Tin smelting slags from Crift Farm, Cornwall, and the effect of changing technology on slag composition

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ABSTRACT: Tin-smelting slag from an early medieval site at Crift Farm in Cornwall was analysed using SEM/EDS. A comparison was made between the chemical composition of this slag, which was produced by a simple hand-blowing technology, and slag from seven tin-working sites of later date which employed a more sophisticated water-powered blowing-house technology. The chemical compositions of areas within single pieces of slag were found to be highly variable. This is suggestive of a highly viscous material, with little mixing during smelting. The Crift Farm slag was found to have a chemical composition sufficiently similar to the later 'blowing house' slags that it could not be distinguished from them by this method of analysis.

Introduction

The south-west of England has a long history of tin-working, from prehistory to the recent past. However, knowledge regarding the methods of tin-smelting prior to the 16th century is scant. By the 14th century substantial water-powered mills termed 'blowing houses' were in use; the earliest reference being to a 'blouynghous' at Lostwithiel, Cornwall, in 1332 (Hatcher 1970). It remains unclear when this development was first introduced and how rapidly it replaced the previous technology (*ie* hand-blowing). Evidence for tin-smelting sites which date from before the time of the blowing houses is extremely rare.

One example of such an early smelting site was discovered at Crift Farm in Cornwall (SX067602) in 1975 (Fig 1). Subsequent excavations revealed a three-roomed building in the style of a Cornish longhouse (Fig 2), which had associated with it ore-processing tools and a waste-dump containing an estimated five tonnes of tin-smelting slag. This would represent many episodes of smelting. Carbon-dating of charcoal recovered from the site indicated that it was in use *c*1200 AD (Buckley and Earl 1990) and this is supported by typological dating of pottery.

The building at Crift Farm (Fig 3) differed from a typical blowing house in several particulars other than style of construction. Documentary sources describing blowing houses state that the availability of water was essential (Greeves 1981), and evidence of leats and waterwheel mounts are clearly visible at several blowing house sites such as Week Ford and Outer Down in Devon. The situation of the site precludes the use of water power, since at 180m OD it is above the spring line and no

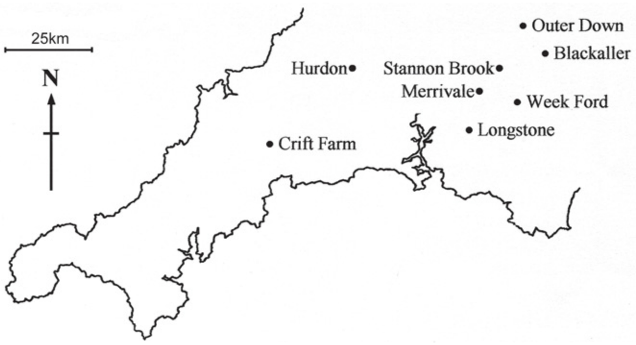

Figure 1: Map showing locations of tin smelting sites in Devon and Cornwall.

Figure 2: Area of the main excavation at Crift Farm, viewed from the south.

streams run along the heights of Crift Down. Further, no archaeological remains of the provision of water power were observed at Crift Farm.

A small amount of slag from Crift Farm has been analysed previously (Tylecote *et al* 1989, Adriaens 1996), but a more extensive study was carried out in order to determine the level of intra-site variation in morphology and composition. In addition, since the site appears to represent an earlier technology than that employed at the blowing houses, a comparison with blowing house slags was made to study the effect of advances in smelting technology. The main difference is one of scale: use of water power would have allowed a greater volume of ore to be processed, and furnaces could be operated under more stringent conditions, *eg* higher temperatures and/or more reducing conditions.

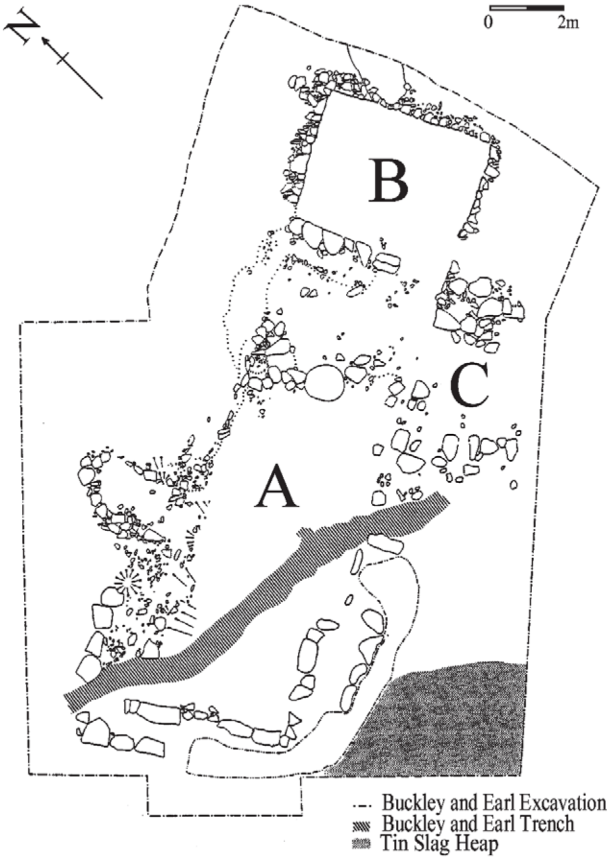

Figure 3: Site plan of the Crift Farm excavation at the end of the 1994 season.

The large quantity of slag in the dump to the south west of the building is unusual. According to contemporary accounts of blowing houses, reprocessing of slag was undertaken, which usually involved crushing the slag, (Gerrard 1986, Earl 1991), and it is assumed that this practice was a continuation of earlier working methods. It might therefore be expected that the amount of slag remaining unbroken on any site where reprocessing was carried out would be minimal. The fact that slag which is of relatively uniform size occurs in such an unprecedented quantity suggests smelting rather than reprocessing as the prime activity at Crift Farm. No areas of finely crushed slag were observed during excavation. In addition, compositional analysis of the slag carried out by the authors, and subsequently by others, indicates that the material is consistently tin-rich.

Given the small size of the prills (<1mm), recovery by hand from crushed slag is unlikely. Panning would be one possible method of separating metal from slag, however the Crift Farm site lacks a suitable water supply.

Excavation

The site was found during ploughing by one of us (E H). It was first examined by Buckley and Earl (1990). Three seasons of survey and excavation by Bradford University showed that the site comprised two buildings, one of which was the focus of the earlier excavation (McDonnell 1993, 1994).

The detailed excavation revealed a medieval longhouse with walls 1m thick, faced inside and out by large granite boulders. The presence of ceramics and a domestic hearth indicated living accommodation at the north end. At the south end a central drain ran down the building, interpreted as evidence for keeping stock. Subsequently the building was altered to retain its domestic occupation, but to change the activity to metallurgy with a waist-high forge in the south end of the building, and tin smelting in an annex added to the east. The small room at the north end probably represents an addition to the domestic part of the building in either its primary or secondary use. At the south end of the building was an extensive spread of tin slag. Although no evidence for a furnace was identified on the Crift Farm site, evidence for crucible-smelting in ceramic vessels is also lacking. It is therefore believed that smelting was carried out using furnace technology in the form of a raised structure, which would leave little or no trace in the archaeological record.

Methods of examination

Approximately 20kg of slag retained during the excavation was examined, sorted and classified into different morphological types.

The approximate melting point of the Crift Farm slag was determined using an electric furnace. Pieces of slag were heated under charcoal for one hour in a clay/graphite crucible, in order to create a partially reducing atmosphere, then were subsequently poured out to determine the relative ease of flow.

Eleven pieces of slag from Crift Farm, and one piece from each of seven other sites in south west England were cold-mounted in resin and polished for examination by optical and scanning electron microscopy. Quantitative analysis of the chemical composition of the slags was carried out using SEM/EDS (beam potential 20kV, filament saturation 3A, working distance 15mm, raster scan at 500x magnification). The area scans avoided visible tin prills (>5 μm) and therefore represent the slag composition.

Scanning electron microscopy allows elements to be detected at levels down to 0.1% by weight under ideal conditions. However, overlapping of peaks in an X-ray spectrum due to the presence of other elements will increase the error for those elements. Where this occurs, 0.5% should be considered as lying at the limit of detection.

The results are presented in Tables 1 and 4, the data for some Blowing House sites (Hurdon, Stannon Brooke and Week Ford), were normalized due to instrumental drift. The calculation of concentration by weight performed by the SEM analyser is not straightforward. The result will vary depending on whether the calculation is based upon the atomic or oxide weight of any particular element, some of which may additionally occur in more than one oxidation state. It is not possible to determine the oxidation states of the elements within the slag, and therefore assumptions must be made regarding the form in which each element exists. Hence, the sum of percentage concentrations may not equal 100%. The level of error in the concentrations quoted is greater for analyses where the sum is not equal to 100%.

The Crift Farm slag

Visually, the Crift Farm slag matrix resembles dark glass. It is predominantly black, but colours range from very dark brown through grey to black, with faint lighter brown banding occasionally visible to the naked eye. Within the matrix, millimetre-scale gas bubbles and granitic inclusions are often visible.

Two morphologically distinct types of slag have been noted (Fig 4). The most common is an irregular rod-shaped tap-slag, typically 10mm in diameter and broken off to 10–30mm in length; there is also a considerable amount of slag which has adhered to rounded pieces of granite. This granite is often seen to be heat-reddened or partially 'melted'.

Experimental melting indicated that at 1000˚C the slag deformed under its own weight, but pouring was not possible; at 1050˚C it poured, but with difficulty and at 1100˚C it poured slowly to form rod-like shapes similar to those described previously. Thus it can be assumed that the temperature in some part of the furnace reached at least 1100˚C. The presence of melted granite would suggest a significantly higher temperature. Samples of fresh granite from Crift Farm heated under charcoal in a clay-graphite crucible for 30 minutes showed slight

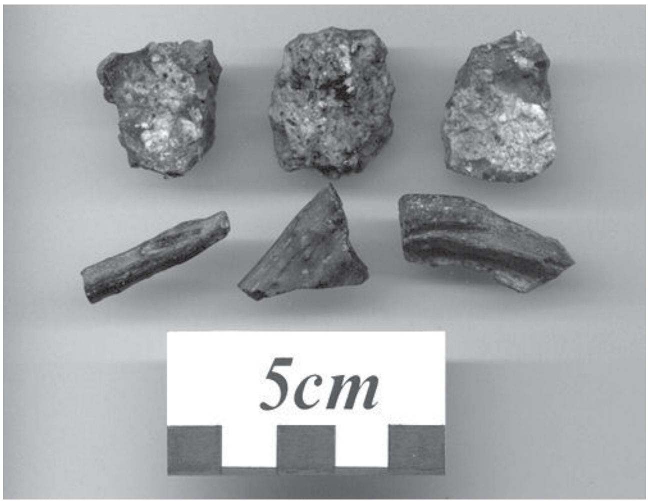

Figure 4: Slag from Crift Farm showing flowed tap-slag and slag with granitic inclusions. Analysis was not carried out on the examples shown. All analysed samples had features typical of tap-slag, with the exception of A4 which was granitic.

deformation of some of the mineral crystals only when temperatures were raised to 1250˚C. However, when in contact with slag, the granite underwent noticeable alteration at 1100˚C. The alteration of the granite is in fact due to a chemical reaction between the molten slag and the granite.

Optical microscopy revealed that the Crift Farm slag was composed of a glassy matrix with no distinct crystalline phases. It contained metallic prills and variable quantities of granitic inclusions (Fig 5). Small needle-like structures were also observed (Malham 1996, Aylett 1996).

SEM analysis of the metallic prills contained in several of the Crift Farm slag samples showed that they were tin (>99% Sn) with no significant impurities. Iron was present at levels at the limit of detectability.

The chemical composition of the slag, as determined by SEM analysis, is shown in Table 1. It is seen to be composed largely of silica with significant amounts of alumina and tin oxide. Iron oxide is also present, and although this element enters the furnace as an impurity, it fulfils the role of a fluxing agent for the tin. The presence of iron is therefore important since the deliberate addition of the most effective flux, lime, did not come into practice until relatively modern times (Earl 1991, 74).

Within a single sample of slag the composition is variable, and this can be related to the light and dark banding which is sometimes observed even when examining the slag by eye. Light areas are enriched in tin in relation to darker areas (Aylett 1996, Adriaens 1996). The high viscosity of the slag precludes mixing inside the furnace, even if it is allowed to pool at the base of the furnace prior to tapping.

The chemical composition of the Crift Farm slag as a whole demonstrates even greater variation than is seen within a single piece of slag. This may be explained in two ways. Firstly, there will be variations in the conditions within the furnace during the course of a single smelt, with more or less tin being reduced from the ore at different times. Secondly, each time tin is smelted the elemental composition of the charge entering the furnace may vary slightly.

Sample A4 in Table 1 is an example of the rounded granitic slag. A4.1 and A4.2 represent the glassy matrix, while A4.4 is the central part of a granite inclusion and A4.3 is a lighter coloured area around the inclusion. The main body of the inclusion is seen to be largely silica, probably deriving from crystals of quartz within the granite, whereas its outer edges are mostly alumina and silica with higher than average levels of potassium and sodium oxides, a composition typical of feldspars. This suggests that while there is some reaction between granitic minerals and slag, conditions are such that there is only partial mixing of constituent elements (Aylett 1996). It is not clear whether the inclusions are gangue minerals associated with the ore, or if they are pieces of the furnace wall which have broken away.

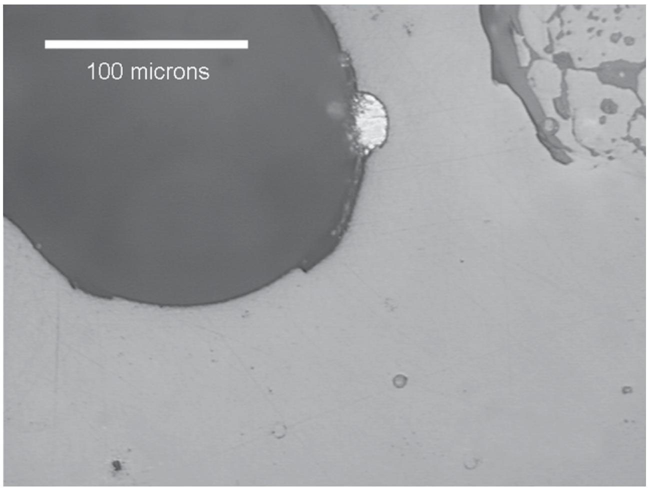

Figure 5: Vitreous slag from Crift Farm showing tin prills and granitic inclusion. Magnification x 270. The sample shown was not analysed, but is typical of the Crift Farm slags.

Based upon the archaeological and documentary evidence, the components of the furnace charge are tin ore (cassiterite), gangue minerals mainly from granite, and charcoal fuel. There is also the possibility of chemical reactions occurring between the slag and the body of the furnace, which may or may not have been lined with clay.

Preliminary studies to determine the probable sources of the elements present in the Crift Farm slag have been undertaken (Aylett 1996). The average composition of the glassy matrix of the slag was compared with a typical Cornish granite, which consists of a number of minerals, the most common being quartz (silica), the alkali feldspars orthoclase (potassium aluminium silicate) and albite (sodium aluminium silicate), and biotite mica (magnesium aluminium silicate). Amounts of iron, titanium, aluminium and magnesium in the slag were seen to be greater than the amounts of these elements present in the granite, and thus they can be attributed to sources other than granite (Table 2).

Cornish cassiterite is not composed of pure tin oxide, and typically contains impurities amounting to around 18% of the total weight. Of these, silica and iron oxides account for the majority (Tylecote *et al* 1989, 442). Since the iron content of cassiterite is approximately five times that found in a typical granite, the ore would be the main source of this element in the slag.

Table 1: Results of SEM/EDS analysis of Crift Farm slags

Sample No.	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	CuO	SnO	WO_3	SbO_2	Total
4a	3.3	4.6	15.5	46.2	0.8	1.6	1.2	3.6	0.2	8.5	0.3	14.4	0.7	0.6	101.5
4b	2.5	4.4	14.7	46.8	0.6	1.6	1.1	3.6	0.1	8.5	0.1	13.6	0.8	0.2	98.6
10a	2.0	4.8	13.6	40.3	0.5	1.8	0.5	5.3	0.4	8.0	0.1	23.8	1.0	0.5	102.6
10b	2.1	4.3	12.8	41.0	nd	1.9	0.7	5.7	0.4	7.7	nd	22.2	1.1	0.3	100.2
10c	2.3	3.0	12.4	52.6	0.4	2.6	0.3	3.6	0.1	5.9	0.2	18.7	1.1	nd	103.2
10d	1.8	4.2	12.5	38.7	0.6	1.8	0.6	5.2	0.4	7.7	0.4	20.6	0.8	nd	95.3
16b	4.2	4.4	16.2	41.5	0.4	2.0	0.7	2.7	0.2	6.2	0.2	17.9	0.6	nd	97.2
16c	5.6	5.2	16.7	42.0	0.3	1.8	0.5	2.4	0.2	6.5	0.2	17.4	0.6	nd	99.2
16d	3.9	3.5	15.1	39.2	nd	1.7	0.7	2.6	0.2	6.1	nd	20.1	0.6	0.2	93.9
16f	4.6	4.0	15.6	40.0	0.3	1.8	0.7	2.5	0.2	6.2	nd	18.2	0.6	nd	94.1
17a	3.4	4.5	16.4	46.8	0.8	1.6	0.8	3.2	0.9	8.5	0.2	16.9	0.6	0.1	104.7
17b	3.3	3.2	15.5	46.2	0.8	1.5	1.0	3.1	0.2	8.7	0.2	16.4	0.6	nd	100.7
17c	2.8	3.8	16.3	46.8	0.6	1.6	0.7	3.1	0.1	8.2	0.1	13.4	0.3	0.2	98.0
17d	3.0	3.7	15.3	44.7	0.7	1.4	0.9	2.9	0.1	7.9	0.1	16.5	0.8	nd	98.0
17e	3.2	4.3	16.0	46.8	0.6	1.4	0.7	2.7	0.1	8.0	0.2	17.9	0.3	nd	102.2
17f	3.4	4.3	16.1	46.0	0.9	1.4	1.0	2.7	0.3	8.1	0.3	17.5	0.3	nd	102.3
18a	3.5	5.3	13.6	47.1	1.0	2.7	0.9	6.0	0.4	7.0	0.3	10.0	0.5	0.3	98.6
18b	3.1	4.6	13.1	47.4	0.9	2.4	0.7	5.4	0.3	7.0	0.2	11.3	1.0	nd	97.4
18c	5.2	4.8	13.1	44.3	0.5	2.6	1.0	5.9	0.4	6.8	0.3	10.6	1.0	0.3	96.8
18d	3.1	4.7	13.3	45.5	0.5	2.6	0.8	5.2	0.2	6.5	0.3	11.8	0.3	0.3	95.1
18e	2.5	4.9	12.4	45.4	0.7	2.2	0.8	5.6	0.3	6.8	0.1	12.5	1.2	0.1	95.5
18f	2.6	5.5	15.1	53.0	0.9	2.8	1.0	6.3	0.4	6.7	0.1	10.2	0.7	0.5	105.8
A4.1	3.4	5.2	20.4	50.1	0.5	1.9	0.6	2.5	0.4	6.0	0.1	12.9	0.8	0.2	105.0
A4.2	3.5	4.9	20.9	52.8	0.2	2.1	0.5	2.0	0.3	6.0	0.1	13.9	0.5	0.4	106.1
A4.3	5.1	0.3	17.0	73.7	0.6	12.4	nd	nd	nd	0.5	nd	0.4	0.1	0.5	110.6
A4.4	nd	nd	0.1	81.5	0.1	0.1	nd	nd	nd	0.2	0.1	0.4	0.1	nd	83.1
B2.1	2.6	4.4	17.7	49.0	0.6	1.4	0.6	3.0	0.2	8.9	0.1	18.7	0.6	0.3	108.1
B2.4	1.1	2.6	41.8	38.2	0.4	0.7	0.3	2.0	0.2	6.2	0.1	7.2	0.7	nd	101.5
19a	2.1	4.9	13.5	49.1	0.6	1.9	0.5	4.4	nd	5.7	0.3	18.1	1.4	0.4	102.9
19b	2.9	4.9	13.7	16.5	0.4	2.1	0.7	3.9	0.2	3.9	0.1	14.0	0.2	0.6	94.1
19c	2.2	4.5	13.4	47.4	0.3	2.3	0.8	4.6	nd	5.6	0.3	15.8	1.0	0.7	98.9
19d	2.4	4.6	13.2	46.3	0.5	2.2	0.8	4.4	nd	5.4	0.2	13.8	0.5	nd	94.3
19e	1.9	4.5	13.3	46.1	0.5	2.2	1.0	4.3	0.2	6.1	0.1	17.6	0.6	0.1	98.5
19f	2.9	4.9	13.2	47.5	0.3	2.3	0.8	5.0	0.3	6.1	0.1	15.8	0.4	nd	99.6
20a	3.6	3.6	17.0	39.9	0.2	1.7	0.7	2.5	0.5	6.6	0.2	19.1	1.6	0.3	97.5
20b	3.4	3.9	17.5	40.0	0.4	1.7	0.6	2.4	0.2	6.7	0.2	17.2	1.9	nd	96.1
20c	4.5	4.3	18.8	40.6	0.5	1.6	0.5	2.5	0.3	6.7	nd	17.1	1.6	nd	99.0
20d	4.1	4.4	17.4	40.2	0.3	1.9	0.8	2.4	0.5	6.6	nd	18.2	1.1	0.3	98.2
20f	3.9	3.5	18.2	40.6	nd	1.7	0.8	2.4	0.4	6.5	0.3	16.4	1.5	0.1	96.3

Note: oxides as wt%; nd = not detected.

Table 2: Comparison of metal oxide:silica ratios for granite and slag.

	GRANITE		SLAG	
Element	Wt% oxide	Wt ratio metal oxide: silica (x 10^3)	Wt% oxide	Wt ratio metal oxide: silica (x 10^3)
SiO_2	2.3	3.4	15.2	44.1
TiO_2	2.8	3.7	16.1	45.9
Al_2O_3	2.9	3.6	14.9	40.9
FeO	3.3	4.4	16.0	44.8
MgO	2.8	3.4	14.9	43.0

Data for granites from Palmer and Eastbrook 1999 74; slag data is the mean result from Crift Farm slag.

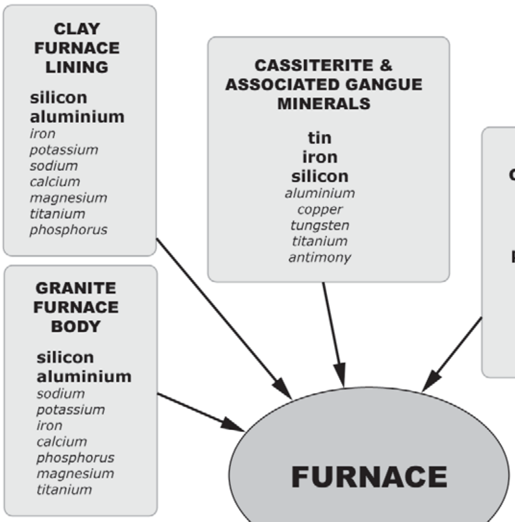

Figure 6: Flow chart illustrating probable origins of elements found in tin-smelting slag. Major components are shown in bold, minor components in italics.

Documentary sources state that charcoal from both peat and wood was used for smelting in the medieval period (Earl 1985, 154). In this study the chemical composition of wood ash was used to represent the input into the furnace from the charcoal fuel; this varies with tree-species and also from region to region, however the major constituents of wood ash are calcium, phosphorus, magnesium and potassium. It also contains minor amounts of silicon, manganese and sodium (Sanderson and Hunter 1981, Thomas 2000). Given the large amount of fuel consumed during a smelt, a significant contribution to the make-up of the slag must be made.

A clay furnace lining, if used, would be another source of silica and alumina. Figure 6 summarises potential sources of the elements contained in the Crift Farm slag.

Blowing House slags

Documentary evidence places the introduction of the blowing house at around the early 14th century (Greeves 1981) and indicates that they were falling out of use by 1700 AD, after which time tin ore was smelted by the reverberatory process (Earl 1991). However, the dates during which particular blowing houses operated are mostly unknown, thus at present it is not possible to comment on how the technology changed over time and how this relates to slag morphology and composition.

Details of the blowing houses from which slags were obtained are given in Table 3. Locations are shown in Figure 1. All slags were unstratified surface finds.

The small number of slag samples from the blowing houses precludes all but a general description of their physical and chemical properties. However, certain

Table 3: Locations of tin-smelting sites and details of slag finds.

Name of Site	Smelting type	Ordnance Survey NGR	Description
Crift Farm, Cornwall	hand-blown	SX 067 602	slag dump to SW of building
Blackaller, Devon	water powered	SX 7377 8377	slag found in river gravel on bank opposite blowing house
Hurdon, Cornwall	water powered	SX 210 823	slag found in disturbed earth to N of earthwork; remains of blowing house
Longstone B, Devon	water powered	SX 5607 6880	slag found close to the blowing house on edge of reservoir
Lower Merrivale, Devon	water powered	SX 5527 7535	slag found inside blowing house to E of furnace
Outer Down, Devon	water powered	SX 6821 8658	slag dump to N of blowing house
Stannon Brook, Devon	water powered	SX 6485 7955	slag found in earth bank close to remains of blowing house
Week Ford, Devon	water powered	SX 6619 7234	slag found on river bank at bottom of slope below the blowing house

similarities in appearance can be noted. They are black in colour, several have a vitreous lustre, although others are more matt and do not greatly resemble glass to the naked eye. The Blackaller slag was stained with iron oxide and contained some relatively large gas bubbles. Several examples of rod-like shapes, suggestive of flow of a highly viscous material, were observed in slag from Longstone, Hurdon and Merrivale. The pieces of slag were in general rather small, some less than 10mm in length, but these had clearly been broken off larger pieces. Siliceous inclusions, mostly measuring less than 1mm, were common to all. Sub-millimetre prills were visible in the Hurdon slag. Optical microscopy subsequently revealed prills to be present in the slags from all seven sites, the number of prills being roughly comparable with the Crift Farm slags. No crystalline phases were present, other than the siliceous inclusions (Fig 7).

Qualitative SEM analysis of tin prills in slag from Hurdon, Outer Down and Longstone showed that they were composed of tin with no significant impurities.

The chemical composition of each of the slag samples was determined from six area scans across their surfaces. The results of these analyses are given in Table 4, and show that the blowing house slags have a characteristic composition. They are silica-based glasses containing significant amounts of aluminium, tin and iron oxides, lesser amounts of sodium, magnesium, phosphorus and calcium oxides, and widely variable amounts of titanium and tungsten oxides. Analyses from individual sites appear more consistent than those from Crift Farm, however comparing these results with published data (Tylecote *et al* 1989) indicates that this is almost certainly due to smaller sample sizes.

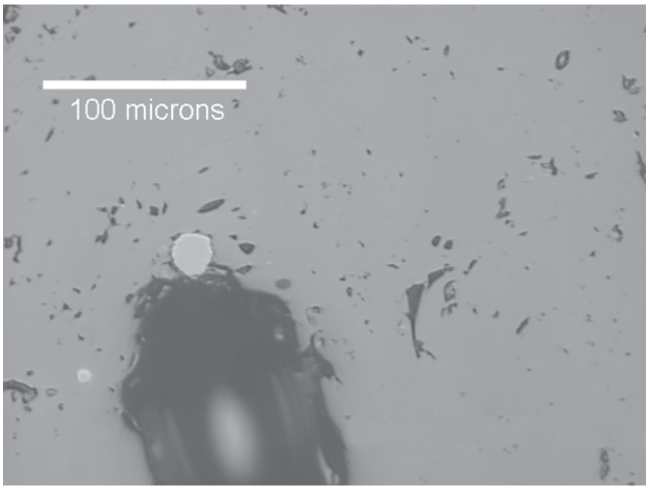

Figure 7: Vitreous slag from Longstone (sample 24) showing tin prills. Magnification x 270.

The separation of tin and tungsten minerals in an ore by gravitational methods is not possible, but tungsten is partitioned into the slag during smelting and thus does not affect the purity of the tin produced. The blowing house at Hurdon in sited in an area rich in tungsten-bearing minerals (Dines 1969), thus the unusually high tungsten oxide levels seen in this slag are not unexpected.

There is considerable variation in elemental concentrations within a single piece of slag: as with the Crift Farm slag samples maximum and minimum values are often more than 1 standard deviation from the sample oxide mean. However, since only a single piece of slag from each blowing house site was analysed the range of variation which might be expected from a bulk sample from any particular site remains unknown. Comparison with published data suggests that the overall variation may be large, as is the case with the Crift Farm slag (Tylecote *et al* 1989, Adriaens 1996, Salter 1997).

Notably, there are no obvious differences between the chemical compositions of blowing house slags and the Crift Farm slag.

Discussion

Prior to the study of material from Crift Farm, no in-depth bulk analysis of tin smelting slags from a single site of any date had been undertaken. This is due to the relative scarcity of slag; many smelting sites are represented by only a handful of slag fragments, and some merely by a single sample. As a result, discussion of the smelting process was, by necessity, based upon data deriving from, at best, only two or three pieces of slag from any particular site. Crift Farm, with its large slag dump, offered a valuable opportunity to investigate the level of variation in physical appearance and chemical composition of slags which had been produced under conditions which could be assumed to be relatively consistent with regard to furnace charge, furnace construction and smelting technique. Thus the validity of interpretations based on the limited data previously available could be examined.

The study has produced much useful information regarding smelting conditions at the Crift Farm site. As experiments show, a minimum liquation temperature of 1100°C must have been obtained in order to produce slag which flowed and formed the shapes observed, but at this temperature the slag would have been highly viscous, thus precluding complete mixing within the furnace. The heterogeneous chemical composition which is observed within each individual piece of Crift Farm slag offers support for a relatively low smelting temperature, as does the appearance of lighter banding which is sometimes seen within the glassy matrix. This change in colour was shown by Adriaens (1996) to be due to a change in chemical composition. That the blowing house slags exhibit a comparable level of heterogeneity points to a similar high viscosity slag being produced in the later water-powered blowing houses.

One implication of a high viscosity slag is that it may restrict the flow of tin metal, which ultimately becomes trapped as prills within the matrix. Both the Crift Farm slag and all the blowing house slags examined to date contain numerous prills, although many are visible only

Table 4: Results of SEM/EDS analysis of Blowing House slags.

Sample No.	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	CuO	SnO	WO_3	SbO_2	Total
Blackaller 22a	2.3	3.4	15.2	44.1	0.4	2.7	2.2	3.1	0.2	14.9	0.2	7.7	0.3	nd	96.7
Blackaller 22b	2.8	3.7	16.1	45.9	0.4	3.0	2.5	3.0	0.1	14.7	0.1	8.0	nd	0.8	101.1
Blackaller 22c	2.9	3.6	14.9	40.9	0.7	2.5	2.1	3.0	0.2	14.1	0.3	7.4	0.4	nd	93.0
Blackaller 22d	3.3	4.4	16.0	44.8	0.6	2.6	2.3	3.1	0.3	15.1	0.3	7.8	0.4	nd	101.0
Blackaller 22e	2.8	3.4	14.9	43.0	0.6	2.7	2.0	3.0	0.2	14.7	0.1	7.8	0.7	0.1	96.0
Hurdon 26a*	0.3	1.7	8.9	36.7	nd	1.0	0.3	4.0	2.5	7.0	0.6	24.9	12.1	nd	100.0
Hurdon 26b*	1.2	2.1	9.2	37.1	nd	1.2	0.2	3.8	2.5	7.0	0.1	23.4	12.2	nd	100.0
Hurdon 26c*	1.4	2.2	10.0	38.1	nd	1.4	0.1	3.7	2.6	6.7	nd	22.3	11.6	nd	100.0
Hurdon 26d*	1.5	2.0	8.4	36.1	nd	1.4	0.4	3.6	2.3	6.9	0.3	26.2	10.8	0.1	100.0
Hurdon 26e*	2.0	2.3	9.9	39.1	nd	1.1	0.1	3.6	2.8	6.6	nd	21.1	11.4	nd	100.0
Longstone 24a	2.3	2.6	9.4	34.7	0.1	1.0	nd	4.6	0.2	6.7	0.3	35.7	0.5	0.3	99.4
Longstone 24b	2.5	2.8	10.0	36.9	0.6	1.4	0.1	4.7	0.3	7.0	0.2	34.8	0.6	0.9	102.8
Longstone 24c	2.5	2.9	9.5	32.9	1.1	1.4	0.1	4.4	0.3	6.3	0.1	34.9	0.3	0.7	97.4
Longstone 24e	1.1	2.1	8.5	32.7	0.7	1.4	0.3	4.5	0.5	6.7	0.5	32.3	0.5	0.1	92.8
Longstone 24f	2.5	2.3	8.1	35.0	0.7	1.3	0.3	4.8	0.1	6.6	0.2	30.7	nd	nd	92.6
Merrivale 23c	2.6	2.6	12.1	44.6	0.9	1.1	0.4	2.3	nd	14.5	0.3	15.7	0.7	5.0	102.8
Merrivale 23d	0.9	2.7	12.1	43.1	0.5	1.0	0.6	2.4	nd	14.1	0.1	16.0	0.5	nd	94.0
Merrivale 23e	1.0	2.8	12.3	43.5	0.4	1.0	0.6	2.5	nd	14.4	0.1	16.1	0.5	nd	95.2
Merrivale 23f	2.1	2.9	13.0	47.4	0.8	1.0	0.4	2.5	0.1	14.9	nd	16.3	0.5	0.1	102.0
Outer Down 21a	2.3	1.2	9.5	42.1	0.9	3.9	1.4	14.3	0.2	17.1	nd	8.9	nd	0.1	101.9
Outer Down 21b	2.3	0.7	9.6	38.0	0.9	3.1	1.4	12.0	0.6	18.4	0.2	11.9	0.9	1.0	101.3
Outer Down 21d	2.6	0.9	11.1	40.7	0.7	4.1	1.4	9.4	0.5	15.8	0.1	10.1	nd	1.1	98.5
Outer Down 21e	2.2	1.1	9.9	40.6	0.7	3.5	1.5	12.2	0.5	18.8	0.1	14.1	nd	0.3	105.5
Outer Down 21f	1.9	1.3	9.0	37.1	0.5	2.9	1.1	15.2	0.3	20.8	0.2	12.1	1.2	0.1	103.7
Stannon Brook 25a*	2.4	3.8	11.5	52.1	0.8	1.4	0.8	2.2	0.4	15.0	0.1	8.8	0.3	0.3	100.0
Stannon Brook 25b*	2.9	3.2	10.8	51.8	0.5	1.3	0.9	2.4	0.4	15.1	0.3	9.3	0.9	0.1	100.0
Stannon Brook 25c*	2.5	3.7	11.1	52.4	1.0	1.3	0.8	2.6	0.4	15.6	0.3	8.3	0.2	nd	100.0
Stannon Brook 25d*	1.7	3.2	11.6	52.8	0.9	1.3	0.9	2.4	0.5	15.0	0.1	8.8	0.2	0.5	100.0
Stannon Brook 25e*	2.4	3.6	10.9	51.4	0.9	1.5	0.7	2.3	0.6	15.6	0.2	9.4	nd	0.4	100.0
Stannon Brook 25f*	2.5	3.8	11.5	51.1	0.9	1.4	0.8	2.4	0.5	15.7	0.1	9.0	nd	0.2	100.0
Week Ford 34a*	2.3	4.5	13.1	47.5	2.4	1.5	0.8	6.6	0.2	12.3	0.3	7.6	0.5	0.3	100.0
Week Ford 34b*	1.6	4.5	13.7	48.0	2.2	1.6	0.5	6.1	0.4	12.4	0.1	7.9	0.2	0.4	100.0
Week Ford 34c*	2.8	5.2	13.8	46.3	2.5	1.4	0.7	6.4	0.3	11.9	0.1	8.4	0.1	9.1	100.0
Week Ford 34d*	2.8	5.2	13.2	45.1	4.7	1.4	0.6	6.1	0.3	11.2	0.3	8.2	0.6	0.3	100.0
Week Ford 34e*	2.3	4.4	13.3	48.7	2.7	1.6	0.7	6.7	0.3	11.7	0.3	6.9	0.4	nd	100.0
Week Ford 34f*	1.4	4.4	12.9	47.2	6.2	1.7	0.6	5.3	0.3	11.6	nd	7.4	0.6	0.3	100.0

Note: oxides as wt%; nd = not detected, * indicates normalized data.

under the microscope. It has not yet been demonstrated that the composition of the prills reflects the purity of the bulk of the tin metal produced. However, assuming that the prills are representative of bulk tin composition, these low levels of impurities suggest that little or no subsequent refining of the smelted tin would have been necessary. Crystals of the intermetallic tin-iron compound known as hardhead are unlikely to have had a detrimental effect on the tin when iron, the main impurity, occurred at concentrations below 1%. Thus, while the blowing house furnaces and their forerunners sacrificed a relatively high proportion of tin to the slag, the metal produced was of high quality.

The presence of small granitic inclusions has been noted in many blowing house slags, as well as in the slags from Crift Farm. While their origin has not yet been satisfactorily explained, there are two main possibilities: firstly, that they are concentrations of gangue minerals introduced into the furnace with the ore, and secondly, that they are parts of the furnace body which have broken off. Given temperatures inside the furnace in excess of 1000°C, partial melting of the minerals which comprise granite would occur, hence the observed blending of granitic minerals into the glassy matrix around inclusions. This would have a detrimental effect on a furnace structure over the long term.

The difference in chemical composition between individual pieces of Crift Farm slag is large. Although few chemical analyses of blowing house slags have been undertaken, based upon what evidence is available it is likely that the variation in chemical composition of slag from any particular site is of comparable extent. Thus to use data obtained from analysis of a single piece of slag is a gross generalisation. Further work is required to determine the limits of blowing house slag variability.

Considering the wide geographical distribution of blowing houses and the long period of time over which they operated, encompassing a switch from alluvial ores to mined vein ores, it is not surprising to see that the chemical composition of slag from one blowing house is different to that from another. Tylecote *et al* (1989) suggested that medieval and earlier slags from Devon generally had higher levels of titanium than those from Cornwall; this study does not support that claim. Most obviously, the data presented here indicates that the ratio of iron oxide to tin oxide in slags varies with geographical location (Fig 1), decreasing from north east Dartmoor to south west Dartmoor, reflecting the relatively higher levels of iron mineralisation associated with tin ores in the north east (Dines 1969). Although the Crift Farm slags, and slags from Cornwall analysed by others (Tylecote *et al* 1989, Salter 1997), show the same low iron oxide to tin oxide ratio, too few Cornish slags have been examined in order to state whether the data is representative of the county as a whole. Cornwall, unlike Devon, contains more than a single ore-bearing area, which means that it may not be possible to treat Cornish slags as a single distinct group.

In the absence of deliberately added lime, the role of fluxing the tin from the slag was taken by iron oxides which entered the furnace as impurities. The beneficial fluxing effects of iron oxides in the charge were balanced against the likelihood of it being co-smelted with the tin, reducing the purity of metal produced. The implications of higher iron levels in tin ores have not been studied. It may have necessitated additional treatment of the smelted metal, thus having an economic impact.

It has been noted in connection with the Bronze Age slag from Caerloggas that an extremely high residual tin content is a potential clue to date and to the level of technology employed (Salter 1997). In this case, it is reasonable to assume so. However, it is not clear whether this would be a reliable guide in areas where the ores contain higher levels of iron impurities, such as Dartmoor, where additional fluxing may have freed more tin from the slag.

As Salter noted, medieval slags and those from earlier periods are visually indistinguishable. Rather more interestingly, Crift Farm slag is chemically indistinguishable from the widely variable chemical signatures which characterise blowing house slags. SEM/EDS analyses of chemical composition cannot, therefore, be seen as a reliable indicator of the smelting technology employed. That said, it may be possible to detect the shift between use of alluvial ores to vein ores through analysis of trace elements.

The fact that slag from a particular site, whatever technology produced it, has a compositional range distinct from slag obtained from elsewhere argues for a certain consistency to the inputs into each furnace. As mentioned previously, the tin and iron contents of slags appear to reflect the compositions of the original ores. It is from the ore, and the gangue minerals associated with it, that the majority of minerals making up the slag would derive. A considerable contribution to the composition of a slag is likely to be made by fuel ash. Much of the calcium in the slags would enter the furnace in the fuel.

Assuming that furnaces are made of granite blocks, silica, alumina and alkali metal oxides may enter the slag due to molten slag reacting with the walls of the furnace itself. This would also be true if the furnaces were lined with clay as some documentary sources suggest they were. Clays are the breakdown products of local granites, so will contain many of the same minerals. Several pieces of furnace lining from blowing houses have been discovered (Tom Greeves pers comm), and all have been partially vitrified and show some exchange of material with the slag which adheres to them. Only one piece of furnace wall, from Week Ford, shows evidence for the granite having been overlain with a lining of another—as yet unidentified—material. The minerals which are released into the slag from the granite or clay would affect its viscosity and melting point to some extent.

Conclusion

The slag from Crift Farm is a black glass containing partially-melted granitic inclusions and small globules of metallic tin. It has a highly variable chemical composition, indicative of a high viscosity melt.

Tin smelting slags produced in small shaft furnaces of the type believed to have been employed at Crift Farm, and those deriving from furnaces employed in later water-powered blowing houses, cannot be distinguished on the basis of their physical appearance or chemical composition. That is to say, developments in smelting technology in the medieval period are not reflected in the properties of the slags.

Inputs into the furnace determine the final make-up of a slag. Ore composition is the most important factor, followed by contributions from fuel ash, and the decomposition either of the furnace body itself or any lining used. Since the inputs into the blowing house furnaces are not greatly changed from those used at Crift Farm, the slags from all these sites are broadly similar. The developments in technology are changes in scale only.

It is very difficult to make meaningful interpretations of the data with so few excavated sites to give firm dating evidence. Information on what types of ores and what processes were in use is also scant. Given the very small sample sizes involved in this study, the data is open to revision in future.

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