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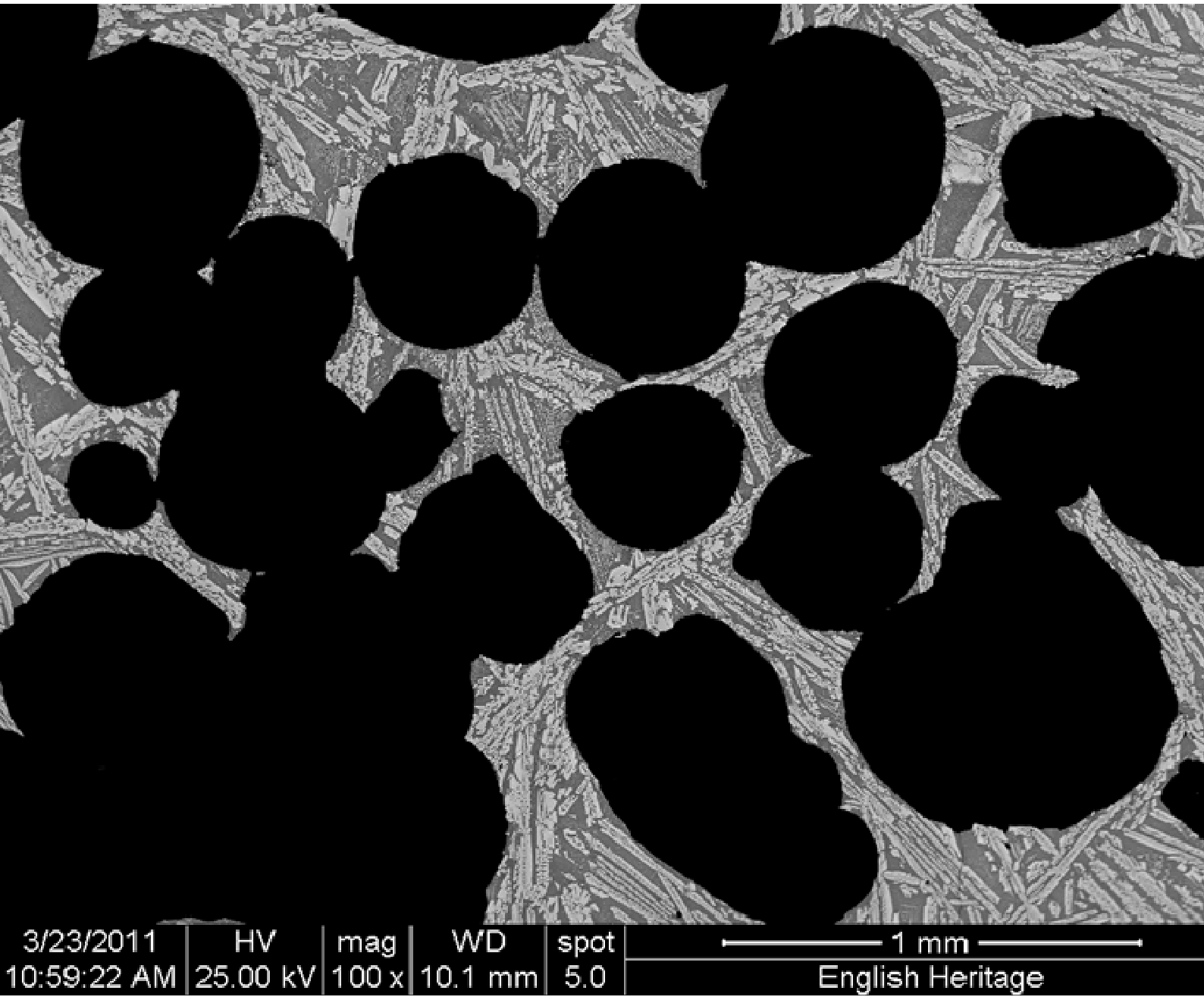
4 LOW FORGE, WORTLEY, SOUTH YORKSHIRE AN INVESTIGATION OF THE SLAGS

TECHNOLOGY REPORT

Brice Girbal



ARCHAEOLOGICAL SCIENCE

ENGLISH HERITAGE

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AN INVESTIGATION OF THE SLAGS

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SUMMARY

A 60 litre bulk sample was taken from an evaluation trench at Low Forge, Wortley. The majority of the material proved to be iron working residues in the form of slag. The subsequent analysis of this debris and comparison with slags from similar sites suggests that water-powered bloomeries were in operation at Low Forge in the period between the late 13th century and mid 16th century. The use of water-power whether for the bellows, the hammer or both can unfortunately not be ascertained. Analysis of the metallic prills in the slags hinted at the production of a phosphorus-rich iron which may explain documentary accounts stating that iron produced was used to make nails. Although no ore was found the chemical analyses indicated that it must have been phosphorus-rich and from carboniferous deposits.

ACKNOWLEDGEMENTS

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DATE OF RESEARCH

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INTRODUCTION

The excavation at Low Forge, Wortley took place in August 2009 under the direction of CS Archaeology. The archaeological evaluation was undertaken in mitigation of a proposed extension to a dwelling within the Scheduled Ancient Monument – water-powered bloomery, iron forge and rolling mill at Low Forge, Barnsley (monument number 34714).

The proposed development area (PDA) laid on the left bank of the River Don, west of Wortley, Barnsley (Fig 1). It consisted of a small square (4m x 4m) abutting the rear wall of 4 Low Forge, Wortley (Ordnance Survey National Grid Reference SK 291 995). An evaluation trench was dug (1.2m wide and 4.8m long) centrally in a NE-SW direction across the PDA and a series of stratigraphic/archaeological layers were uncovered. Industrial debris was found in the deepest context in the form of a slag mound (context 120). A 60 litre bulk sample was taken from this slag deposit as well as several selective 'good example' samples. Assessment of ceramic finds found in the adjacent strata has enabled the industrial activity (iron working) to be dated around the later medieval period (later 13th to mid 16th centuries).

The report will contain the detailed examination of the sampled slag.

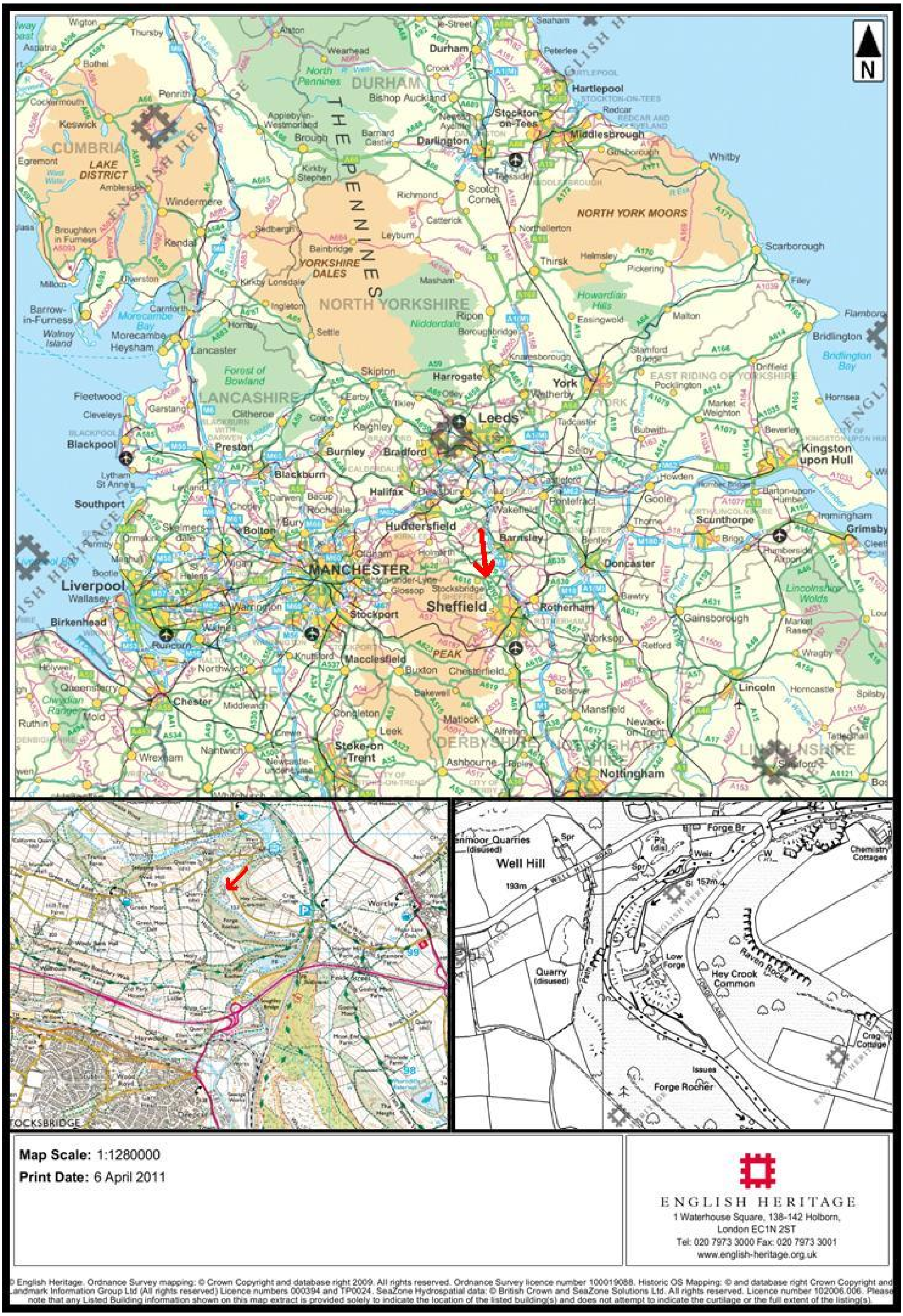

Fig 1. Location of Low Forge, Wortley, South Yorkshire.

HISTORICAL BACKGROUND

Medieval records suggest that iron was worked at Low Forge since at least the 14th century (Mott 1949–51). A deed from 1621(Wharncliffe Deed Wh.D.503, 2 April 1621, Sheffield City Library) mentions the workings of a complex water-powered works with bloomery and string hearth (Allison 1949–51; Mott 1971, 64–69). By 1658 the bloomeries were rebuilt as a forge and worked in conjunction with another forge further upstream (Top Forge) to produce bar iron. These were part of the Spencer Syndicate which was a complex network of partnerships monopolising the iron trade in Derbyshire, Southern Yorkshire and Lancashire (Mott 1971, 65). Around that time there is evidence for Top Forge operating as a finery reworking pig iron from blast furnaces (Scurfield 2009). This was then sent to Low Forge for the production of bar iron and then taken to a Slitting Mill upstream of Top Forge where the bars were turned into rods for sale mainly to nail makers in Mortomley (Mott 1971; Scurfield 2009).

Records show that in 1713 both Low Forge and Top Forge were extensively rebuilt with the installation of a new water-powered hammer at Low Forge (Mott 1971, 69). After the break up of the Spencer Syndicate in the mid 18th century, Low Forge became part of the Wortley Ironworks controlled by the Cockshutt family (Andrews 1956). During that time the iron produced was still made into wire or rods but was also sent downstream to the Tin Mill where it was rolled into thin plates for equipment such as shovel blades (Mott 1971, 79–71). Some time after 1787 puddling furnaces were installed which enabled the production of high quality wrought iron using coke. In 1825 a new rolling mill was added as well as a beam steam engine installed in 1849. By the late 19th century Low Forge was specialising in the production of high quality bar iron but the rise in the use of mild steel catalysed its closure in 1929 (Scurfield 2009).

Archaeologically, the principle remains at Low Forge comprise the water-powered tilt hammer installed in 1713, parts of 2 puddling furnaces as well as the structural remains of the forge with mountings for the beam engine and the water wheel pit (Scurfield 2009). In addition, the weir, a leat, mill pond, waste dumps, several standing and ruined workshops and workers' cottages partially survive (Scurfield 2009). Little is known about the industrial activity before the forge was built in 1658 but it is believed that the buried remains of the earlier bloomeries underlie the waste dumps of the later works (Scurfield 2009). The material made available to this study provides an excellent opportunity to analyse this debris in order to resolve the nature of industrial activity and inform on the technological processes involved prior to the forge.

ARCHAEOLOGICAL CONTEXT

Little archaeological evidence for water-powered bloomeries in Britain has been found to date. Only nine 'possible' bloomeries employing water as a source of power have been investigated archaeologically (Bayley *et al* 2008, 58–59; Tylecote 1986, 202–212). Unfortunately due to the nature of the remains the quality of evidence from these sites is often less than ideal (Dungworth 2010). This section will summarise the archaeological evidence of known water-powered bloomeries.

The remains at Chingley, Kent (on the lands of Boxley Abbey) are of an early hammer forge (Crossley 1975, 6–17). Three main phases of use/construction have been found. Although the later and better preserved phase is conclusively an iron working forge (with surviving anvil pits and smithing hearths), tap slag was found in and around the earlier construction (a wheel pit and timber frame dated to the first half of the 14th century). This is suggestive of earlier smelting. Unfortunately it is unclear as to whether the furnaces were operating nearby or even if they were water-powered. The impression of the excavator (due to the scarcity of slag) was that smelting occurred in the higher woodlands of the Weald and the iron was perhaps brought to Chingley (or another valley-bottom forge) for smithing while the slag was brought fortuitously (Crossley 1975, 14–15).

The primary evidence for a water-powered bloomery at Kyrkeknott (formerly Byrkeknott), Durham is the weekly account roll of a forge-master in the early 15th century. This document not only consists of the minute account of expenses for an entire year (1408–9) but also provides details of the building and furnishing of the forge itself (Lapsley 1899, 509–529). There is mention of the building of a water course and wheel as well as the running of a bloom and string hearth. Although it presents a good description of the labour, raw materials and tools required for the running of the bloomery and forge it does not specify what the wheel powered. It is generally assumed that it powered the bellows for the bloom hearth as there is no mention of a powered hammer (Lapsley 1899, 509–529). Mott (1961) on the other hand, argues that some of the tools and equipment listed suggest (indirectly) the powering of a hammer as well as bellows; "such massive mounting of the axletree would not have been required merely to depress the bellows" (1961, 157). Unfortunately there is still no confirmative evidence to settle the debate. Archaeologically there is very little evidence apart from what is reported by Tylecote (1960). He argues for the site's location at Harthope Mill as opposed to Bedburn Forge which had been proposed by Lapsey (1899, 510). The subsequent excavation of the bank and millpond revealed some 'primitive' slag but no dating evidence. However, the excavation of the mill uncovered a hard ferruginous layer containing slag, charcoal, iron ore nodules and fines which could be dated from the pottery finds to the 14th/15th centuries (Tylecote 1960, 454–457).

Evidence for a water-powered iron mill at Bourne Pool, Aldridge, Staffordshire comes from a 17th-century brief drawn up on behalf of the lord of the manor of Aldridge that include the summaries of various bundles of manor-court rolls (Gould 1969–70). These

describe an iron mill owned by a Simon Montford. Documentary evidence has shown that the mill must have belonged to the period between AD1474 (when he inherited from his father) to AD1495 (when he was executed). The excavation revealed remains of a possible slag heap, and scatters of slag (all tap) as well as charcoal extending about 15m north of the sluice. Firm, heat-affected surfaces were also found on the dam where the wheel was thought to have been mounted (Gould 1969–70, 61–62). Unfortunately the excavation was very limited leaving the exact location and function of the iron mill open to debate. No datable evidence was recovered leaving the dating for the site entirely upon documentary sources.

No archaeological excavation as yet taken place at Timberholme, North Yorkshire and all the information available is restricted to the interpretation of geophysical surveys carried out in 1995 (Vernon *et al* 1998). The site is located next to the River Seph. The surveys suggest that there was a leat that traversed the site at its southern end before running into the river. A large area of slag is believed to occupy the land between the river and the leat while further up is a feature interpreted as a pond or simple reservoir (most likely belonging to an industrial phase preceding the supply of water solely by the leat). On the north side of the leat (opposite the slag) is a square structure (about 10m x 10m) which may be the furnace site (a high bloomery). Two areas of high gradiometer readings immediately south of the structure could be the remains of the demolished furnace, bridging or filling the leat (Vernon *et al* 1998, 72–75). Although the geophysical surveys are informative, the lack of any archaeological intrusion means that there is no dating or physical evidence for a water-powered bloomery.

The archaeological remains at Rockley Smithies, Barnsley, Yorkshire are unusually good. Three working platforms could be identified each containing a wheelpit (at right angles to the dam), a bellows house and a hearth (Crossley and Ashurst 1968). The northern most hearth is believed to have been for smelting; a bloomhearth (a clay-lined ring of stone 61–69cm internal diameter) built against a bank of natural clay and gravel to the north of the main tail-race. The others were interpreted as stringhearths due to their lack of provision for slag tapping. The remains of two *in situ* wheels revealed them to be of the overshot type and about 3.4m in diameter. Several periods of use were identified (each bringing modifications) and pottery finds enabled the sites use to be dated to the early 16th to mid 17th centuries. It seems that the earlier race was lined with timber and later lined with stone. A foundation for an anvil with two periods of working floors coated with hammerscale and an adjacent reheating hearth were also found but no evidence for a water-powered hammer was recovered. It is believed that the bloomery and smithies were demolished in the middle of the 17th century although the most southern working area (wheelpit 3 and associated features) seems to have been abandoned before the rest of the site (Crossley and Ashurst 1968, 19–35).

Muncaster Head, Cumbria was mentioned in an agreement of 24 September 1636 between William Pennington of Muncaster and William Wright of Broughham in which a forge or iron works was to be set up (Tylecote and Cherry 1970, 71–72). The

excavations revealed a race in which a sluice gate with masonry slot was found (~1.2m high). It is argued that there must have been a permanent weir across the river while the water going through the gate was controlled by putting square timbers (~0.2m) in the slot; removing and adding them to regulate the flow. No evidence for a by-pass was found but a stone lined wheel pit was clearly identifiable (~2m wide at the bottom). Oak timber fragments were found and believed to be the remains of an undershot wheel (~4.5m in diameter). Calculations showed that a wheel of this type was capable of producing between 15 and 17 horsepower (Tylecote and Cherry 1970). The hammer is thought to have been on a working floor 2m above the bottom of the wheel race. It has been proposed that it was powered by its own wheel and the bellows by a smaller one further up the race. The platform extended northwards and became harder composed of a slag ore and clay concrete. A lower ground level was identified to the north of the platform and it has been suggested as the location for the hearths (smelting area) supported by the large number of furnace bottoms and pieces of cast iron found in the race. However, the examination of the area remained ambiguous. To the west of this supposed smelting area was the remains of a charcoal heap about 10.5m in diameter and up to 0.5m thick in some areas. In the southern and western parts of the site, remains of a later agricultural building were found of which the foundations cut through layers of hematite. The majority of the pottery and ceramic finds have been dated to the late 16th to early 18th centuries (Tylecote and Cherry 1970). Recently, Bowden (2000, 45–46) unconvinced by the little evidence found for the location/use of the site has expressed his doubts as to the true purpose and location of the bloomery.

Smelting activity at Fasagh, Loch Maree is most evident from the elongated horse shoe shaped area defined by slag and upcast heaps, evidence of filled in water leats and tailraces (Photos-Jones *et al* 1998, 24). Unfortunately the excavation was very limited and only targeted two major anomalies identified in a geophysical survey. These were shown to be anvil blocks. Each consisted of a large tree trunk (~1m diameter) with remains of an iron collar in the centre for the positioning of the anvil proper. The tree bases were encased in an artificially produced conglomerate consisting of a ferruginous mass holding together quartz pebbles and other materials (Photos-Jones *et al* 1998, 24–28). The casing of anvil A had clear notches taken out of the four sides which extended to two channels running along the NE and SW sides of the feature. A level platform made of the same material was also identified to the SW of the anvil casing. Two slots were associated with the platform and it has been suggested that (taking into account the size of the anvil block) it was the base for a powered hammer. No evidence of furnaces was found and although other features were evident they were not excavated (Photos-Jones *et al* 1998).

There is documentary evidence from 1720 where Stony Hazel Forge, Rusland, Cumbria was referred to as a bloomery or iron forge with a coal house, a dam, a weir and floodgates (Bowden 2000, 73). In 1724–5 it was leased by the Backbarrow and Cunsey companies to be subsequently abandoned. It was excavated in 1968–1969 by Davies-Shiel (1970) and re-excavated in 1985 by Cranstone. There is evidence of a ruined weir (in the 1960s), a 76m long head-race, 82m long millpond, 34m water race and two main

buildings (Davies-Shiel 1970). The remaining forge building would have had two broad openings on the west wall for the axles of the water wheels. Excavation has shown that the northern wheel powered the hammer and the other powered the bellows. The main feature is the hearth which is a rectangular stone construction (2.7m x 2.5m) abutting the western wall of the building in between the water wheels. A 0.2m squared hole in the wall above the hearth interpreted as a 'pig hole' (where pig iron was fed into the hearth) had led Davies-Shiel to suggest that it was a finery. However, traces of hematite ore were found in the hearth and there is evidence for an ore bin in the NE corner of the building (Bowden 2000, 75). This led to the re-interpretation of the structure as a bloomery. The hole may have been a lever-duct to the bellows wheel water supply but it is also possible that the hearth had a double function and could also be used as a finery (Bowden 2000, 75–76).

Goscote (Rushall) is another possible water-powered bloomery. Documentary sources indicate that iron production took place in the Walsall area from at least the 14th century (Greenslade 1976). There is also mention of a bloomery in operation at Goscote in 1576 (Dilworth 1976, 93) but no other information is provided. Excavations took place in 1964 by G R Morton and the Walsall Archaeological Society which identified a substantial bloomery slag heap (NRG SK 0219 0128) adjacent to a tributary of the river Tame (Fordbrook). Unfortunately the excavation remains unpublished. More recent excavations (SK 0222 0130) by Richard Cherrington of Benchmark Archaeology have not provided any further insights into the type of technology and use of water-power at Goscote (Dungworth 2010, 15).

As can be seen from the above there is very little evidence for water-powered bloomeries; the excavations/surveys often being very limited and rarely able to confirm the use of water-power (for bellows or for hammer). This study provides a unique opportunity to examine slags (potentially) produced by this under researched and little understood technology. The analysis of the slags has the potential to reveal/enlighten aspects of industrial production and the scientific analysis will add to the database of the few water-powered bloomery slag analyses to date.

AIMS AND OBJECTIVES

The primary aim of this project is to gain a clearer understanding of water-powered bloomeries in Britain and their role in iron production of the late to Post-Medieval period.

The objectives will include the recognition and study of the various types of slags (furnace bottoms, tap slags and possible smithing wastes). This morphological examination will be supplemented by scientific analysis to identify possible ore sources, smelting procedure and possible types of product (iron/steel). The results will be compared with data from other known water-powered bloomeries (Bayley *et al* 2008, 57–58).

Several questions will be addressed:

- Do the remains reveal a particular technological trait? Do they result from a water-powered bloomery? Were they smelting iron from ore or was it a refinery?
- How does the technology fit into the wider metallurgical tradition of Medieval and Post-Medieval Britain?
- How does the chemical composition of the slag compare with material from other water-powered bloomeries? What is the relevance of this for iron production in the late to Post-Medieval period?
- What sort of iron alloy was produced (plain iron, phosphoric iron or steel?)

METHODOLOGY

Visual Analysis

The assemblage was washed and then examined visually. The 60 litre bulk sample was wet sieved at 10mm, 5mm, 2mm and 1mm. 200g sub-samples were taken from the 5mm, 2mm and 1mm material as the analysis of the whole samples was deemed unnecessary and too time costly. Although the 200g sub-samples for the 5mm and 2mm material were treated as discussed below, the 1mm material was only probed for hammerscale. The small fraction (<5mm) appeared to represent small fragments of the same sorts of slag and material seen in the large fractions. Distinctive characteristics such as colour, texture, shape and size were considered. This visual analysis is important to reveal which processes the fragments have resulted from, in turn suggesting possible technological traits (Bayley *et al* 2001). The metallurgical debris was then categorised by material type and then sub-divided again and grouped under shared morphological properties. All the material was weighed to the nearest gram. Due to the large quantity of fragments they were not counted individually but assessed by group type.

Micro-structural and Chemical Analysis

Samples were selected for micro-structural and chemical analysis. These were chosen to represent the assemblage as a whole (see scientific analysis section for more details). The bigger samples were cut with a linear precision saw (Buehler IsoMet 4000) removing a part of the fragment a few mm thick while the most friable material was broken with a hammer and one edge ground flat with rough wet and dry paper. The samples were then embedded in epoxy resin (Struers epo-thin) and polished to a 1- micron finish. For photographs showing the location of the cut samples please refer to Appendix 1.

The polished samples were carbon coated and examined using a scanning electron microscope (SEM – FEI Inspect F). This allowed the identification of individual micro-structural phases such as wüstite (FeO) and fayalite (Fe_2SiO_4). Images were collected using the back-scattered electron detector – the brightness of each region being related to the average atomic number of that region. The chemical composition of each sample was obtained using the energy dispersive X-ray spectrometer (SDD X-act EDS) attached to the SEM. The data was collected mainly through bulk analyses at magnifications between 100x to 500x depending on the size of the crystalline structures. An average composition was determined by taking the mean of 7 to 12 bulk readings per sample. The more homogenous the sample the fewer readings were required to reach a reliable average. Areas analysed were carefully selected to show a good representation of the crystalline phases and of low porosity while areas of unusual heterogeneity (corrosion or contamination) or ones making up a minor percentage of the overall sample were avoided. A spot mode which allows an accurate reading of an area less than 10 micron^2 was used to confirm the crystalline phases present. Iron prills in each sample (if present) were also spot analysed.

Compositions of slags, ores and clays were calculated assuming that all elements were present as oxides (stoichiometric). Analytical parameters were kept constant at an accelerating voltage of 25kV, spot size of 5 (approximately 1.2nA), processing time of 5 and acquisition time of 120 seconds per spectra. The spectra were de-convoluted using the Oxford Instruments INCA software. Compositions were normalised to 100wt% to allow comparisons of samples with varying degrees of porosity.

To verify the reliability of the chemical data retrieved by SEM-EDS, the Swedish Iron Slag standard (W:25R) was analysed. Ten areas were examined (Table 1) and the results compared to the reported values (Kresten and Hjarthner-Holdar 2001). This confirms that the data presented is accurate. The soda levels are higher than those reported but analysis of glass reference materials suggests that the values reported here are reliable (Dungworth 2011). The SEM-EDS has a detection limit for most elements of ~0.1wt% and ~0.2wt% for P_2O_5, SO_3 and BaO. The data was rounded to one decimal place while compositions below the detection limit of the measured element were labelled <detection limit (eg <0.1). The elements analysed for the slag samples were Na, Mg, Al, Si, P, S, K, Ca, Ti, V, Cr, Mn, Fe and Ba while Co, Ni, Cu, Zn, As, Zr, Nb, Mo, Sn, Sb, Ce,

W, Pt and Pb where also sought for in the iron prills. Any element below the detection limit in all samples is not displayed in the data tables.

Table 1. Ten analyses of the Swedish Iron Slag standard (W:25R) with the average reported value (Kresten and Hjarthner-Holdar 2001).

No.	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
DL	0.10	0.10	0.10	0.10	0.20	0.10	0.10	0.10	0.10	0.10	0.10
1	1.58	0.32	8.41	23.50	0.24	0.26	1.18	1.60	0.41	3.22	59.27
2	1.33	0.23	8.38	23.67	0.35	0.16	1.13	1.63	0.25	3.23	59.64
3	1.32	0.37	8.41	23.55	0.22	0.23	1.30	1.56	0.32	3.28	59.43
4	1.60	0.31	8.55	23.19	0.26	0.28	1.23	1.58	0.27	3.33	59.38
5	1.42	0.36	8.46	23.87	0.23	0.35	1.18	1.60	0.19	3.13	59.20
6	1.47	0.36	8.35	23.43	0.32	0.25	1.18	1.59	0.31	3.28	59.44
7	1.67	0.37	8.58	23.70	0.34	0.18	1.17	1.58	0.29	3.24	58.86
8	1.58	0.32	8.42	23.64	0.33	0.32	1.18	1.63	0.20	3.18	59.20
9	1.52	0.39	8.80	23.26	0.30	0.24	1.14	1.56	0.34	3.15	59.30
10	1.56	0.32	8.43	23.59	0.25	0.23	1.22	1.51	0.24	3.15	59.49
Mean	1.51	0.34	8.48	23.54	0.28	0.25	1.19	1.58	0.28	3.22	59.32
St.Dev	0.12	0.05	0.13	0.20	0.05	0.06	0.05	0.03	0.07	0.06	0.21
Reported	0.61	0.38	7.14	24.73	0.26	0.10	1.02	1.42	0.32	3.01	57.10

Three ferrous standards (MBH11X C1 K, MBH14M B.S. 66K and NIST11/4 Cr1/2Mo IARM 35IN) were tested to check the reliability of the iron inclusion compositional data. The recorded compositions were compared to those reported and the elements showing the greatest inaccuracies (Co and Ni) were adjusted/corrected accordingly. The standard data tables are displayed in Appendix 2.

MORPHOLOGICAL EXAMINATION

Two types of samples were taken from the excavation; a 60 litre bulk sample from context 120 (the slag heap) and a non-representative selection of several slag fragments showing the array of morphological properties from the same context. The assemblage was separated into several categories of material. Four major material types were found – slag, fuel, rock/mineral and hammerscale. These were then sub-divided by different morphological properties of which eleven sub-types of material have been identified (Table 2).

Table 2. The weight in grams of the different material types. Numbers in brackets represent how many grams are magnetic. All material is from context 120 and the material smaller than 10mm are 200g sub-samples.

Sampled Material	SLAG					FUEL			ROCK/ MINERAL	HAMMERSCALE	
	Honeycomb diagnostic	Honeycomb semi-diagnostic	Honeycomb non-diagnostic	Dense tap slag	Amorphous lumps	Charcoal	Coal	Clinker	Rock/Mineral	Spherical	Flake
60L >10mm	3197	7447	2774	1913	568	8	97	177	1922	–	–
60L >5mm	----------	----------	159 (10)	----------	----------	------	16	4	21 (3)	–	–
60L >2mm	----------	----------	133 (14)	----------	----------	------	22	2	43 (18)	0.20	0.05
60L >1mm	----------	----------	----------	----------	199 (32)	----------	----------	----------	----------	0.19	0.83
Selective	6067	695	–	–	1242 (216)	–	–	–	–	–	–

Honeycomb Slag

The slag from the 60 litre bulk sample is all fragmentary and there are no complete pieces. The >10mm fragments range in size from about 1cm to11cm with the majority between 2cm and 5cm in length. Their depth (thickness) ranges from 0.3cm to 3.7cm. Below 10mm there are no slags with both surfaces surviving. The fragments in the selective sample tend to be larger up to 16.7cm in length and 4.4cm in depth. They are mainly dark grey in colour with a few patches of dark reddish brown. This reddish brown is more pronounced on the larger fragments. Their top surfaces are a mixture of smooth and shiny (tap slag appearance) or rippley with some large (1cm to 2cm) gas holes (Fig 2). Some of the smaller fragments are very rippley where the top surface partially solidified (as it cooled) and rippled as slag underneath carried on flowing (like the skin on cream).

Fig 2. Top surface of diagnostic honeycomb slag.

Fig 3. Bottom surface of diagnostic honeycomb slag.

Fig 4. Good example of honeycomb textured slag.

The porosity ranges from a few mm on the smaller samples to about 2cm on the larger fragments. Their undersides tend to be rougher and undulated (Fig 3). This is probably due to the slag running over small stones/pebbles and retaining their shape as it cooled. Some show multiples flow episodes (dribbles of slag joined together – especially on some larger pieces) while some of the smaller fragments show flow tap slag features with well melted surfaces. In profile (on their broken sides) they are very porous – a honeycomb 'crunchie bar' texture with lots of tiny spherical holes 1mm and less in size (Fig 4). This makes the slag very light. In some of the larger pieces there are some larger holes which are oval (flattened) in profile; undoubtedly trapped gas. The larger fragments also have charcoal impressions and sometimes inclusions (up to 2cm) on their top surfaces. On their undersides these charcoal impressions tend to be smaller (0.2cm to 1cm). None of the fragments are magnetic.

The majority of the slag from the 60 litre bulk sample (>10mm) is honeycomb slag that has lost a diagnostic surface (semi-diagnostic). They are the same type of slag described above but have only one diagnostic (top or bottom) surface (Figs 5 and 6). One of these surfaces has been broken off; often a fine layer of smooth slag (like a skin) above the more 'crunchie' interior has chipped off revealing the honeycomb texture which is characteristic of this slag type. The majority of the fragments are between 1cm and 4cm in length (smaller/more fragmentary than above slag). Although not quite as evident as the more complete slag fragments discussed above there are some small charcoal impressions/inclusions on the intact (surviving) surfaces.

Fig 5. Top surface of semi-diagnostic honeycomb slag.

Fig 6. Bottom surface of semi-diagnostic honeycomb slag.

There are also quite a few honeycomb textured slag fragments with no surviving (diagnostic) surfaces (Fig 7). These have been classed as undiagnosic honeycomb slag but are undoubtedly smaller broken fragments of the more complete slags discussed above. They are the most fragmentary pieces in the assemblage and range from 1cm to 4.5cm in length, the majority being between 1cm and 2.5cm. All sides are fractured surfaces showing the characteristic honeycomb texture. Due to their lack of surviving surfaces they have no inclusions or impressions. This slag type is what seems to make the majority of the slag fragments below 10mm in size. Some of these are magnetic but it is probably

more due to their small size (being picked up by a stronger magnet) than them showing strong magnetic properties.

Fig 7. Non-diagnostic honeycomb slag.

Dense Tap Slag

All of the samples are fragmentary with no complete pieces. These are quite dense. They range in size between 1cm and 8.6cm in length and 0.3 to 4.4cm in depth. The majority are between 1.5cm and 5cm in length and have both surviving top and bottom surfaces (Fig 8). These reveal smooth, flat and sometimes rippley top surfaces which suggests that they must have flowed (very characteristic of tap slag). They are dark grey in colour with small brownish orange and dark red patches. Their undersides are heavily undulated and have small charcoal impressions (less than 1cm). On some of the larger pieces there are large (1cm to 2.5cm) voids on the top surfaces. The smaller fragments are clear flow slag; small individual runlets with smooth and rounded top surfaces.

In profile, their broken edges reveal solid/dense slag with relatively low porosity (a few voids which are larger in the bigger pieces). However, on some of the fragments it is clear that there is a progression between dense and honeycomb slag as some of the edges of the tap slag have the texture of the latter. Perhaps the slag produced when the furnace was not running at optimum conditions had different morphological properties (denser, heavier tap slag containing more iron oxide). Another possibility is that they are slags resulting from a different technology, perhaps older slag brought in to be refined. On the other hand, the fact that they seem quite glassy and that they have 'crunchie bar' textured

slag in some parts suggest they resulted from the same or similar process/technology. Chemical analyses should enlighten this. They do not have any visible inclusions.

Fig 8. Dense tap slag.

Amorphous Lumps

Fig 9. Amorphous lumps.

Fig 10. An amorphous lump showing amalgamation of several materials.

These are quite small ranging in size from 1cm to 4.2cm in length. They are amorphous in shape and look like an amalgamation of several materials (Figs 9 and 10). Dark brownish grey in colour with prominent dark reddish yellowy orange patches. They are rough to the touch and slightly brittle. They appear to be a mixture of clay, slaggy ash and coal. They have lots of small holes (less than 2mm) but not as many as the honeycomb texture of the other slags. Many of the fragments have melted slag/ash or vitrification which means

that they must have been subject to very high temperatures. They are very light and due to their differing morphology must be the product of a different technology than the honeycomb slag. The fact that there are some coal inclusions would suggest that they are unlikely to be smelting waste. Coal was not used in bloomery furnaces but it was utilised as a fuel for smithing, therefore, it is more likely to be smithing waste (perhaps residues of a working floor – smithing pan). It is not inconceivable considering that there is surviving evidence of a water-powered hammer forge that some smithing (perhaps of the iron blooms produced) took place on site. In support, is the fact that these fragments are magnetic, indeed the only ones in the whole assemblage.

There are two amorphous shaped lumps of slags in the selective sample (Fig 11). One is quite large (about 13.8cm x 12.9cm x 9.5cm) while the other is smaller (about 7.3cm x 6.8cm x 6.3cm). The larger fragment is quite light and has a few gas holes ranging in size from a few mm to about 1cm. It is dark brownish reddish grey in colour with patches of yellowy orange. Its surface is quite bulbous suggesting that it was once well melted and quite rough. On one side there are the remains of burnt clay. This is yellowy brown in colour and friable. There is a bit of vitrification where it makes contact with the slag and it is composed of fine clayey silt with small pebbles/stones (about 1 to 2mm) grog. The shape and texture of the slag suggests that it did not leave the furnace (was not tapped) and could therefore be furnace slag. The smaller sample is similar in colour and texture but has a vitrified coating which has started to crack. It is also magnetic and may contain some iron prills or because it is not particularly dense it may have an abundance of iron oxide (magnetite). Its shape and texture also suggests that it is furnace slag. Both fragments have charcoal impressions and residues (around 1cm in size).

Fig 11. Selective amorphous lump.

Fuel

Two sorts of fuel were found in the 60 litre bulk sample; charcoal and coal (Fig 12). The charcoal is sparse with only 28 small pieces found larger than 10mm. They are mainly oak with some type of diffuse-porous wood which have a distinct curved appearance (like small curved branches). The small curved shape of some of the charcoal suggests that they may have used managed woodlands (pollarded or coppiced) perhaps cultivated locally. They are all within 1cm to 2.3cm in length with most being around 1cm. Coal was found in more abundance. The fragments are very angular in appearance and graphite black in colour. They are quite small, most around 1cm in length but there are a few larger pieces up to 3cm in length. However, most of the fuel retrieved was burnt coal (clinker). It is dull black in colour with a coating of lighter grey. The fragments are sandy and friable to the touch as well as amorphous in shape. They are very porous with numerous tiny (less than 0.5mm) holes and extremely light in weight. Most pieces are around 1cm but there are some larger ones up to 3.5cm in length. The visual examination of fragments below 10mm revealed that there was a majority of coal with some charcoal and less clinker.

Fig 12. Fuel found in assemblage: charcoal (left), coal (middle) and clinker (right).

Rock/Mineral

Some rocks/minerals were found in the 60 litre bulk sample. The majority of the fragments above 10mm are sandstone and were perhaps used in the furnace structure. The sandstone pieces are mainly flat sided (like slate) of varying thicknesses ranging from 0.7cm to 2.7cm. They are light yellowy grey with some darker red patches and black

spots. Most are fragmentary between 1cm and 2cm but there are larger ones up to 11cm in length. The sandstone is fine grained but there are a few thicker grained yellowy fragments. Attached to one of these more friable pieces is some brown yellowy reddish orange slag (about 3cm in length). This strengthens the idea that the stone was used, or at least associated with, the industrial production. The rest (a minority) are small pebbles or stones which were probably naturally deposited.

Other

Two large plano convex cake fragments were found during the watching brief prior to the excavation. They have not been included in the material groups above due to their lack of context. It is believed that they have come from context 120, resting on the slag mound (personal communication Scurfield 2010). Due to their unique and interesting properties they will be described here but will not feature in the rest of the study as the lack of a precise context may lead to confusion or mis-interpretation (especially when dealing with just a couple of examples that have such a distinct morphology).

Fig 13. Large plano-convex fragment.

Fig 14. Large plano-convex fragment.

The largest fragment is 52.4cm in length, 39.9cm in width (incomplete) and 15.1 cm in depth (Figs 13 and 14). The top surface is quite rough with some projections of slag. It is dark grey in colour but the majority of the surface is covered in yellowy orange patches. This may imply that it was in contact with the bloom or that it has high iron content. It is magnetic over its whole surface and very dense (35kg). The fragment is plano-convex in profile and oval in plan (although not complete in width). The unbroken edges are rounded (reasonably smooth) and it is almost certainly a furnace or hearth bottom. The bottom is quite smooth with small undulations and a coating of dusty, friable dark grey material. This may be the residues of clay. There are yellowy orange patches and two medium protrusions of slag that interrupt the smooth convex base. The slag is vitrified in places and metallic blue in colour. On the top there are some largish (up to 3cm)

charcoal impressions/residues. In profile it is solid with a few broken and spherical holes (up to 1cm in diameter).

Fig 15. Smaller plano-convex fragment.

Fig 16. Smaller plano-convex fragment.

The other fragment is smaller and more incomplete. It is 23.6cm in length (incomplete), 22cm in width (incomplete) and 7.2cm in depth (Figs 15 and 16). It is quite rough but almost flat on the top surface. It is dark purplish grey in colour with some yellowy orange patches. There is one small protrusion of slag spoiling its almost flat top surface. The bottom surface is quite smooth and convex. Like the larger fragment discussed above there is a coating of dusty dark grey material which may be remains of clay. In profile it is solid with a few irregular and spherical holes (less than 0.6cm). It is very dense (4584g) and slightly magnetic over its whole surface hinting at high iron content. This fragment could be a large run of tap slag but its solid consistency/nature compared to the other tap slag in the assemblage would indicate that it is more likely a piece of furnace or hearth bottom.

SCIENTIFIC EXAMINATION

Eleven samples were taken for analysis; six honeycomb slags of which two were diagnostic, two semi-diagnostic, one non-diagnostic and one selective (LF01 to LF06). Two dense tap slag samples were also taken (LF07 and LF08) and three amorphous lumps of which one was from the selective fragments (LF09, LF10 and LF11). See Appendix 1 for location of cut samples.

Microstructure of Slags

All the slags (apart from LF09, LF10 and LF11) in the assemblage have microstructures typical of iron bloomery slags (McDonnell 1986; Morton and Wingrove 1969 and 1972). All the honeycomb slag (LF01 to LF06) is very porous with thin sections of slag networks surrounding spherical holes (Figs 17 and 18).

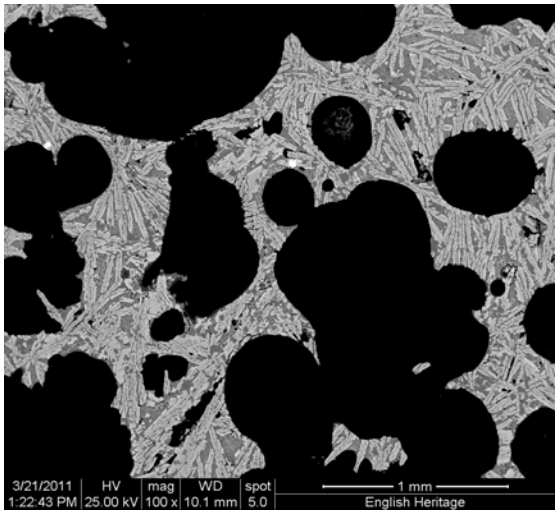

Fig 17. Spherical porosity in LF01.

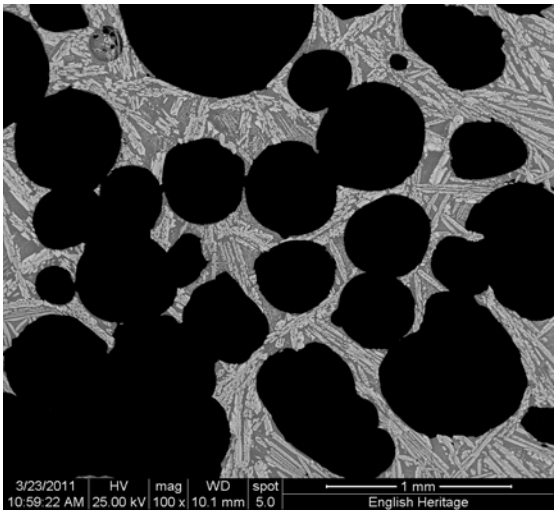

Fig 18. Spherical porosity in LF04.

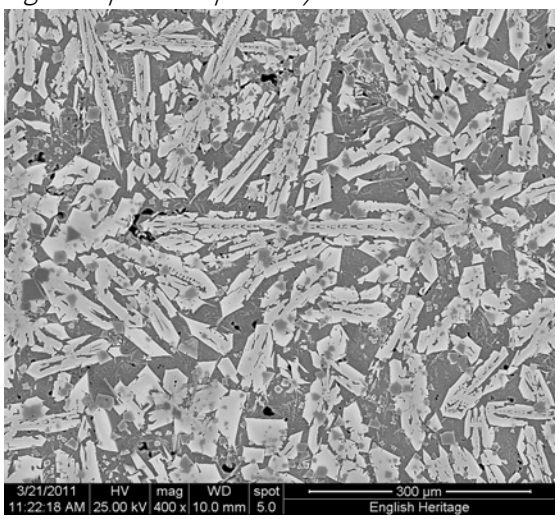

Fig 19. Skeletal fayalite laths in LF01.

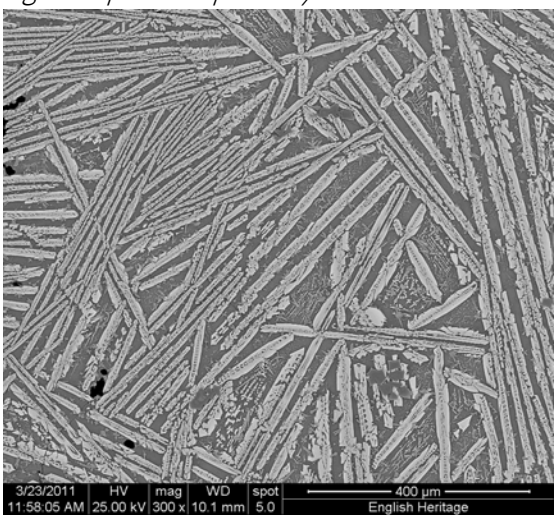

Fig 20. Elongated fayalite laths in LF04.

Although the more solid tap slag samples (LF07 and LF08) are less porous they also have areas with concentrations of spherical holes. This may indicate that they are the same slag as the honeycomb textured ones but represent more consolidated parts (eg the edges of the slag run). This is further supported by the similarity in microstructure of samples LF01 to LF08. They all have well formed skeletal sometimes feathery fayalite laths (Fe_2SiO_4, Fe sometimes partially substituted by Mn, Ca and Mg). These represent the most abundant phase and varied in size from 200 to 1000 micron averaging around 500 micron. Their skeletal and very elongated (thin) shape suggests very fast cooling (Figs 19 and 20). In the majority of cases the fayalite laths became thinner and more elongated towards the natural edges of the samples (Fig 21) while in some areas the fayalite formed in spinefex structures (Fig 22) — triangular patterns with smaller laths within — which is also indicative of fast cooling (Clough 1986, 287–8). Sample LF08 due to its small size and close proximity of the natural edges (top, bottom and one side) almost fully consisted of tiny and very elongated fayalite crystals. Only a small area furthest away from these edges revealed the more skeletal laths so dominant in all the other samples. Grainy fayalite was present in some samples but not as common.

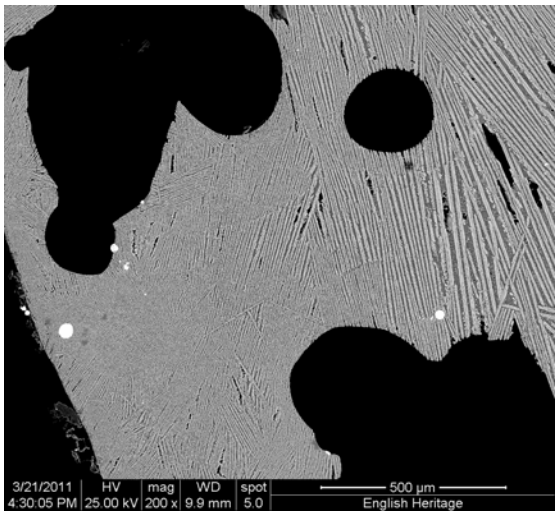

Fig 21. Elongated fayalite laths on natural edge in LF02.

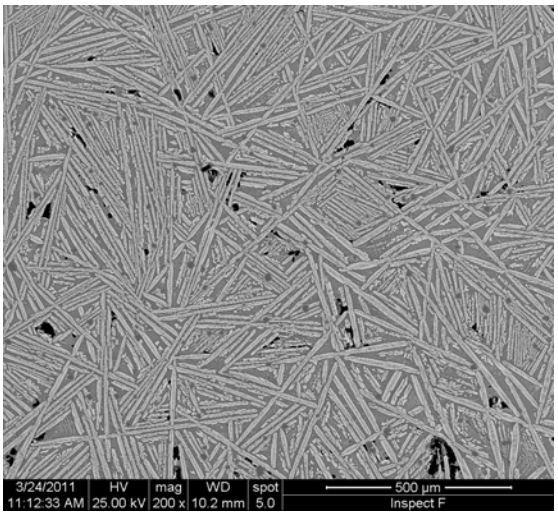

Fig 22. Spinefex fayalite in LF07.

Samples LF01 to LF08 differ from typical early bloomery slags by containing a large proportion of exotic phases, primarily hercynite ($FeAl_2O_4$) and leucite ($KAlSi_2O_4$). The hercynite was present as small (10 to 60 micron but averaging around 40 micron) angular crystals scattered all over the samples (Figs 23 and 24). Morton and Wingrove (1972, 480) also identified hercynite in their slags but contrary to their findings that these contained no Mg, the spinels found in the slags from Wortley have Mg partially substituting Fe. This was also noticed in Dungworth's (2010, 18) analysis of slags from the possible water-powered bloomery at Goscote. The spot analyses of the hercynite crystals revealed that there was a degree of chemical zoning whereby the core was often Mg rich while the edges had increased concentrations of iron oxides. This is a phenomena also observed by Dungworth (2010, 18). Most samples also contained small proportions of cross-shaped spinels with greater proportions of Fe (Figs 25 and 26). These tended to

concentrate in between the larger fayalite laths within the glassy matrix. The other exotic phase was leucite. This was less abundant than the spinels but tended to form small concentrations of globular crystals sometimes forming larger networks often concentrated around porosity (Figs 27 and 28). Small proportions of anorthite ($CaAl_2Si_2O_8$) were also present at the bottom of sample LF06.One of the most striking observations was the absence of any free iron oxides. Whereas typical early bloomery slags have large contents of FeO (wüstite) none of the slags analysed in this study contained significant proportions of iron oxides. These were limited to natural edges where tiny wüstite dendrites and possibly magnetite (Fe_3O_4) formed solidification fronts (Figs 29 and 30). A small concentration of globular wüstite was present in sample LF03 but its rounded aspect and tight concentration may be suggestive of the re-oxidisation of a metallic prill (Figs 31 and 32). The glassy matrix was quite prominent in all samples but often dominated by tiny crystalline almost dendritic fayalite (Figs 33 and 34).

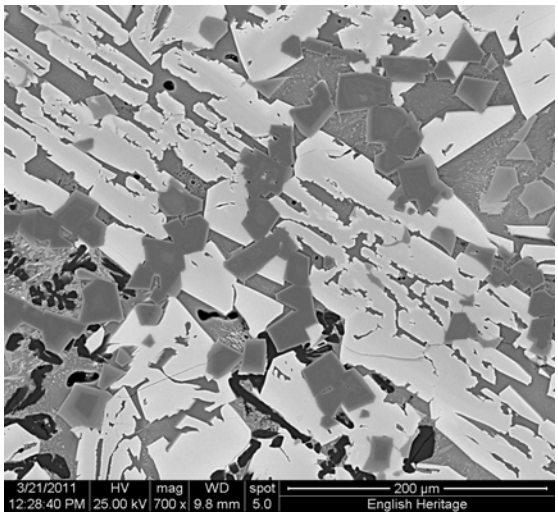

Fig 23. Hercynite grains (mid grey) in LF01.

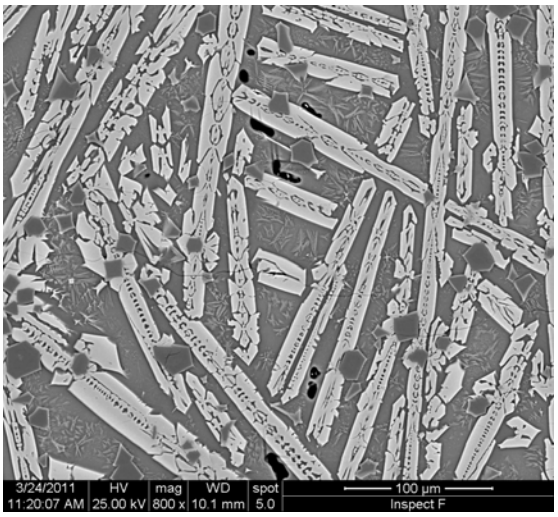

Fig 24. Hercynite grains (mid grey) in LF07.

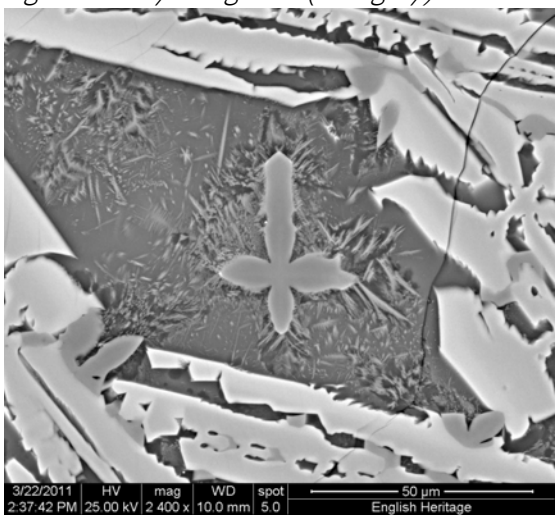

Fig 25. Cross shaped Hercynite grains (mid grey) in LF03.

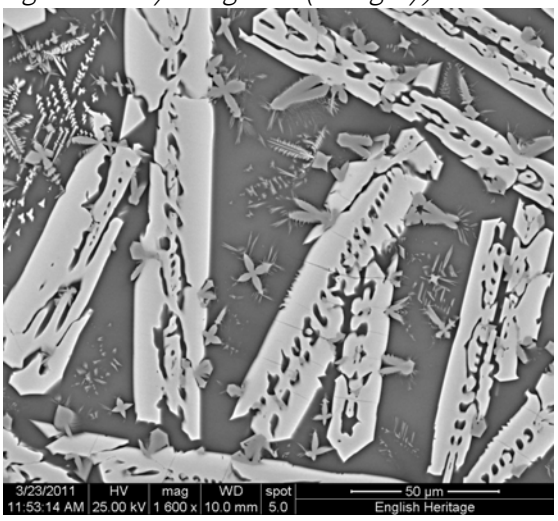

Fig 26. Cross shaped Hercynite grains (mid grey) in LF04.

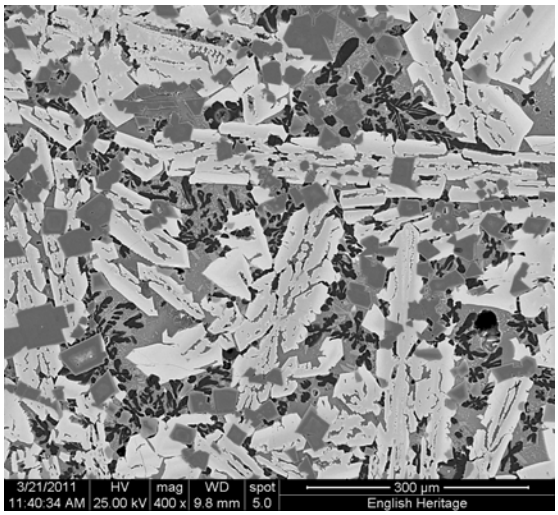

Fig 27. Globular leucite concentrations (dark grey) in LF01.

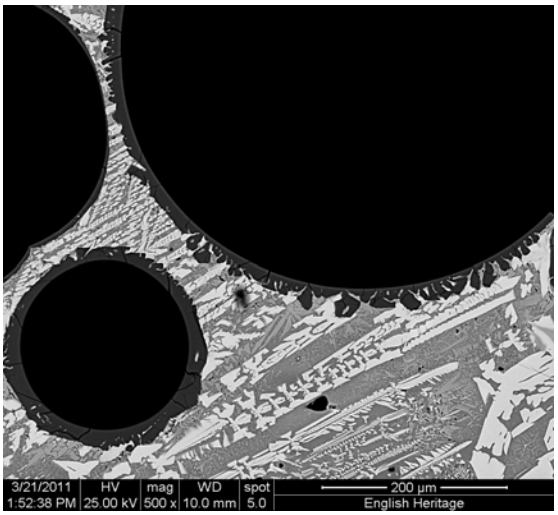

Fig 28. Globular leucite (dark grey) around porosity in LF01.

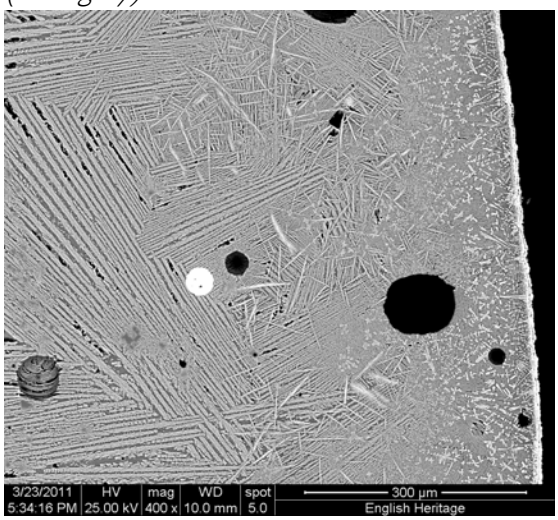

Fig 29. Wüstite dendrites on solidification front in LF06.

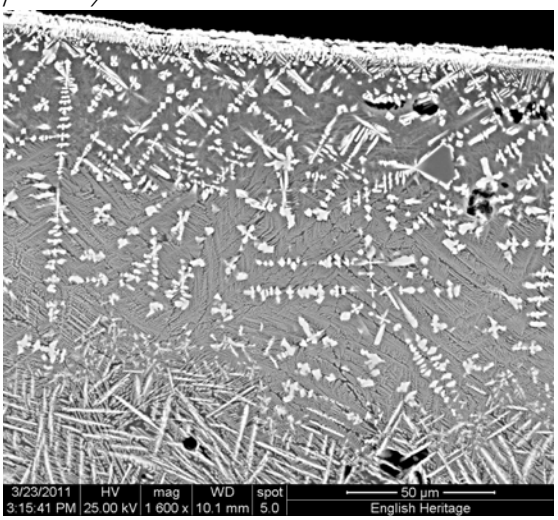

Fig 30. Wüstite dendrites on solidification front in LF06.

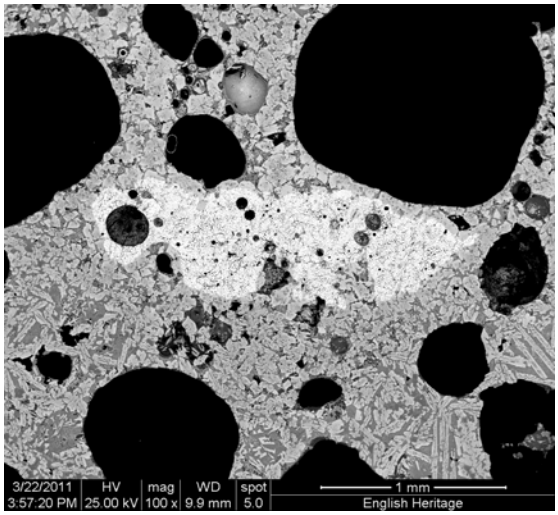

Fig 31. Wüstite concentration in LF03.

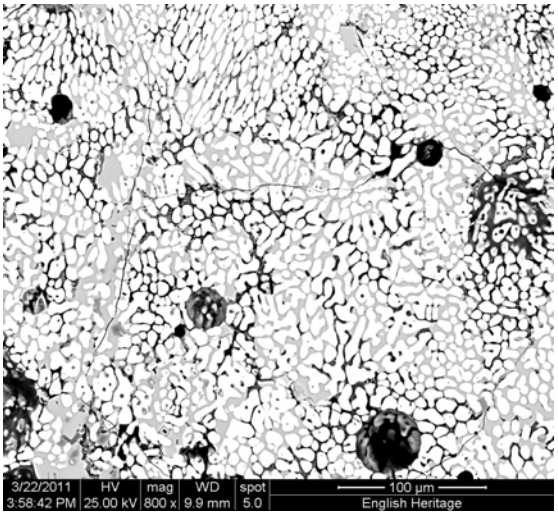

Fig 32. Wüstite concentration in LF03.

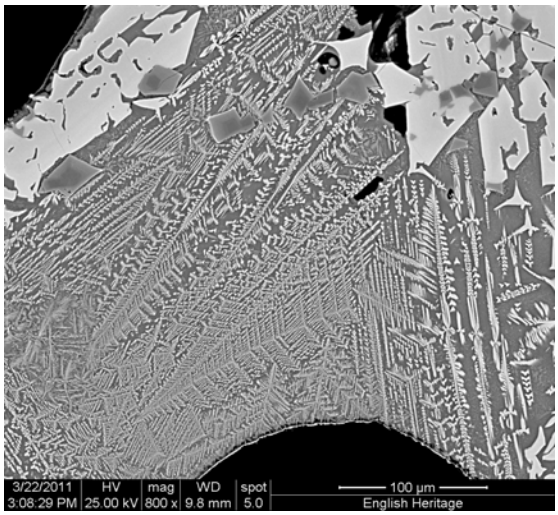

Fig 33. Dendritic fayalite in glassy matrix in LF03.

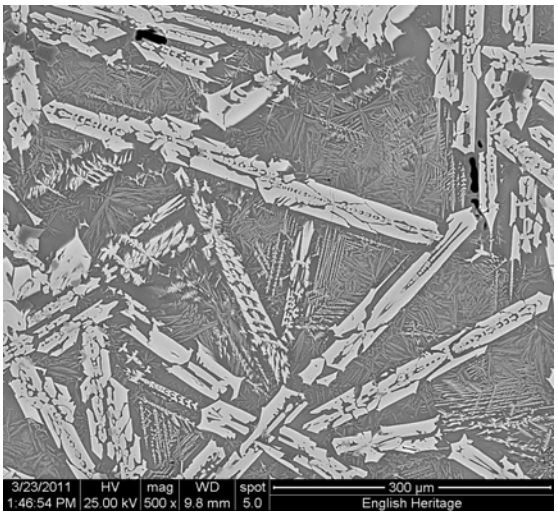

Fig 34. Dendritic fayalite in glassy matrix in LF05.

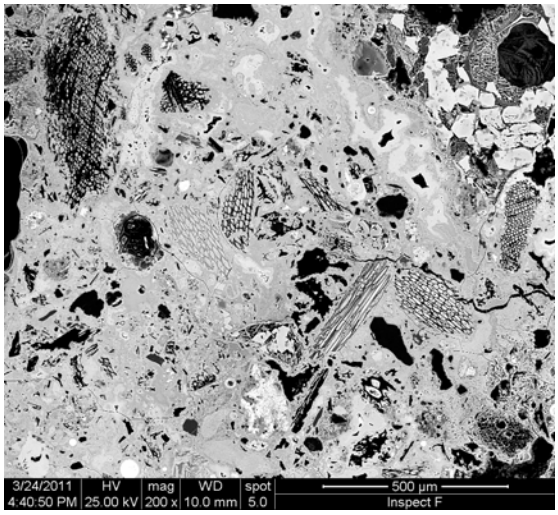

Fig 35. Fuel inclusions in LF09.

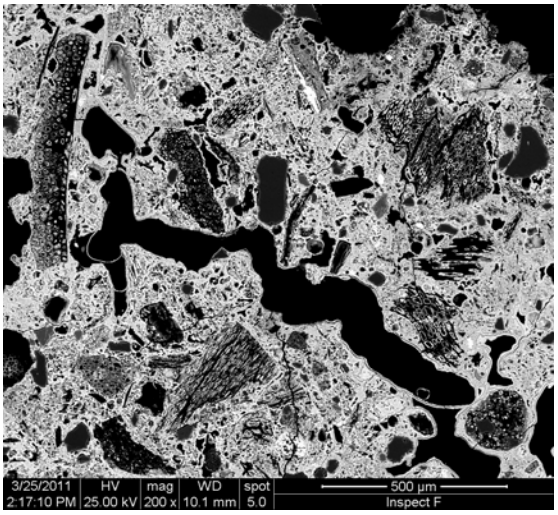

Fig 36. Fuel inclusions in LF10.

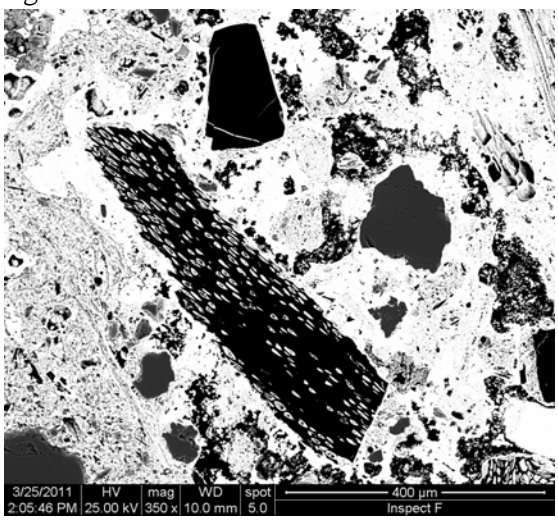

Fig 37. Charcoal, coal and quartz inclusions in LF10.

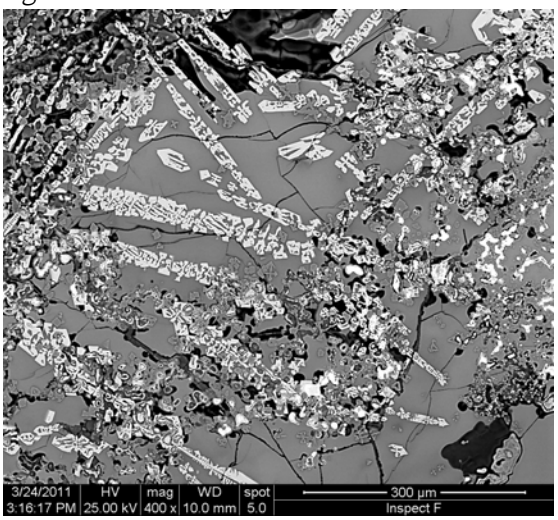

Fig 38. Skeletal fayalite (light) in a glassy matrix in LF09.

Samples LF09 and LF10 were very different from the slags described above. These were taken from the amorphous lumps which appeared to be amalgamations of several materials. The microstructures reflected this visual interpretation revealing many coal and charcoal inclusions in an iron-rich matrix (Figs 35 to 37); much of which appeared to represent iron corrosion. LF09 contained large expanses of glassy phase or matrix with a mixture of overlying concentrations of anorthite (Figs 38 and 39). The anorthite was present as elongated rectangular (20 to 120 micron) grains. Hercynite and leucite were also present but very sparse. The leucite concentrated in globular networks while the hercynite was mainly cross shaped and rich in iron oxide as observed in the slags. LF09 also contained areas of slag very similar to those discussed above. These tended to concentrate on one specific part of the sample and must have been in contact with the other material at reasonably high temperatures due the reactions on the join line. Two hammerscale flakes about 1mm in length were present in LF09 (Fig 40). Both samples have some wüstite; dendritic networks in LF09 and more globular concentrations in LF10. It is possible that these two amorphous fragments were smithing waste which may explain the trapped coal fragments and hammerscale. Another possibility is that they are the remains of a working floor (smithing pan) which would also account for the charcoal and slag.

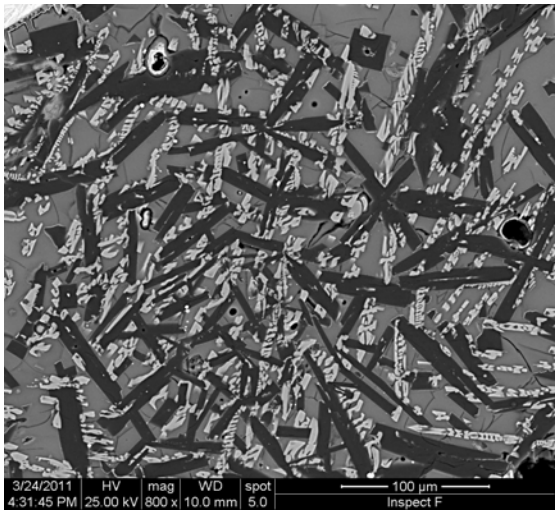

Fig 39. Skeletal fayalite (light) and anorthite (dark) in a glassy matrix in LF09.

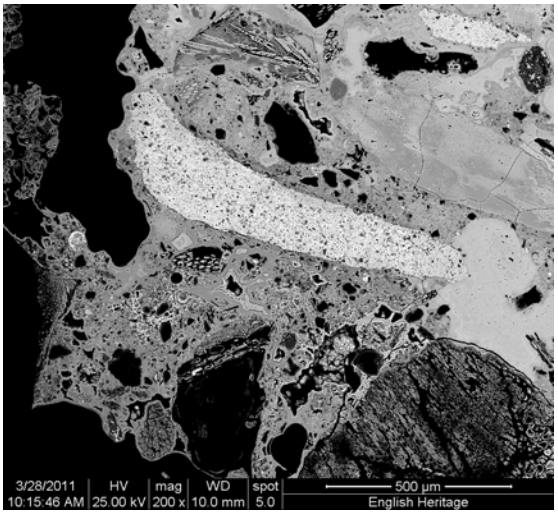

Fig 40. Hammerscale flake in LF09.

Sample LF11 was again different from the rest. The microstructure was reasonably homogenous throughout. It mainly composed of a large proportion of quartz grains in a glassy matrix (Figs 41 and 42). Tiny, perfectly spherical phosphorous-rich iron prills were scattered within this matrix while bloating voids dominated the centre. The quartz grains suggest that this was a ceramic while the lack of structure in the glassy matrix means it must have been fully molten (highly vitrified) yet not reached temperatures high enough to melt the quartz. This would explain the amorphous and undiagnostic appearance of the fragment and the formation of tiny spherical iron prills. Slag was attached to one side of the sample sharing the same characteristics/microstructure and chemical properties as the slag fragments discussed above (Fig 43). The slag had partially reacted with the

ceramic material suggesting that they were in contact at high temperatures (Fig 44). The vitrified clay must therefore have had a connection with the smelting activities at Low Forge and it is not unconceivable that it was part of a furnace structure but the poor preservation of the fragment limits further interpretation.

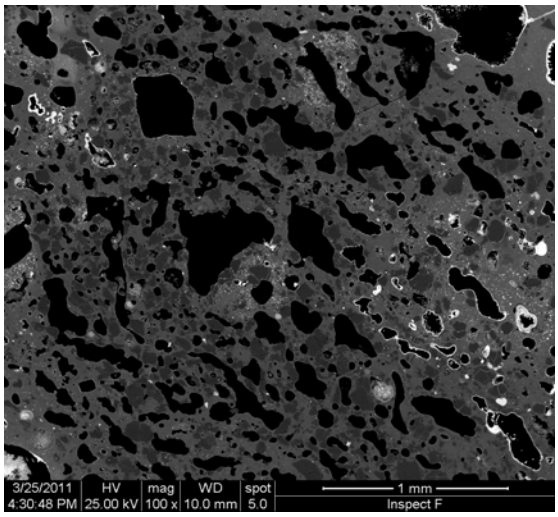

Fig 41. Porosity in the centre of LF11.

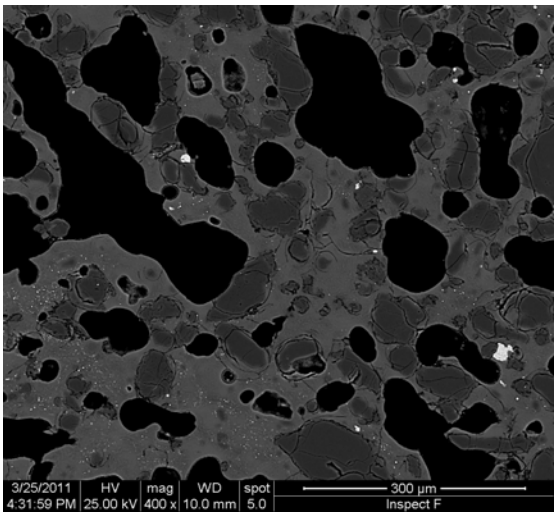

Fig 42. Quartz grains in LF11.

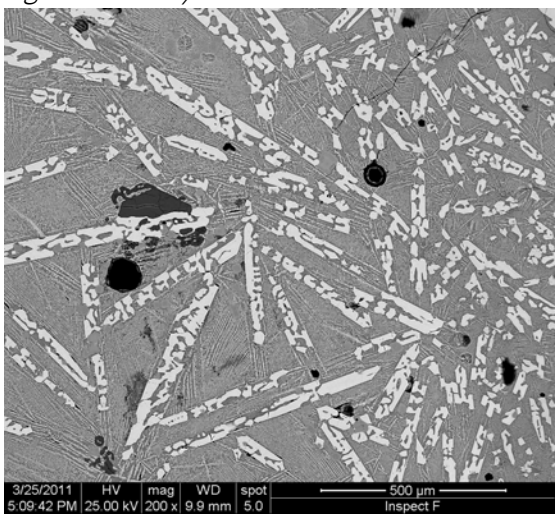

Fig 43. Slag on edge of LF11.

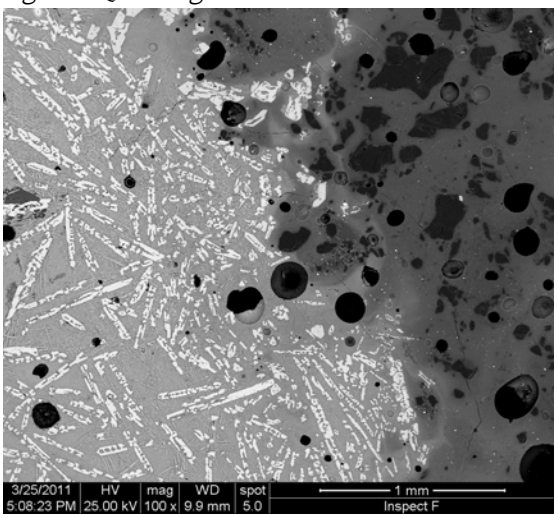

Fig 44. Slag on edge of LF11.

Slag Chemical Compositions

The average chemical composition for each sample is given in Table 3 below. It is evident from the results that all the slags (LF01 to LF08) are all very homogenous with around 40wt% FeO (perhaps some Fe_2O_3), 30wt% SiO_2, 13wt% Al_2O_3, 3wt% MgO, 2.5wt% K_2O, 3wt% MnO and about 1.5wt% P_2O_5. Samples LF09 and LF10 differ more in composition and the increase in FeO (as much as 80wt%) would support a smithing origin as opposed to smelting. However, the presence of charcoal and coal as well as bloomery slag and hammerscale in their microstructure would suggest that they are fragments of a working floor (smithing pan). Sample LF11 showed microstructural properties associated to highly

vitrified clay. This is supported by the chemical composition as it is consistent with other clays and furnace structures with a majority of SiO_2 (~65wt%) and considerable contents of Al_2O_3 (~16wt%) and FeO (~8wt%).

Table 3. Average chemical composition of each sample.

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
LF01	0.3	2.9	12.8	29.5	1.4	0.2	2.4	5.0	0.5	2.9	41.6
LF02	0.3	2.5	13.9	30.9	1.6	0.3	2.4	4.5	0.5	2.9	39.7
LF03	0.3	2.8	13.3	29.6	1.8	0.1	2.5	5.6	0.5	3.4	39.6
LF04	0.3	2.4	14.0	31.6	1.5	0.2	2.5	5.1	0.6	3.1	38.4
LF05	0.4	2.9	13.5	31.5	1.7	0.1	2.5	6.2	0.6	3.5	36.6
LF06	0.3	2.0	13.1	28.6	1.9	0.2	2.3	4.0	0.5	2.3	44.4
LF07	0.3	3.1	13.6	30.4	1.3	0.2	2.2	5.6	0.6	3.3	38.9
LF08	0.4	3.0	12.8	31.7	1.5	0.3	2.2	4.7	0.5	3.4	39.0
LF09	0.3	1.8	11.7	25.3	2.1	0.4	1.4	1.8	0.4	1.8	52.5
LF10	0.3	0.2	2.8	12.3	1.5	0.5	0.2	0.7	0.1	0.1	81.0
LF11	0.7	1.6	16.1	64.6	0.4	0.1	4.4	1.7	0.9	1.1	8.3

Iron Prills

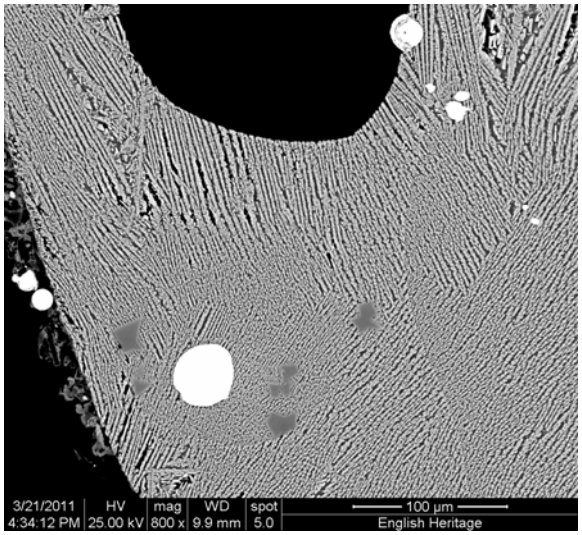

Fig 45. Spherical iron prills in LF02.

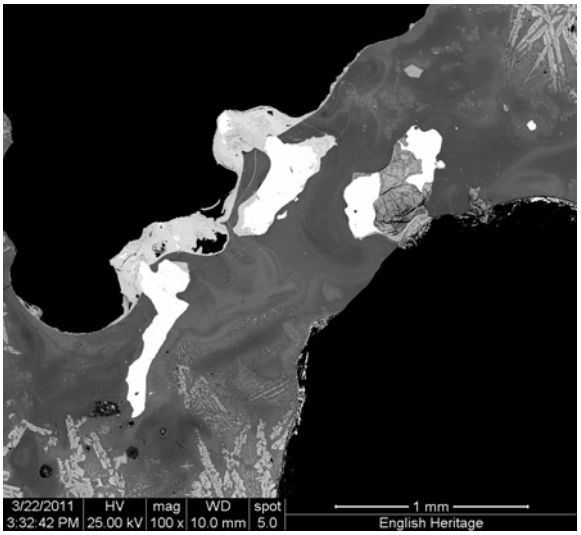

Fig 46. Large irregular prills in LF03.

All samples apart from LF07 and LF10 had iron prill inclusions. Most prills were small (<50micron) and spherical (Fig 45) but there were a few larger (up to 1000 micron), more irregular/globular prills in samples LF02 and LF03 (Fig 46). The small spherical prills appeared to be pure iron with no other substantial elements (Table 4). A few prills appeared to have Mn and Ni contents right on the detection limit. The major anomaly was concentrations of P (up to 1.5wt%) in the large irregular prills found in LF03. As these were the largest concentrations of metallic iron in the assemblage it raises questions on the representativeness of the smaller spherical prills that are so often taken to represent the type of iron produced (Dungworth 2009; 2010; Girbal 2010). It is possible that small

metallic inclusions (with a larger relative surface area) would be more likely to react with surrounding slag. Please refer to Appendix 3 for individual iron prill data.

It is possible that the iron produced was rich in phosphorus but it may also be due to the high phosphorus content of the slags (Table 4). Tylecote (1962a, 253) argues that "we can expect to find that the P content of the metals is about ½ to ¼ that of the slag". This would suggest that the iron may have contained as much as 0.8wt% P. However, the dynamics of phosphorus in the smelting process have yet to be fully understood as it can usually be found in varying proportions in both the metal and the slag. It is likely that smelting parameters and the behaviour/content of other elements affect phosphorus in ways we do not as yet fully understand. Nevertheless it suggests the use of ores with considerable amounts of phosphorus (Piaskowski 1989). Two samples (LF02 and LF03) were etched (2% nital) showing that the iron was primarily ferritic (Fig 47) but some of the larger prills in sample LF02 showed pearlitic microstructures. This once again raises the question of the representativeness of small iron prill inclusions found in slags of the original iron produced. The presence of ferritic iron may be explained due to its decarburisation in the slag. The phosphoris content in the prills would also prevent the carburisation of the iron.

Fig 47. Optical micrograph of a spherical prill with ferrite microstructure in LF02.

The perfectly spherical prills in the glassy matrix of LF11 (discussed above – Fig 48) show characteristics of having been fully molten. As the clay was clearly vitrified it must have been subject to extreme temperatures and was likely associated with a furnace structure. It is possible that the iron oxide in the clay reduced (due to the proximity of burning charcoal) to form these metallic prills. These also have high concentrations of P (up to 2.7wt%) which may be a contribution from the fuel ash.

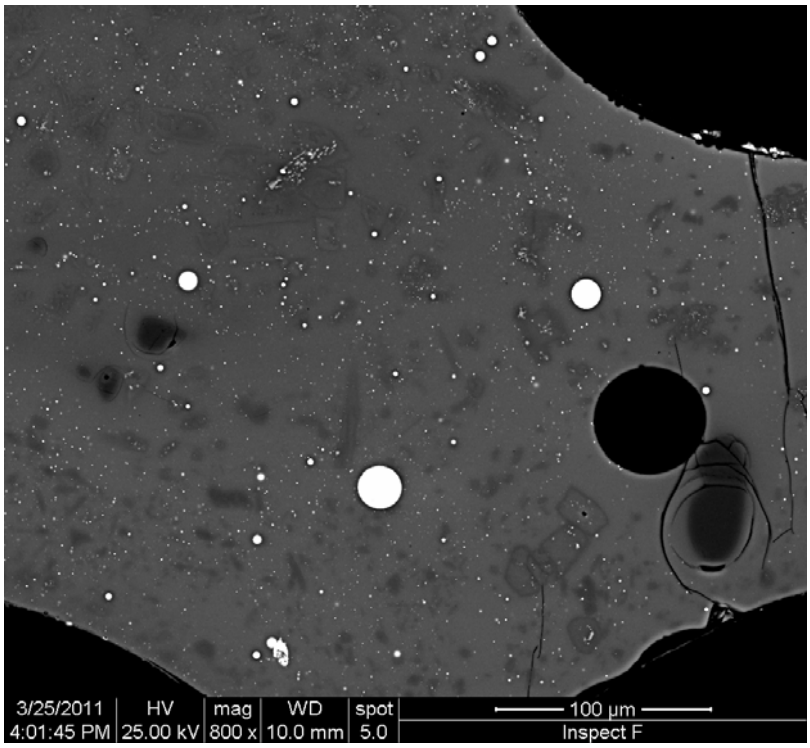

Fig 48. Perfectly spherical iron prills in LF11.

Table 4. The average chemical compositions of iron prills in the samples.

Sample	Prill Shape	P	Mn	Fe	Ni
LF01	small spherical	<0.2	<0.1	99.2	0.1
LF02	small spherical	<0.2	<0.1	99.2	<0.1
LF03	large irregular	1.3	<0.1	98.0	<0.1
	small spherical	<0.2	<0.1	99.2	<0.1
LF04	small spherical	<0.2	<0.1	99.5	<0.1
LF05	small spherical	<0.2	0.1	99.2	<0.1
LF06	small spherical	<0.2	<0.1	99.2	<0.1
LF08	small spherical	<0.2	0.2	98.9	0.2
LF09	small spherical	0.8	<0.1	98.5	<0.1
LF11	tiny spherical	2.5	<0.1	96.6	0.1
	other	0.5	<0.1	98.7	<0.1

DISCUSSION

The slags from Low Forge were very morphologically distinct. This very frothy honeycomb textured slag has been found at other possible water-powered bloomery sites. Tylecote (1960, 455) described the slag at Kyrkeknott as having a fine and widespread porosity "giving it a honeycomb texture" but with a smooth and upper surface typical of tapped slag. This parallels exactly the slag found at Low Forge. Dungworth (2010, 16) also describes the slag from Goscote as honeycomb textured while Vernon *et al* (1998, 77) analysed frothy slag from Timberholme. Tylecote and Cherry (1970, 98) and Photos-Jones *et al* (1998, 28) mention the presence of porous slag from Muncaster Head and Fasagh. This may not be a coincidence and may prove to be the main morphological aspect of metallurgical residue enabling water-powered bloomery sites to be identified.

The chemical compositions of the slags from Low Forge were very homogenous and similar to other analyses effectuated on slags from possible water-powered bloomeries (Table 5). It is clear that they are almost identical to the slag analyses from Goscote, Bourne Pool, Kyrkeknott, Timberholme and Rockley Smithies. Indeed they are also very similar to the analyses of slags produced from ores from carboniferous deposits (Morton and Wingrove 1972, 482). This compositional similarity and the presence of a large quantity of spinels (also observed by Morton and Wingrove 1972) in the microstructures suggests that carboniferous ores were used at Low Forge. Morton and Wingrove (1972, 483) state that the general structure of slags from carboniferous ores is spinel and fayalite in a glassy matrix with the occasional presence of leucite in dendritic form. This would be a good description of the slags from Low Forge.

Table 5. Average chemical composition of slags from possible water-powered bloomeries (FeO also accounts for any Fe_2O_3). The average for Low Forge was taken from samples LF01 to LF08. References: 1 – Tylecote and Cherry 1970, 90; 2 – Morton and Wingrove 1969-70, 64; 3 – Dungworth 2010, 17; 4 – Tylecote 1960, 454; 5 – Vernon et al 1998, 78; 6 – Photos-Jones et al 1998, 26; 7 – Morton and Wingrove 1972, 482.

Ref	SITE	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
1	Muncaster Head	0.2	<1.0	4.8	19.8	0.4	<0.1	1.2	3.7	<0.5	<1.0	67.5
2	Rushall/Goscote	–	5.7	12.6	26.9	0.8	<0.1	–	6.4	–	1.0	43.9
3	Goscote	0.2	7.4	12.3	28.9	0.3	<0.1	2.5	7.1	0.5	1.3	39.4
2	Bourne Pool	–	5.4	11.6	24.7	0.5	<0.1	–	6.9	–	1.8	44.9
4	Kyrkeknott	–	3.8	8.3	30.9	0.4	0.1	–	4.1	0.3	4.6	44.5
5	Timberholme	0.4	2.2	8.4	25.5	1.4	–	1.3	14.9	0.6	1.0	38.3
6	Fasagh	0.2	0.7	1.6	13.4	2.1	0.7	0.3	1.1	<0.1	0.9	79.0
7	Rockley Smithies	–	1.8	13.7	26.9	1.8	nd	–	7.0	–	2.1	39.6
	Low Forge	0.3	2.7	13.4	30.5	1.6	0.2	2.4	5.1	0.5	3.1	39.8

It is apparent that the slags analysed in this study are quite different from those found at Muncaster Head and Fasagh. Morton and Wingrove (1972) argue that this phenomenon is based on the type of ore used. Ore found at Muncaster Head was very rich which may account for the higher FeO, lower Al_2O_3 and MgO contents. Of course since the metallurgical technologies employed at any of these sites have not been determined (not

proven to utilise water power to operate furnace bellows) it is possible that these two sites did not use the same technology as the others. However, it seems unlikely that the technology (in this case water-powered bloomeries) is to be accountable for the similarity in chemical composition since other sites, such as West Runton share similar composition but have no evidence for the use of water-power (Dungworth 2010, 20; Tylecote 1962b, 212).

Although porous slag was described at Muncaster Head and Fasagh, honeycomb texturing was not mentioned. This would imply that the slag may not have been quite as porous as the other possible water-powered bloomeries. One possible reason for this is that slag must be fluid enough for gas to enter but also viscous so that it cannot escape. The low alumina contents of the slags from both sites would have meant that the slag was of low viscosity whereas the higher alumina contents of the slags resulting from the carboniferous ores would have had a higher viscosity. This would account for their greater porosity.

Another point of interest is the possible addition of a limestone flux to the smelting process. Morton and Wingrove (1969-70) argue for the use of a limestone flux to increase the iron yield at Goscote (Rushall) and Bourne Pool. This was based on the high levels of CaO present in the slags (~6–7wt%) and the lack of it in the ores (~1wt%) found on both sites. The slags at Low Forge have similar CaO contents (~5wt%) but unfortunately no ore was found meaning that its contribution to the composition of the slags cannot be determined.

CONCLUSION

A 60 litre bulk sample from the excavation at Low Forge was examined which was primarily composed of metallurgical waste (slag). The subsequent visual and scientific analyses have shown that it is the residue of iron production, most likely from bloomeries. The pottery finds suggest a 13th to 16th century date for this activity. The distinct honeycomb texture of the slag analysed is consistent with accounts of slag from possible water-powered bloomeries. The microscopic examination revealed microstructures containing a large proportion of spinels which is also consistent with the slag analyses from other possible water-powered bloomeries (Morton and Wingrove 1972). In addition the chemical composition almost matched the slag from several of these sites. This chemical similarity is most likely due to the use of comparable ores from carboniferous deposits (Morton and Wingrove 1972) but combined with the similar morphological aspects of the residue, it suggests that they employed a similar technology. The hammerscale present in the assemblage indicates that smithing was occurring on site contemporary with the smelting and may be evidence of the string hearth mentioned in the deed of 1621. Unfortunately without further archaeological investigation it is impossible to prove whether the water was powering the bellows, the hammer or both.

The analyses of the iron prills present in the slags have hinted at the production of phosphoric iron. This may explain the historical reference stating that the iron was primarily sold to nail makers in Mortomley (Scurfield 2009). A phosphoric iron would make the iron brittle and unsuitable for certain applications. Yarranton (1677, 58) mentions the production of an iron in England that is distinguished by its cold brittleness suitable for making nails. If the iron produced was indeed phosphoric then it is unlikely to have been steel, as phosphorus inhibits carburisation of iron. On the other hand both ferritic and pearlitic iron was noticed in the slags so it is possible that the phosphorus was unevenly distributed in the iron which would also explain its absence in the majority of the small prills. Whatever the nature of the metal it is very likely considering the high phosphorus content of the slags that the ore was rich in phosphorus.

Although it is not possible to ascertain the exact use of water power, the analysis of the slags suggest that water-powered bloomeries were in operation at Low Forge sometime between the 13th and 16th centuries. Further archaeological examination would be required to assess the full extent of industrial activity in this period. Nevertheless, the slag analyses provide comparative data to further our understanding of the technological choices between the end of the bloomery and the adoption of the blast furnace.

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APPENDIX 1. LOCATION OF CUT SAMPLES

LF01 top

LF01 bottom

LF02 top

LF02 bottom

LF03 top

LF03 bottom

LF04 top

LF04 bottom

LF05 top

LF05 bottom

LF06 top

LF06 bottom

LF07 top

LF07 bottom

LF08 top

LF08 bottom

LF09 top

LF09 bottom

LF10 top

LF10 bottom

LF11 top

LF11 bottom

APPENDIX 2. METAL STANDARD DATA

11/4CR1/2MO 1ARM 35IN

Spectrum	SiO_2	Cr_2O_3	MnO	FeO	CoO	NiO	Cu_2O	ZrO_2	MoO_2
1	0.63	1.20	0.54	95.68	0.51	0.25	0.20	0.34	0.40
2	0.62	1.18	0.55	95.91	0.52	0.18	0.10	0.11	0.57
3	0.69	1.22	0.56	95.99	0.43	0.09	0.13	0.00	0.63
4	0.61	1.22	0.62	95.87	0.46	0.10	0.15	0.00	0.71
5	0.59	1.21	0.58	95.50	0.58	0.22	0.13	0.28	0.67
6	0.64	1.23	0.63	96.08	0.41	0.15	0.12	0.05	0.43
7	0.64	1.22	0.54	96.03	0.43	0.21	0.16	0.00	0.51
8	0.59	1.21	0.61	96.20	0.43	0.19	0.14	0.20	0.17
9	0.66	1.18	0.57	95.81	0.44	0.12	0.13	0.00	0.82
10	0.63	1.20	0.61	95.67	0.38	0.18	0.18	0.16	0.74
Mean	**0.63**	**1.21**	**0.58**	**95.87**	**0.46**	**0.17**	**0.15**	**0.11**	**0.56**
Reported	**0.59**	**1.13**	**0.54**		**0.013**	**0.122**	**0.17**	**0.002**	**0.47**

MBH 14M B.S. 66K

Spectrum	Al_2O_3	SiO_2	P_2O_5	SO_3	MnO	FeO	CoO	NiO
1	0.02	0.08	0.12	0.46	1.15	97.61	0.47	0.00
2	0.12	0.08	0.11	0.57	1.03	97.48	0.41	0.08
3	0.02	0.06	0.17	0.53	1.09	97.53	0.40	0.10
4	0.04	0.10	0.14	0.39	1.10	97.54	0.44	0.14
5	0.00	0.04	0.10	0.55	1.20	97.45	0.51	0.06
6	0.07	0.04	0.15	0.38	1.13	97.67	0.47	0.00
7	0.00	0.18	0.14	0.43	1.06	97.55	0.53	0.01
8	0.07	0.09	0.05	0.34	1.14	97.79	0.36	0.05
9	0.05	0.04	0.08	0.47	1.23	97.51	0.47	0.06
10	0.01	0.09	0.04	0.64	1.17	97.42	0.40	0.14
Mean	**0.04**	**0.08**	**0.11**	**0.48**	**1.13**	**97.56**	**0.45**	**0.06**
Reported	**0.002**	**0.004**	**0.062**	**0.322**	**0.86**		**0.013**	**0.012**

MBH 11X C1 K

Spectrum	SiO_2	P_2O_5	V_2O_5	Cr_2O_3	MnO	FeO	CoO	NiO	Cu_2O
1	1.05	0.23	0.15	0.33	1.31	92.16	0.46	0.59	0.23
2	1.17	0.10	0.18	0.33	1.39	92.15	0.34	0.64	0.20
3	1.12	0.12	0.17	0.32	1.35	91.94	0.56	0.66	0.26
4	1.12	0.15	0.22	0.32	1.32	91.92	0.51	0.71	0.23
5	1.15	0.15	0.15	0.33	1.37	91.93	0.45	0.71	0.26
6	1.18	0.21	0.12	0.27	1.25	92.06	0.60	0.62	0.19
7	1.23	0.13	0.13	0.38	1.35	91.87	0.64	0.61	0.17
8	1.12	0.04	0.15	0.26	1.27	92.34	0.49	0.66	0.17
9	1.16	0.11	0.16	0.34	1.35	92.07	0.52	0.63	0.16
10	1.20	0.18	0.16	0.28	1.35	91.79	0.56	0.73	0.24
Mean	**1.15**	**0.14**	**0.16**	**0.32**	**1.33**	**92.02**	**0.51**	**0.66**	**0.21**
Reported	**1.14**	**0.108**	**0.13**	**0.28**	**1.22**		**0.05**	**0.59**	**0.23**

APPENDIX 3. INDIVIDUAL IRON PRILL DATA

The chemical compositions of iron prills in the samples.

Sample	P	Mn	Fe	Ni
LF01	<0.2	<0.1	99.1	<0.1
	<0.2	<0.1	99.2	0.2
	<0.2	<0.1	99.3	0.1
	<0.2	<0.1	99.3	<0.1
	<0.2	<0.1	99.2	0.1
LF02	0.2	0.1	99.0	<0.1
	<0.2	0.2	99.2	<0.1
	<0.2	<0.1	99.3	<0.1
	<0.2	<0.1	99.2	<0.1
	0.2	<0.1	99.3	<0.1
LF03	1.5	<0.1	97.9	<0.1
	1.2	<0.1	98.2	<0.1
	1.2	<0.1	98.0	0.1
	<0.2	<0.1	99.2	<0.1
	<0.2	<0.1	99.4	<0.1
	<0.2	<0.1	99.1	<0.1
LF04	<0.2	<0.1	99.5	<0.1
LF05	<0.2	<0.1	99.2	<0.1
	<0.2	0.1	99.3	<0.1
	<0.2	0.1	99.2	<0.1
LF06	<0.2	<0.1	99.1	<0.1
	<0.2	<0.1	99.2	0.1
	<0.2	<0.1	99.2	0.1
	0.3	<0.1	99.1	<0.1
	<0.2	<0.1	99.3	<0.1
LF08	<0.2	<0.1	98.9	0.1
	<0.2	0.2	98.9	0.3
	<0.2	0.2	98.9	0.1
LF09	0.3	<0.1	99.1	<0.1
	<0.2	<0.1	98.4	<0.1
	<0.2	<0.1	98.3	<0.1
	0.8	<0.1	98.4	<0.1
	<0.2	<0.1	98.3	<0.1
LF11	2.7	<0.1	96.3	0.1
	2.3	<0.1	97.0	0.1
	2.3	0.1	96.7	0.1
	0.5	<0.1	98.7	<0.1
	0.5	<0.1	98.7	0.1






ENGLISH HERITAGE RESEARCH DEPARTMENT

English Heritage undertakes and commissions research into the historic environment, and the issues that affect its condition and survival, in order to provide the understanding necessary for informed policy and decision making, for sustainable management, and to promote the widest access, appreciation and enjoyment of our heritage.

The Research Department provides English Heritage with this capacity in the fields of buildings history, archaeology, and landscape history. It brings together seven teams with complementary investigative and analytical skills to provide integrated research expertise across the range of the historic environment. These are:

* *Aerial Survey and Investigation*
* *Archaeological Projects (excavation)*
* *Archaeological Science*
* *Archaeological Survey and Investigation (landscape analysis)*
* *Architectural Investigation*
* *Imaging, Graphics and Survey (including measured and metric survey, and photography)*
* *Survey of London*

The Research Department undertakes a wide range of investigative and analytical projects, and provides quality assurance and management support for externally-commissioned research. We aim for innovative work of the highest quality which will set agendas and standards for the historic environment sector. In support of this, and to build capacity and promote best practice in the sector, we also publish guidance and provide advice and training. We support outreach and education activities and build these in to our projects and programmes wherever possible.

We make the results of our work available through the Research Department Report Series, and through journal publications and monographs. Our publication Research News, which appears three times a year, aims to keep our partners within and outside English Heritage up-to-date with our projects and activities. A full list of Research Department Reports, with abstracts and information on how to obtain copies, may be found on www.english-heritage.org.uk/researchreports

For further information visit www.english-heritage.org.uk

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