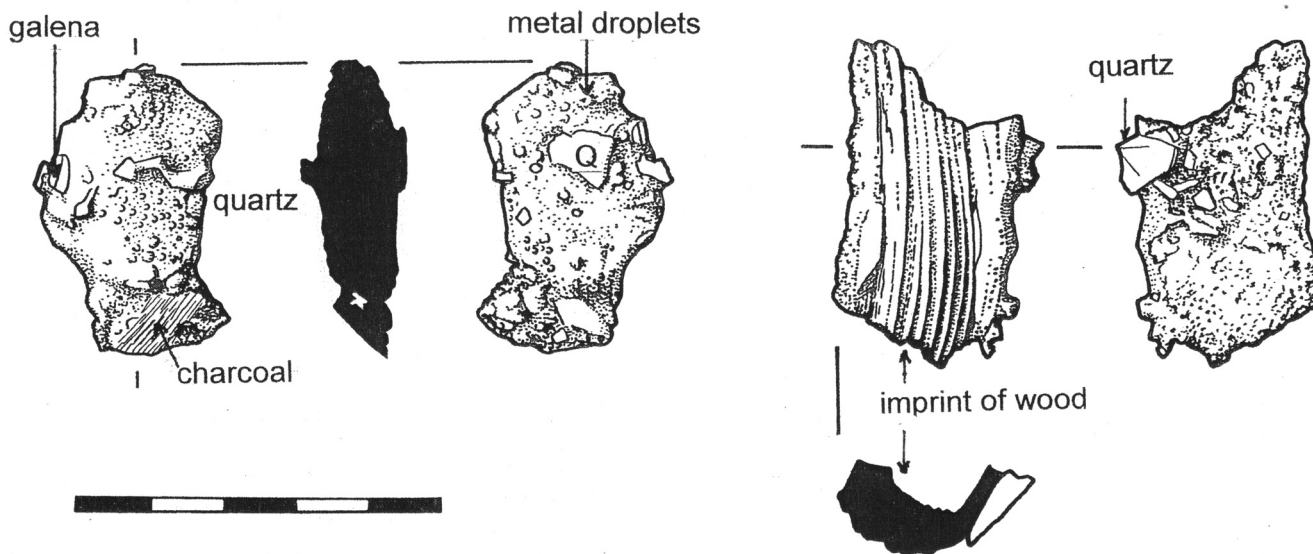


Figure 19: Part smelted and fused galena coated with lead metal droplets and impression(s) of burnt wood. Scale 50mm



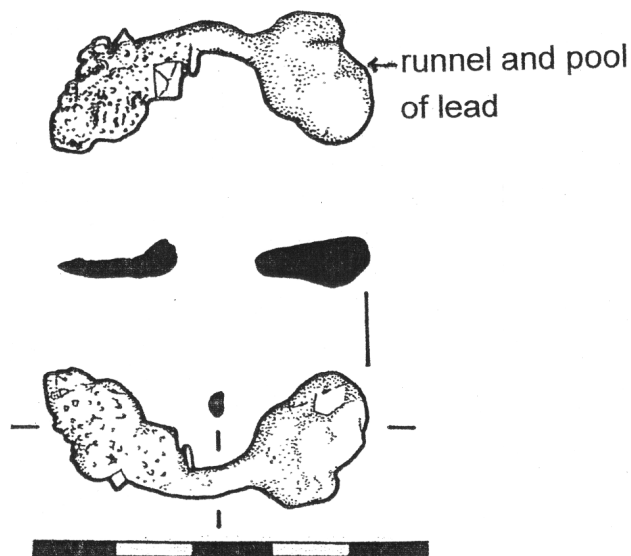
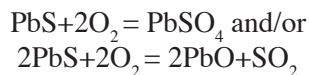


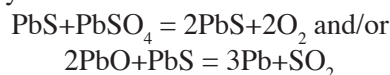
Figure 20: Almost fully-smelted galena, the original ore lump has collapsed and has a runnel of lead metal emanating from it. Scale 50mm.

firms the interpretation offered for the process of bole smelting described from the medieval hearth at Beeley in Derbyshire (Blanchard 1992, 11), with the oxide reacting directly with the un-roasted ore as shown in the following equations:

oxidation:



followed by simultaneous reduction:



One wonders whether under more oxidizing conditions, but with sufficient fuel and duration of smelt, these primitive boles might actually have been more efficient. Where too-reducing conditions are met with in parts of the hearth, lead sulphide will re-form, whilst too hot and reducing conditions may result in the deposition of eutectic lead-glass slags, resulting in an overall loss in lead metal yield. The latter seems to have taken place, to a greater or lesser extent, within the medieval boles excavated at Banc Tynddol, though here the presence of such slags might just represent the outcome of one or more unsuccessful smelts within a sequence, or a minor part of an otherwise successful smelt and yield of metal, or else an attempt at re-smelting lead slags gathered from elsewhere. Larger boles may proportionately have produced rather more slag and also experienced much greater lead loss, yet overall these would probably still have been more efficient on fuel relative to the amount of lead metal produced.

At Banc Tynddol the presence of a significant amount of cobbled and only part-smelted galena also attests to a problem of insufficient temperature and/or duration of smelting within some parts of the bole pile, and in that respect at least the similarity of the experimental hearth reconstruction to whatever sort of bole structure may have been in use during the early-medieval period is probably close. Moreover, there seems little doubt that the dynamics and efficiency of these boles would always have been difficult to control, particularly when subject to the vagaries of wind and changeable weather. Nevertheless, careful choice of weather conditions, for example choosing a period which was experiencing a series of constant, prevailing, and dry winds (such as one might occasionally find in May/June or September/October) might considerably aid the efficiency of the smelt and yield. This is just the sort of area that now requires a considerable amount of experimental investigation, and one for which historical records have so far yielded little.

With respect to the wind effect it was therefore particularly interesting to find that the greatest production of lead metal within the experimental hearth occurred around the margins of the bole closest to the two 'wind arches', in particular the eastern opening. This may suggest that smelting was most effective at the interface of the most oxidizing and reducing conditions within the furnace. Furthermore the much smaller galena fragments do not appear to have undergone smelting any more effectively than the larger 'walnut-sized' pieces. In fact, the evidence we had suggested that the ideal size of ore particle for smelting under these conditions was about 10–20mm ('hazel nut' size), something supported also perhaps by the archaeological evidence from area PSS6 at Banc Tynddol where this size of cobbled ore fragment is commonly found both underneath and around the site of the former hearths.

There are many individual variables which need to be tested in future experiments, including the dimension of boles, the quantities and ratio of ore to fuel, the methods of stacking, the type of walled hearth surround, the presence or absence of 'wind arch' openings and funnels, and of course the all-important factors of wind speed, wind constancy, temperature and dryness. Continuous monitoring of the latter during the smelting alongside a record of the various temperature(s) reached within different parts of the bole stack would be a very useful aid to understanding the factors affecting the success of the smelt and the efficiency of lead yield. Clearly 'freezing' the smelt at different stages in its progress can help us to understand the process a good deal better. One

way to do this would be to rake out the burning hearth or possibly to quench it. Needless to say, there are important health and safety considerations to address in trying to attempt this!

Opportunities available today to carry out such experiments on lead furnaces in the open together with the permission of landowners and statutory conservation bodies are becoming rarer and rarer. In this respect we have been very fortunate, although there are of course risks inherent in carrying out the work, in particular conducting close-up photography during the smelting process. Partly for this reason the boles have been kept small and their operation limited to just one or two people at a time. It would certainly be desirable now to repeat the above process exactly, using the same amount of ore but with slightly more fuel, and carried out under much more constant wind conditions.

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