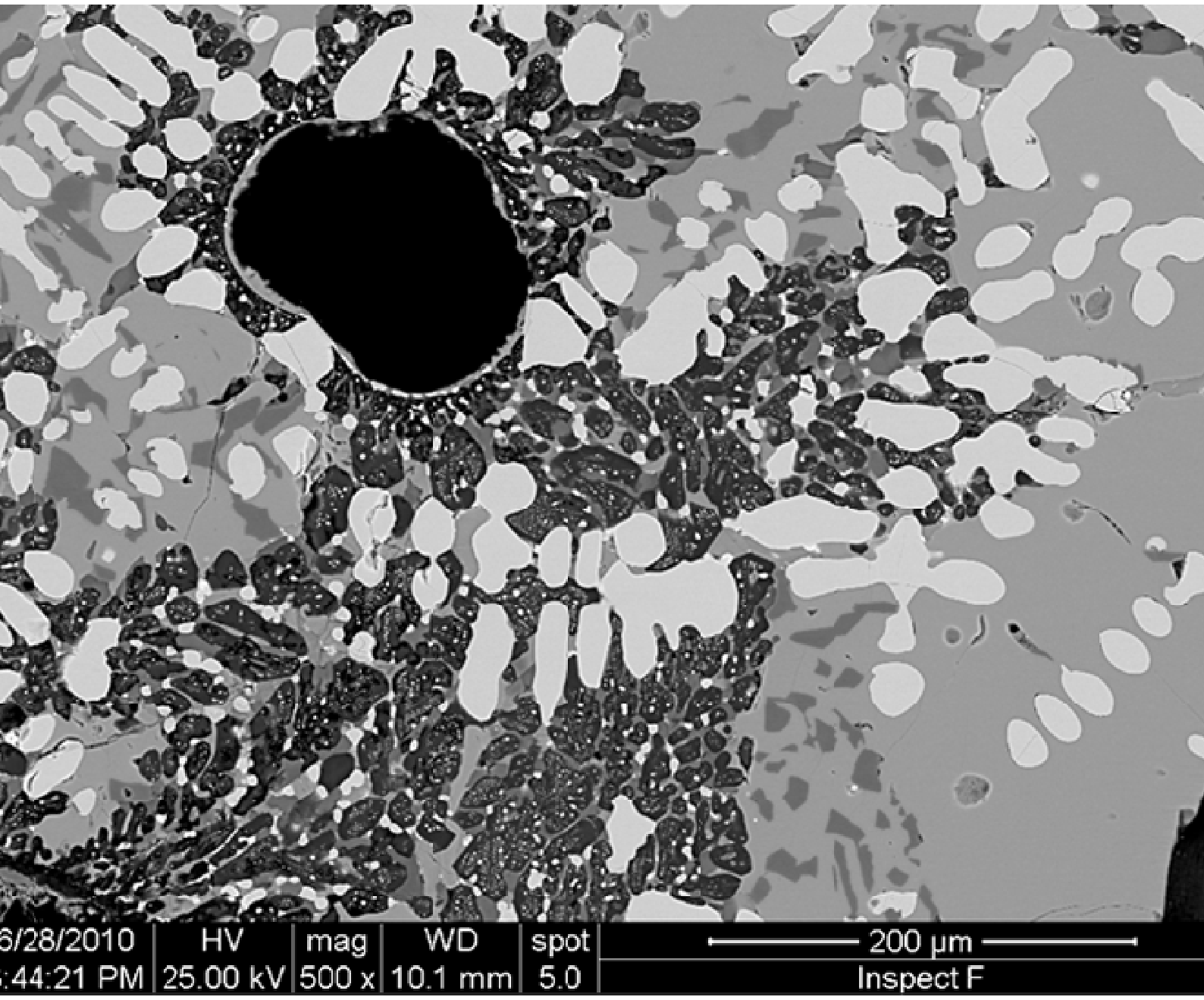
RESEARCH DEPARTMENT REPORT SERIES no. 78-2010 ISSN 1749-8775

MICHELMERSH, ROMSEY, HAMPSHIRE
ANALYSIS OF THE SLAG

TECHNOLOGY REPORT

Brice Girbal



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Research Department Report Series 78-2010

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ANALYSIS OF THE SLAG

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NGR: SU 3367 2586

ISSN 1749-8775

SUMMARY

84kg of industrial debris was retrieved from the Iron Age site of Michelmersh. Approximately 60kg of slag was identified and analysed scientifically in the hope to gain a clearer understanding of iron manufacture in Iron Age Wessex. Their morphology revealed that iron was being smelted/produced in the slag pit furnace tradition characteristic of pre-Roman iron technology. The debris showed little micro-structural and compositional variability which suggests that it was all produced by the same or similar technology. Several points of interest were raised such as the high manganese oxide content of the slags. It is argued that the assemblage forms part of a new geological group as discussed in Paynter 2006 and it is proved that other production sites on similar geology produced slags characteristic by their high manganese oxide contents. It has not been possible to identify Michelmersh as the production site for the Danebury currency bars but several other iron artefacts from Danebury have revealed compositional parallels with the iron prills and slags analysed in this study suggesting that they may have been made locally.

ACKNOWLEDGEMENTS

I would like to thank David Dungworth for all his patience in teaching me how to use the scientific equipment and for all his help with data processing and report writing. I would also like to thank Harriet White and Sarah Paynter for all their help with site comparisons and with writing the report. Tim Young deserves special mention for his assistance in identifying the ores. Wessex Archaeology, in particular Sue Nelson and Paul McCulloch need thanks for providing the material analysed in this study and help with context information.

ARCHIVE LOCATION

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DATE OF RESEARCH

May-July 2010

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INTRODUCTION

The excavation at Michelmersh took place in May 2008 under the direction of Wessex Archaeology. It was commissioned by NLJV on behalf of the National Grid to undertake a programme of targeted archaeological excavations and watching brief in mitigation of a 32km pipeline route between Barton Stacey (Ordnance Survey National Grid Reference SU 44247 42811) and Lockerley (NGR SU 30294 25118), Hampshire. The mitigation works included nine areas of targeted excavation (MT 01-09).

The area concerned here is MT08 (Michelmerch NGR SU 3367 2586 – Fig 1) which yielded approximately 60kg of slag. Most of the slag was recovered from a large pit which contained bone that has given a radiocarbon date of 790–520 cal BC (personal communication Paul McCulloch 2010). The report will contain the detailed examination of all the slags recovered.

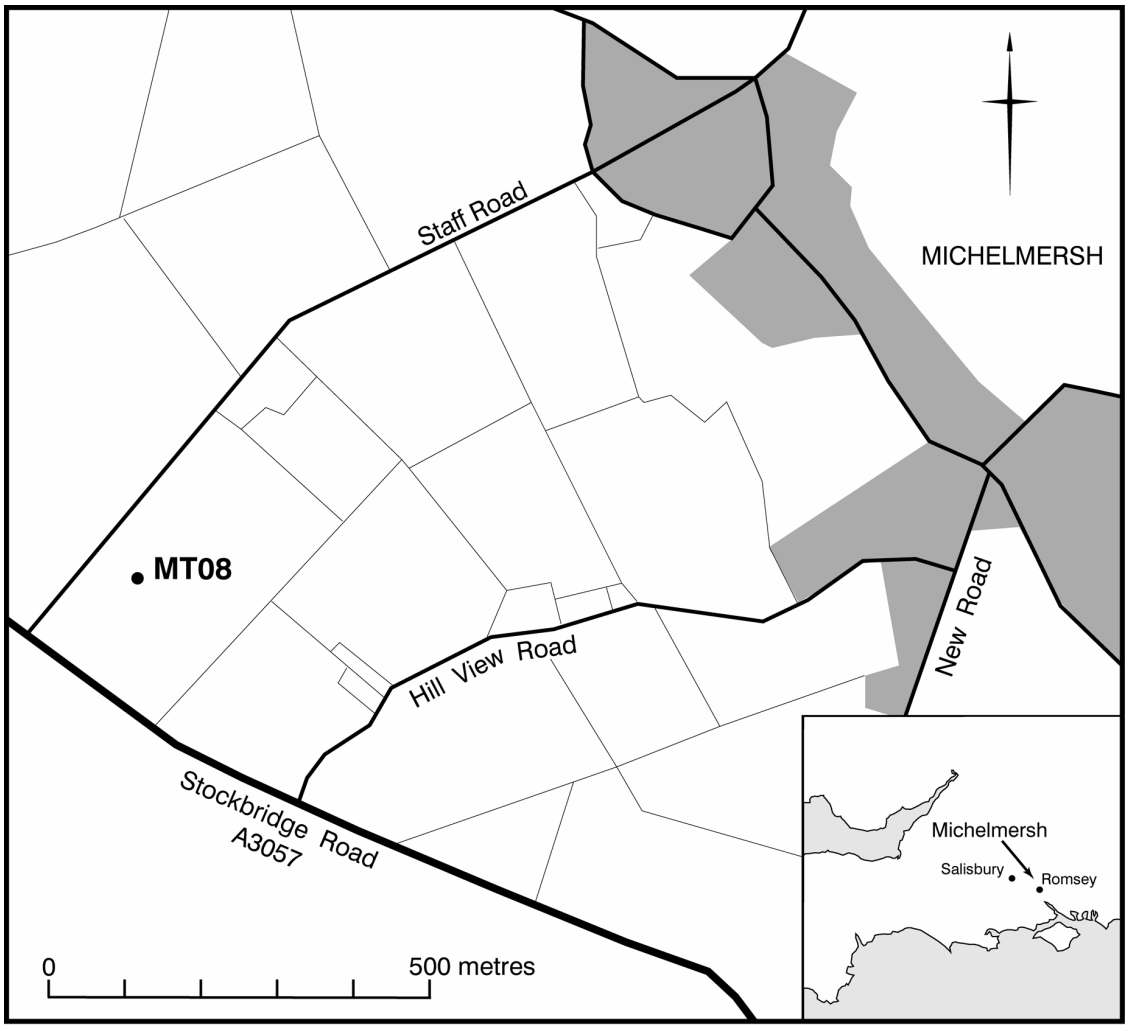

Fig 1: Location of MT08 at Michelmersh (Trevor Pearson)

BACKGROUND

In order to recognize the importance of slag remains (waste product of iron making – in this case the bloomery process) it is essential to understand the principles behind the production of prehistoric iron. Iron ore (a rock rich in iron oxide) is burnt along with charcoal in a furnace; a structure usually made of clay or soil in which the charge (ore and charcoal) is held. The carbon monoxide produced by the burning charcoal reduces the iron oxide in the ore to metallic iron (Schrufer-Kolb 2004, 7). This is possible at a temperature of about 800°C which is well below the melting point of iron at 1540°C (Tylecote 1962, 183). However, iron ores not only consist of iron oxides but also contain many unwanted elemental compounds and minerals. It is therefore necessary to remove those from the iron ore during smelting. These gangue minerals combined with iron oxide have a lower melting temperature than iron (about 1150°C) and can be removed by liquation (Tylecote 1962, 183). To produce iron in solid state it is therefore necessary for temperatures to be above 1150°C but below the melting point of iron enabling the impurities in the ore to melt away in the form of slag (Schrufer-Kolb 2004, 7).

Unlike the iron, which is often turned into objects (by smithing) and frequently transported, the slag is usually discarded where the iron production took place. Because of this, slag is very important as an indicator of past iron production. Slag also stores a lot of information. The morphology of the slags is a good indicator of the type of technology employed; ie the furnace size, shape, etc (Bayley *et al* 2001; Gordon 1997; Paynter 2007). Having been through the smelting process it also stores information about the ingredients used in the smelt. The charge (charcoal and ore) as well as the furnace wall (which may partially melt) all contribute to the elemental compositions of the slags (Crew 2000; Fulford and Allen 1992, 197; Pleiner 2000, 252-3; Serneels 1993). Different types of raw material (diverging in composition) would therefore leave their unique traces in the slags.

Some studies (with varying levels of success) have attempted to provenance ore sources by matching certain elements in slags and known ore deposits. Recently, Paynter (2006) showed a correlation between geological areas and slag composition; regions of similar geology would produce comparable raw materials which would be reflected in the slag compositions. These studies have also been extended to the analysis of slag inclusions in iron artefacts. Slag inclusions trapped in metal objects are thought to retain (in part) elements of the smelting slag and therefore the raw materials employed to produce the iron. It has been argued that by comparing their compositions to slags from production sites or ore deposits it may be possible to provenance their manufacture (Blakelock *et al* 2009; Buchwald and Wivel 1998; Coustures *et al* 2003; Desaulty *et al* 2009; Dillmann and L'Héritier 2007; Hedges and Salter 1979; Salter 1982; Schwab *et al* 2006).

The evidence for prehistoric iron manufacture at MT08 is of considerable importance. The archaeology of Iron Age Wessex has been the subject of considerable study which has framed much of our understanding of the Iron Age in the British Isles (Cunliffe 1983, 1991, 1993). Prehistoric iron artefacts from the region have been studied intensively

(Ehrenreich 1985; Hedges and Salter 1979) but very few iron production sites are known. Only a handful of iron production sites have been identified within Wessex and many of these do not stand up to close scrutiny. Evidence for prehistoric iron smelting has been claimed for Cow Down at Longbridge Deverill and All Cannings Cross (Cunnington 1923; Tylecote 1986, 139) but none of the claimed slag has been accessioned by Wiltshire Heritage Museum and cannot now be traced.

Hedges and Salter (1979) examined the slag inclusions in iron currency bars from a hoard excavated within the hillfort at Danebury (12km north of Michelmersh) and compared the results with currency bars from Beckford and Gretton. The compositions of the slag inclusions for each hoard were distinguishable from each other and, while local ore sources could easily be suggested for both Beckford and Gretton, the source of the Danebury currency bars was not identified. Ehrenreich (1994) notes that few iron production sites are known in Wessex and suggests that most iron was imported into the region. The detailed investigation of the iron smelting debris from Michelmersh provides a unique opportunity to examine prehistoric iron manufacture in this important region.

AIMS AND OBJECTIVES

The aim of this report is to provide a comprehensive account of the industrial debris recovered during the archaeological excavation at Michelmersh to gain a clearer understanding of iron manufacture in Iron Age Wessex.

The objectives will include the recognition and study of the various types of slags (furnace bottoms, flows and possible smithing hearth bottom) and the ore. 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 the Danebury currency bar hoard (Hedges and Salter 1979) as well as other prehistoric iron smelting slags (Paynter 2006; Oliver and Applin 1979; Dungworth 2007; Starley 1998).

Several questions will be addressed:

1. Do the remains reveal a particular technological trait (Paynter 2007)?
2. How does the technology fit into the wider metallurgical tradition of Iron Age Britain (Paynter 2007)?
3. How do the chemical compositions of the assemblage fit into the regional patterns identified by Paynter (2006)? What is the relevance of this for the provenancing of prehistoric iron?
4. Where might the manufactured Michelmersh iron have been going?

5. Do the chemical compositions reveal similar traits to the Danebury currency bars? Were the currency bars found at Danebury made in Wessex?

METHODOLOGY

Visual Analysis

The assemblage was washed and then examined visually. 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 then selected for micro-structural and chemical analysis. These were chosen to represent a good proportion of the fragments sampled and the assemblage as a whole (see scientific analysis section for more details). The bigger samples were cut with a rock saw removing a slice through the fragment about 3-5mm thick while smaller ones were 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. In the case of the slag cakes the samples collected were too large to polish and were therefore cut in half. These were labelled with a numerical suffix (eg SC1.1, SC1.2, etc) and analysed separately. For photographs showing the location and orientation of the cut samples please refer to Appendices 1 and 2.

The polished samples were then 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 3 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 while three iron prills per sample were spot analysed. Some slag samples had adhering clay and these were analysed separately (2 to 4 bulk readings).

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. Volumetric proportions of each mineral phase present (wustite, fayalite, hercynite and 'glassy matrix') were measured using the SEM's Oxford Instruments mapping tool which separates phases by their differing brightness (dependant on the phase's atomic number – backscattered electron). Percentage areas were calculated by selecting one micro-structurally representative region per sample.

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 forthcoming). 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 two decimal places while compositions below the detection limit of the measured element were labelled BDL (below detection limit). 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 ores and 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	BaO
DL	0.10	0.10	0.10	0.10	0.20	0.10	0.10	0.10	0.10	0.10	0.10	0.20
1	1.36	0.35	9.49	22.26	0.21	0.26	1.12	1.59	0.21	3.20	59.72	0.22
2	1.16	0.36	8.08	21.71	0.18	0.16	1.16	1.53	0.26	3.14	62.07	BDL
3	1.33	0.35	8.41	23.77	0.21	0.28	1.06	1.46	0.26	3.23	59.57	BDL
4	1.24	0.35	8.23	24.31	0.20	0.28	1.10	1.47	0.28	3.88	58.54	BDL
5	1.28	0.43	8.20	23.92	0.26	0.31	1.18	1.45	0.29	3.70	58.84	BDL
6	1.27	0.35	7.95	22.09	0.32	0.18	1.12	1.48	0.31	3.23	61.60	BDL
7	1.35	0.32	8.37	22.69	0.25	0.23	1.09	1.54	0.33	3.30	60.48	BDL
8	1.45	0.28	8.56	23.95	0.20	0.24	1.12	1.45	0.28	3.85	58.49	BDL
9	1.22	0.37	7.68	22.87	0.27	0.12	1.10	1.55	0.23	3.38	61.09	BDL
10	1.33	0.40	7.98	22.84	0.29	0.36	1.07	1.65	0.31	2.87	60.77	BDL
Mean	1.30	0.36	8.30	23.04	0.24	0.24	1.11	1.52	0.28	3.38	60.12	BDL
St.Dev	0.08	0.04	0.49	0.90	0.05	0.07	0.04	0.07	0.04	0.33	1.28	0.05
Repo-rted	0.61	0.38	7.14	24.73	0.26	0.16	1.02	1.42	0.32	3.01	57.10	0.08

Three ferrous standards (11X C1 K, 14M B.S. 66K and 11/4 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, Ni, Mn and Si) were adjusted/corrected accordingly.

XRD Analysis

Samples were selected for X-Ray Diffraction (XRD). These were approximately 1cm³ in size and taken as close to the SEM samples as possible so that the same material was analysed. They were then crushed manually with a steel pestle and mortar and sieved (Endecotts - 250 Micron aperture). The process was repeated until all the material was ground to a fine powder. After each sample the pestle and mortar was cleaned with a fine brush and compressed air so as to avoid cross-sample contamination. The fine powders were then analysed in the Bruker D8 Advance XRD with a LynxEye detector and copper anode X-ray tube. Analytical parameters were kept constant with a 0.19 discriminator lower level and 0.08 discriminator window width. The tube was set at 40 mA and 40kV while the probe was effectuated at a 2 theta angle of 10° to 80°. The increment step size remained at 0.02 and the scan speed at 0.5 sec/step. The spectra were scrutinised using the X'Pert Highscore software by PANalytical and the mineral phases were identified using the ICDD (International Centre for Diffraction Data) database.

MORPHOLOGICAL ANALYSIS

The assemblage was separated into several categories of material. Three major material types were found – slag, ore and clay. These were then sub-divided by different morphological properties of which eight sub types of material have been identified; each type/group weighed to the nearest gram by layer/context they were found in (Table 2).

Table 2: The weights in grams of the differing material types by context/layer.

CONTEXT (feature)	SLAG Cakes	Blocks	Flow Tendril	Undiag-nostic	Smith-ing	CLAY Burnt	Vitrified (slag)	ORE Ore
28026 (28025)	-	789	-	-	-	34	32	-
28027 (28025)	-	-	-	479	-	9	-	-
28031 (28030)	-	-	-	-	-	10906	-	140
28035	-	785	14	-	-	2	-	-
28036	-	-	-	-	-	11	-	-
28041	-	-	-	-	-	54	-	27
28043 (28042)	-	-	-	-	-	1664	22	-
28045 (28042)	-	-	-	-	-	157	-	-
28046 (28042)	-	-	-	-	-	163	-	-
28047 (28042)	-	-	-	-	-	26	-	-
28048 (28039)	21004	14982	2996	3717	-	579	1009	380
28057 (28056)	-	-	-	-	-	104	-	-
28058 (28056)	-	-	-	-	-	2074	-	-
28060 (28059)	-	-	146	124	-	3	-	-
28067 (28039)	1958	2637	511	638	-	551	10	95
28068 (28039)	-	-	-	-	-	1944	-	1065
28069 (28039)	-	-	-	-	1152	3404	-	54
28070 (28025)	7110	-	-	-	-	-	-	65
28073 (28025)	-	-	-	-	-	26	-	-
28075	-	-	-	-	-	89	52	-
28077	-	-	-	-	-	17	-	-
28081	-	-	-	-	-	20	-	-
28085	-	-	-	-	-	26	-	-
28086	-	-	-	-	-	12	-	-
28090	-	-	-	-	-	41	-	25
28092	-	-	-	-	-	77	-	-
28094	-	-	-	-	-	101	-	-
28099	-	-	-	-	-	78	-	-
TOTAL	30072	19193	3667	4958	1152	22172	1125	1851

All the slags in the assemblage are mainly dark grey (black) with some dark brownish red and light grey patches. This indicates that they are probably the remains of iron working as opposed to other non ferrous metals (Wynne and Tylecote 1958, 339).

Slag Cakes

The assemblage has around 30kg of slag cake fragments (Table 3). These are characteristic due to their usually flat top surfaces and rounded bottoms (plano-convex in profile). These cakes are often referred to as furnace bottoms (Bayley *et al* 2001; Dungworth 2007; 2009) but to avoid mis-representation before detailed analysis is done the author prefers to use the more general descriptive term, slag cake. They are characteristic of smelting furnaces where the slag was not tapped but allowed to collect at the bottom of the furnace or in a purposely dug pit (Paynter 2007).

The ones represented here have both surviving top and bottom surfaces (complete depth – Figs 2 and 3) but are quite fragmentary with no complete cakes in the assemblage. This is not surprising as they were all found in secondary fill layers of pit 28039. Re-deposition would have required some form of handling or moving around of the debris making breakage likely.

All the slag cakes have a reasonably flat and rough top surface. This is usually well consolidated to a two to four cm thickness. Below this top crust is less consolidated flow slag (Fig 3). This is consistent for the majority of the fragments. The flow slag appears as overlapping dribbles/networks of slag and reveals the direction of the flow. This flow is usually vertical and in some cases diagonal when the slag runs over/around an obstacle or on the bottom of the enclosing structure (eg SC13). These flow features resemble the flow slag tendrils which will be discussed below. All fragments have a similar depth/thickness ranging from seven to eleven centimetres suggesting that they are the result of a similar technology. Nine out of the fourteen fragments have clay residues on one side (Fig 4). These are all curved meaning that they were probably in contact with the furnace wall or that the pit was lined with clay. The curves revealed an approximate internal diameter of the structures (pits or furnaces) to be around 45-50cm.

Fig 2: Top surface of fragment SC1. Note the yellowy orange corrosion which may have been in contact with the bloom.

Fig 3: Bottom flow surface of fragment SC1.

Fig 4: Rounded clay side of fragment SC4. Note the orangey corrosion which may be the result of contact with the iron bloom.

Some of the fragments (nine – see Table 3) are covered with an orangey flaky material. The slag cakes with this material are not magnetic but that the fragments with little or less are (SC1, SC6, SC9 and SC14) suggesting that it may be corrosion. This corrosion is only found on the top of the slag cakes and may indicate that they were in contact with the bottom of the bloom (bloom formed above slag cake).

An important characteristic is the charcoal/wood impressions. These are quite large (up to 3.5cm wide and 8cm long) and more numerous within the networks of flow slag than on the top surfaces. It is possible that the flow slag ran around or impregnated charcoal/wood covering a slag pit as described by Paynter (2007). As more slag was produced it would have burnt through this organic layer leaving space for the accumulation of slag. The remains of wood or charcoal would therefore leave their impressions in the solidifying slag (Paynter 2007).

The slag cake from layer 28070 (SC14) is particularly interesting because it is denser and more consolidated than any of the other fragments. This may indicative that it was less viscous (more fluid) and perhaps the result of a different technology. Although it is not complete it has surviving top and bottom surfaces. One side is also curved and reasonably smooth where it solidified against the enclosing feature. The bottom of the fragment is covered in chalk which may have been fused to it when the slag was still hot. Chalk is the underlying geology in this area and if this is the case then this cake may be from the bottom of a slag pit dug below a furnace.

Table 3: Individual descriptions of slag cakes.

Slag Cake	Context (feature)	Size (l x w x d cm)	Weight (g)	Inclusions	Completeness
SC1	28048 (28039)	23.5 x 18.2 x 9.8	3602	Possible unreduced ore on top or corrosion from bloom. Slightly magnetic in some areas on top.	Fragment. Complete depth.
SC2	28048 (28039)	18.3 x 15.6 x 9.0	2551	Clay on one side. Lots of orange on top (oxidisation/ rust)	Fragment. Complete depth. Curved side with clay.
SC3	28048 (28039)	19.3 x 15.4 x 9.1	2239	Clay on one side. Lots of orange on top (oxidisation/ rust)	Fragment. Complete depth. Curved side with clay.
SC4	28048 (28039)	14.7 x 12.4 x 8.2	1117	Clay on one side. Lots of orange on top (oxidisation/ rust)	Fragment. Complete depth. Curved side with clay.
SC5	28048 (28039)	18.2 x 8.7 x 11.0	2054	Clay on one side. Lots of orange on top (oxidisation/ rust)	Fragment. Complete depth. Curved side with clay.
SC6	28048 (28039)	19.1 x 14.6 x 9.3	1916	Tiny bit of clay on one side. Slightly magnetic on top.	Fragment. Complete depth.
SC7	28048 (28039)	19.4 x 14.6 x 11.1	2199	Clay on one side. Some orange on top (oxidisation/ rust).	Fragment. Almost complete depth. Curved side with clay and curved bottom.
SC8	28048 (28039)	12.9 x 10.3 x 9.8	1263	Some orange on top (oxidisation/ rust).	Fragment. Complete depth.
SC9	28048 (28039)	16.8 x 10.7 x 8.6	1380	Slightly magnetic on top.	Fragment. Complete depth.
SC10	28048 (28039)	15.9 x 7.2 x 8.2	1001	Vitrified clay (broken/melted) on one side and part of top.	Fragment. Almost complete depth. Curved side with clay.
SC11	28048 (28039)	13.0 x 6.2 x 7.0	511	Clay on one side. Some orange on top (oxidisation/ rust).	Fragment. Almost complete depth. Curved side with clay.
SC12	28048 (28039)	16.5 x 14.2 x 7.0	1171	Lots of orange on top (oxidisation/ rust).	Two fragments. Complete depth.
SC13	28069 (28039)	18.5 x 9.6 x 10.2	1958	Some orange on top (oxidisation/ rust).	Fragment. Complete depth. Bottom shaped by rock or furnace.
SC14	28070 (28025)	25.6 x 25.4 x 8.4	7110	Slightly magnetic on parts of the top. Bottom covered in clay or chalk.	Large fragment. Complete depth. One side is rounded /curved – shaped by furnace?

Slag Blocks

Slag blocks are the second most numerous type of slag making 19.2kg of the assemblage. These fragments are named as such because they have no surviving diagnostic surfaces making their provenance (in the furnace) harder to determine. The fragments range in size from about five to sixteen cm in length and are all amorphous in shape. Their colour is similar to the slag cakes ranging from dark grey to dark brownish red with patches of light grey and orange.

The slag blocks all have large charcoal/wood impressions. On some fragments these impressions are aligned in one direction (Fig 5). This parallel alignment has also been

noted in the Thorpe Lea Nurseries assemblage (Starley 1998, 10). It could be suggestive of purposely placed/arranged organic material to cover a slag pit which the slag would then burn through but retain impressions (Paynter 2007). The majority of the fragments have flow features and their consistency would suggest that they are smaller fragments of the slag cakes that have lost their diagnostic surfaces/edges. Another possibility is that there is a continuum from flow – block – cake and the blocks are under-developed slag cakes. This slag may have solidified within the furnace around the charcoal charge retaining the shape of the charcoal. It could also be the first layer of slag which burnt through or impregnated the organic plug of the pit.

Fig 5: Parallel charcoal impressions on a slag block fragment.

About one third (5370g) of the fragments have burnt clay attached. This may support the theory that the slag blocks solidified within the furnace structure but the slag cakes also had clay residues, therefore the pit may have been lined with clay.

Slag Flow Tendrils

These are characterised by their well melted surfaces and evidence that they flowed; fingers of slag sometimes overlapping one another (Fig 6). Unlike tap slag they seem to have a vertical flow which suggests that this movement of slag occurred in the furnace (Dungworth 2009, 7). Few references to these have been made but they are generally

associated with iron smelting sites; Dungworth (2009, 7), Crew (2000, 39) and Tylecote (1992, 49) refer to these as slag prills but the author prefers the term tendril which will be used in this description.

The tendrils ranged in size from 1.5 to 7cm. Two types of flow slag tendrils were identified; about half (weight) of the fragments are quite large (4–7cm) while the others are smaller (1.5–4cm). The larger fragments all have charcoal impressions and are almost certainly smaller fragments of the slag blocks but have been characterised in this group due to their predominant flow like appearance. The smaller fragments have no or fewer charcoal impressions (Fig 6). This is probably because these had high surface tension and did not 'wet' the surface of the charcoal (Dungworth 2009, 7). The majority have break fractures which suggests that they may have been part of bigger fragments. It is quite likely that some of these are indeed broken parts of the flow slag observed on the slag cakes. However, some appear to be whole. These could be slag drips that have become detached from the larger cakes and fallen into the pit or even perhaps small slag runs that remained isolated, unable to consolidate into larger masses of slag.

Fig 6: Small slag tendrils.

Smithing Slag

A possible smithing slag was found in context/layer 28069. Its oval plan and plano-convex profile (Fig 7) suggests that it may be a smithing hearth bottom (Bayley *et al* 2001, 15).

The piece is complete and fully consolidated in appearance. It has dimensions of 16.4 cm in length, 10.8cm in width and 6.3cm in depth. It weighs 1152g which is above average for a smithing hearth but well within the norm (Bayley *et al* 2001, 15). On the surface it is yellowy, orangey brown in colour and is not magnetic. A fresh fracture revealed a dark grey and very porous interior with many small spherical holes. The fact that nothing else in the assemblage looks like smithing or metal working waste means that further analyses (micro-structural and chemical) are required to ascertain its provenance/technology.

Fig 7: Possible smithing slag.

Non-diagnostic Slag

There is 4.9kg of non-diagnostic slag in the assemblage. The fragments are all amorphous in shape and quite small (1–8cm) with the majority around 1–3cm. Due to their small size they do not reveal any major diagnostic characteristics. However, their density and colour indicates that the fragments were more likely the result of ironworking rather than the manipulation and production of other metals. The lack of hammerscale or any other substantial iron smithing debris would lead to suggest that most of this material was produced by iron smelting.

Clay

The majority of the clay found (22.2kg) is fired but not vitrified. About half (10.9kg) came from context 28031 which was described as 'deliberate backfill' relating to a breakdown of a possible oven. The fragments are mainly small and fragmentary but there are some larger pieces of up to 25cm in length and 5 to 7cm thick. These larger pieces have curvature and smoothed surfaces suggesting that the clay debris was probably part of a bigger structure. The clay is quite brittle and coarse grained. It has many largish (up to 6mm) chalk inclusions and none of it is vitrified. This means that the clay debris was not subject to the high temperatures associated with the production of metal suggesting that it is more likely to have had a domestic use as opposed to being furnace remains (metallurgical technology).

There is also some daub with characteristic parallel wattle impressions. The rest of the clay is smaller grained in fabric but more fragmentary resulting in a lack of diagnostic features. There are two possible furnace rims within the assemblage (contexts 28043 and 28058). These are fine grained and characteristic as rims, however, the overall lack of diagnostic features in the clay material reveals nothing of possible industrial production. Very little of the clay was found in slag containing contexts further emphasising the possibility of domestic as opposed to industrial use.

Ore

Approximately 1.8kg of ore was found on site (Table 1). The remains seem to be hematite and although it is hard to determine the majority appear to have been roasted. The bulk of the ore was found in pit 28039 with 380g recovered from context 28048, 95g from 28067, 1065g from 28068 and 54g from 28069. Some of these (90g in 28048 and 42g in 28067) are very magnetic which may be indicative of roasting; the heats reducing the iron oxides and turning the ore into hematite/magnetite (personal communication Paynter 2010). All the ore remains are fragmentary (no more than a few centimetres) with exception to context 28068. These are larger non magnetic fragments and were the only finds in this context. This may be suggestive of ore processing in that layer but the possibility that they are discarded fragments cannot be ruled out.

SCIENTIFIC ANALYSIS

Fourteen slag samples were taken for analysis: four slag cakes (SC), five slag blocks (SB) and five slag tendrils (ST) all of which came from context 28048 and 28067 where the majority of the slag was found. The exception is one slag cake that was sampled from context 28070. In addition three ore samples (MO) were taken from contexts 28031, 28048 and 28068 (where most of the ores were found).

Microstructure of Slags

All the slags in the assemblage have microstructures typical of iron bloomery slags (McDonnell 1986; Morton and Wingrove 1969). The area percentages of the crystalline phases in each sample are given in Table 4.

Table 4: Area percentage of the micro-structural phases in each slag sample.

SAMPLE (context)	Slag Fragment	Fayalite	Wüstite	Glassy matrix	Hercynite
SC1.1 (28048)	SC1 Top	66	25	6	<3
SC1.2 (28048)	SC1 Bottom	53	38	8	<1
SC2.1 (28048)	SC2 Top	62	33	5	<1
SC2.2 (28048)	SC2 Bottom	69	21	7	<3
SC3.1 (28048)	SC3 Top	55	37	6	<3
SC3.2 (28048)	SC3 Bottom	55	39	4	<2
SC14.1 (28070)	SC14 Bottom	69	11	20	Not Detected
SC14.3 (28070)	SC14 Top	40	51	9	Not Detected
SB1.1 (28048)	SB1 Whole	65	24	10	<1
SB2.1 (28048)	SB2 Whole	67	25	8	<1
SB3.1 (28048)	SB3 Whole	65	26	6	<3
SB4.1 (28048)	SB4 Whole	68	24	8	<1
SB5.1 (28067)	SB5 Whole	68	24	7	<1
ST1.1 (28048)	ST1 Whole	70	14	14	2
ST2.1 (28048)	ST2 Whole	70	15	14	<1
ST3.1 (28048)	ST3 Whole	73	12	15	<1
ST4.1 (28048)	ST4 Whole	74	18	8	<1
ST5.1 (28067)	ST5 Whole	69	21	8	<2
SH1.1 (28069)	SH1 Whole	28	62	10	Not Detected

Fayalite (Fe_2SiO_4, Fe sometimes partially substituted by Mn, Ca and Mg) was the most abundant phase making between 40% and 74% of the area of the slag. In the majority of the samples the fayalite was present as well formed equiaxed grains sometimes with a mixture of feathered laths (Fig 8). The grains varied in size between 200 and 500 microns and the laths between 400 and 2500 microns. This was largely dependant on the part of the samples in which they occurred. The closer to the natural edges or solidification fronts

the smaller the crystals. Laths were also more prominent close to natural edges, solidification fronts and around larger gas holes. Smaller and more lathy crystals indicates faster cooling and it is therefore not surprising to find these close to natural edges or porosity.

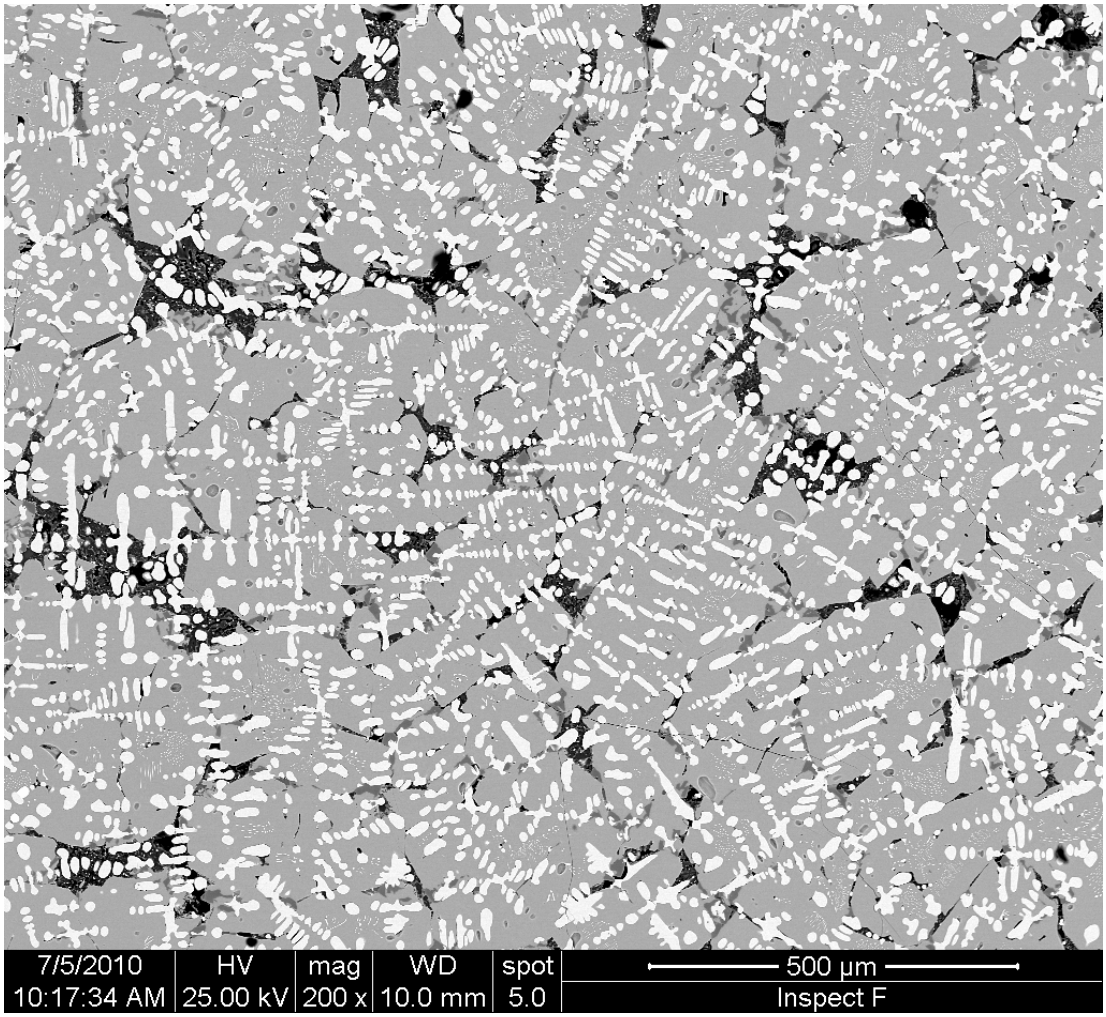

Fig 8: Equiaxed fayalite grains in sample SC1.1

Wüstite (FeO, possibly magnetite in sample SC14) made between 11% and 50% of the samples. It was present in two major crystal forms. Well formed wüstite dendrites were the norm in most of the samples although it sometimes took a more globular/dotty shape (especially in sample SH1.1). All samples also had varying proportions of eutectic wüstite within the fayalite crystals. This phase was mainly present as eutectic precipitation (dotty) but also sometimes quite myrmekitic (wormlike – Fig 9). The dendrites like the fayalite varied greatly in size and fineness (between 50 to 500 microns in length) largely dependant on their position in the sample. In general there tended to be fewer wüstite dendrites close to natural edges or larger gas holes. Conjointly the eutectic wüstite was

denser on fayalite laths than on equiaxed grains (that in some cases had no eutectic wüstite even though surrounded by it – Fig 9). It was also noted that the eutectic wüstite was more concentrated in areas with no or little free standing wüstite.

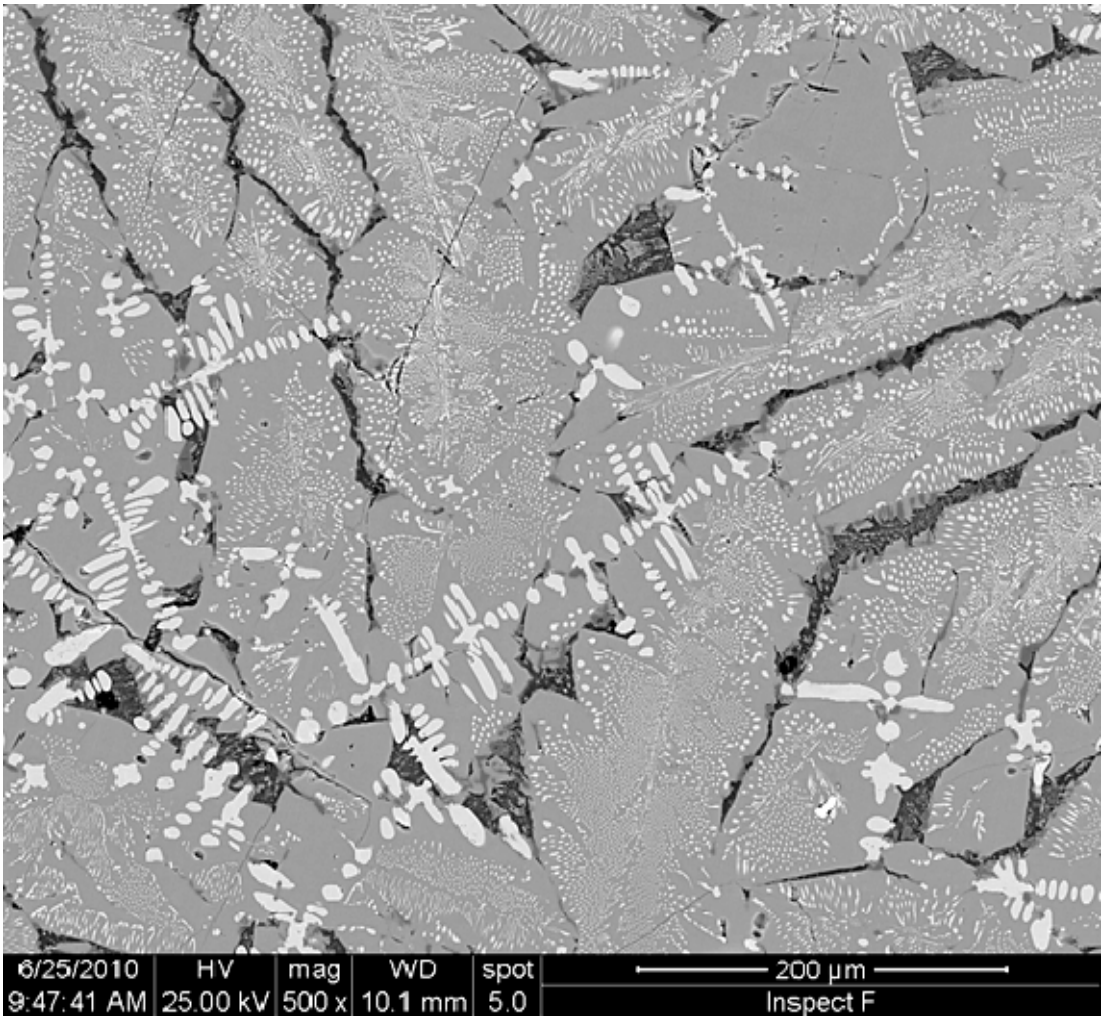

Fig 9: Eutectoid precipitation and myrmekitic wüstite in sample ST4.1.

Hercynite ($FeAl_2O_4$) was present in all the microstructures analysed (apart from SC14 and SH1). This phase was scarce usually making less than 1% of the total volume but some samples had as much as 2 to 3%. It was mainly present as small grains (5 to 30 microns) and clustered around the glassy matrix or the larger free standing wüstite dendrites (Fig 10).

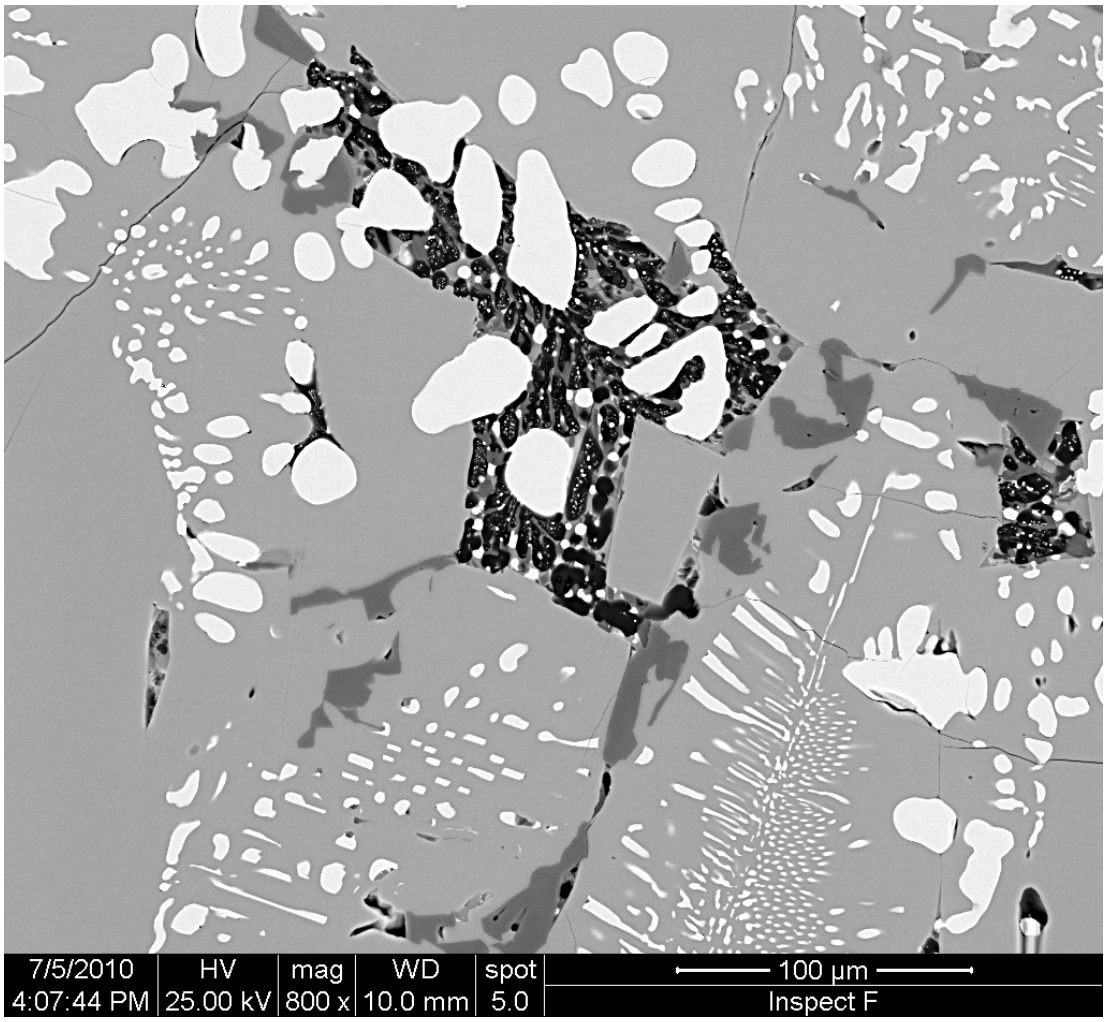

Fig 10: Hercynite grains (dark grey) close to leucite filled glassy matrix (black) in sample SC3.1.

The remainder of the sample compositions were listed in Table 4 as glassy matrix (McDonnell 1986); however, careful examination shows extensive de-vitrification in these areas (Figs 10–12). In most samples the glassy matrix contains tiny fayalite laths (Fig 11). Leucite ($KAlSi_2O_4$) was also present in some samples forming a leucite/fayalite matrix. In other cases well formed leucite globules were prominent sometimes with eutectoid wüstite within them (Fig 12). This de-vitrification suggests that the slag was kept at reasonably high temperatures for prolonged periods. It would also explain the concentration of hercynite around the glassy matrix as the excess alumina may have crystallised as it was de-vitrifying. The presence of hercynite and leucite suggests that the ore (other than iron and silica) was rich in other elements (alumina and potash) or that the furnace wall made a significant contribution to the slag.

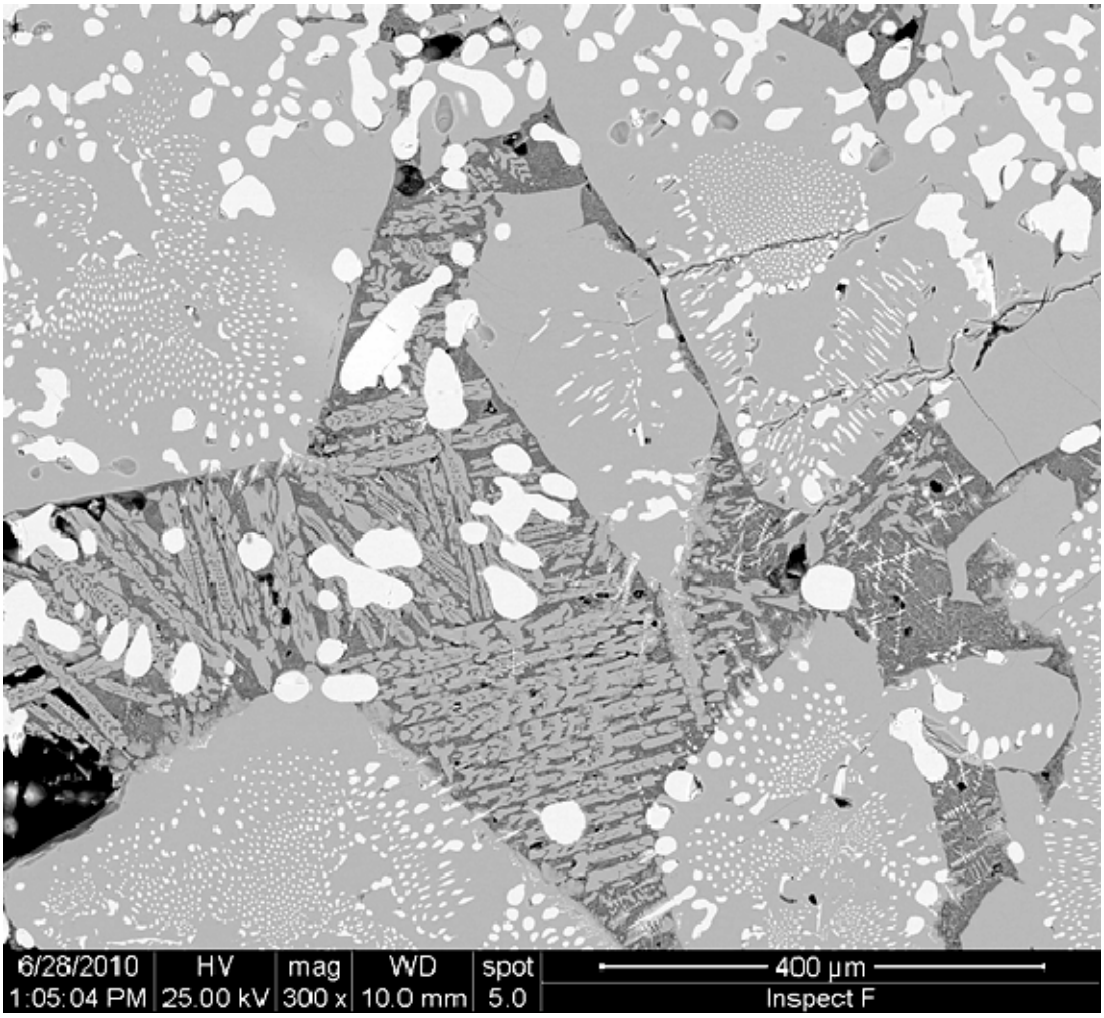

Fig 11: De-vitrified glassy matrix with clear fayalite laths in sample SB2.1.

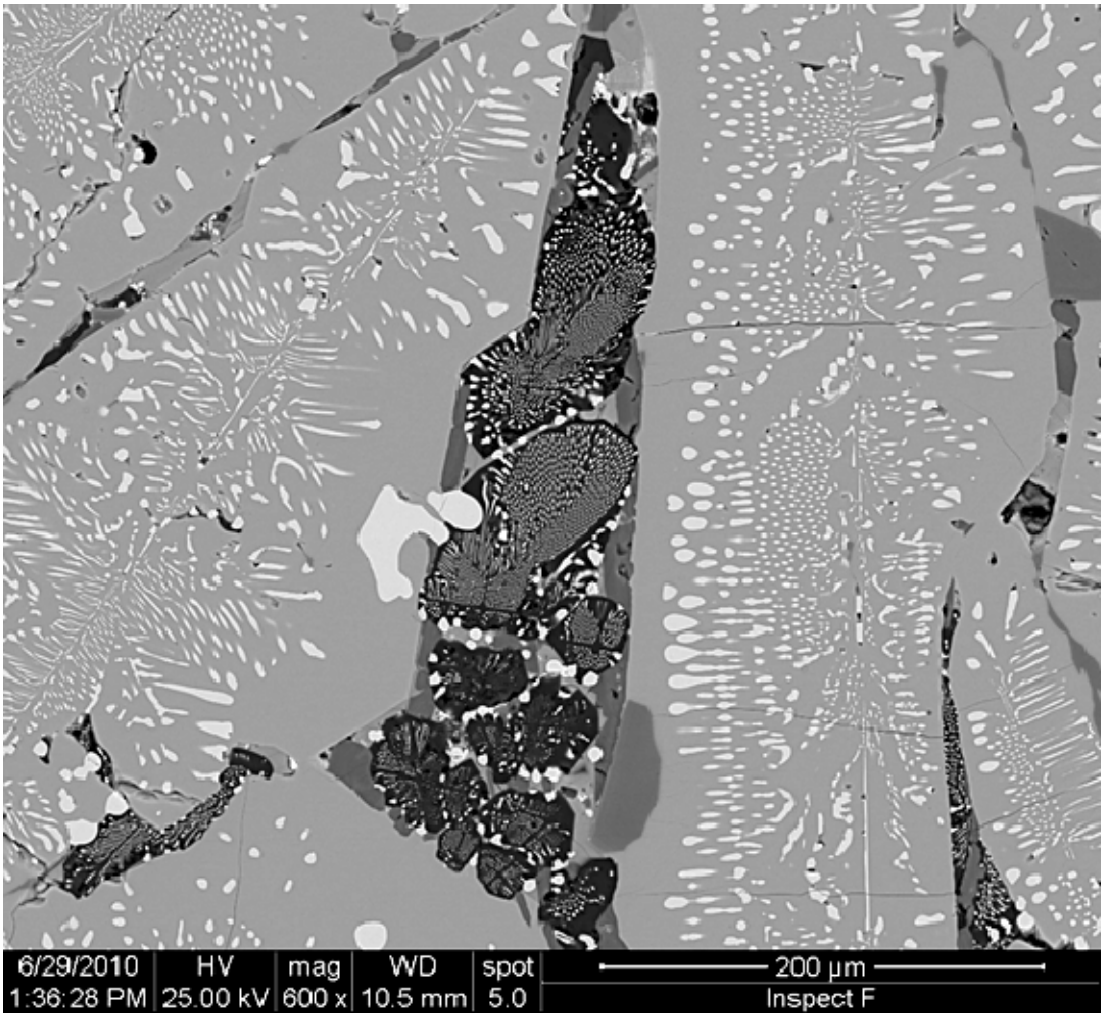

Fig 12: Leucite grains (darkest) with eutectoid wüstite (white) within sample SB5.1.

There was no major micro-structural difference between slags from different contexts. The exception was fragment SC14 which did not contain any hercynite and was more heterogeneous than other samples. The bottom half of the fragment was reasonably free of dendritic wüstite making 11% of its area whereas the upper half had around 51%. This fragment had already been noted as different from the others (less viscous); therefore, it is not a great surprise to find a diverging microstructure.

Although there is no evident variation in slags from different contexts the microstructures did vary between the different slag types. The fayalite in the slag tendrils was more lathy and smaller than the other samples suggesting that they cooled faster. This is not surprising as they are the smallest fragments (high surface area for a small volume) while their flow-like features suggest that they may have dribbled away from the greater heat of the furnace. They also have the least amount of iron oxide with an average of 16% (Table 5) and are the most homogenous slag type. The fact that the individual tendrils are so

homogenous would suggest that they were always hot enough to be in a molten state (Dungworth forthcoming).

Slag cakes on the other hand have the highest percentage of wüstite with a 31.8% average (apart from the possible smithing slag which will be discussed later). It is possible that being at the bottom of the furnace they collect more of the iron. They are also the most heterogeneous with the most solidification fronts. This suggests that the cakes are composed of layers of slag whereby the underlying layers partly solidified as more slag fused to the mass (multiple flow episodes). It is also worth noting that the cakes would contain slag from the duration of the smelt even when it was not working at its optimum condition. At the start, for example, when optimum temperatures have not yet been reached producing micro-structurally different slag (eg more iron oxide - Humphris *et al* 2009).

Sample SH1.1 is very different from any other in the assemblage. It has very high proportions of iron oxide (Table 5); so much so that it is hard to distinguish the other phases. It has globular wüstite and skeletal fayalite laths (Fig 13). There is less wüstite present on the top edge but it gradually gets thicker towards the centre. Due to its morphology it was believed to be a smithing slag and the lack of similarity with other samples at micro-structural level would emphasise this hypothesis. McDonnell (1986, 184) identified that iron oxide in smithing slags often takes "the form of rounded globular dendrites".

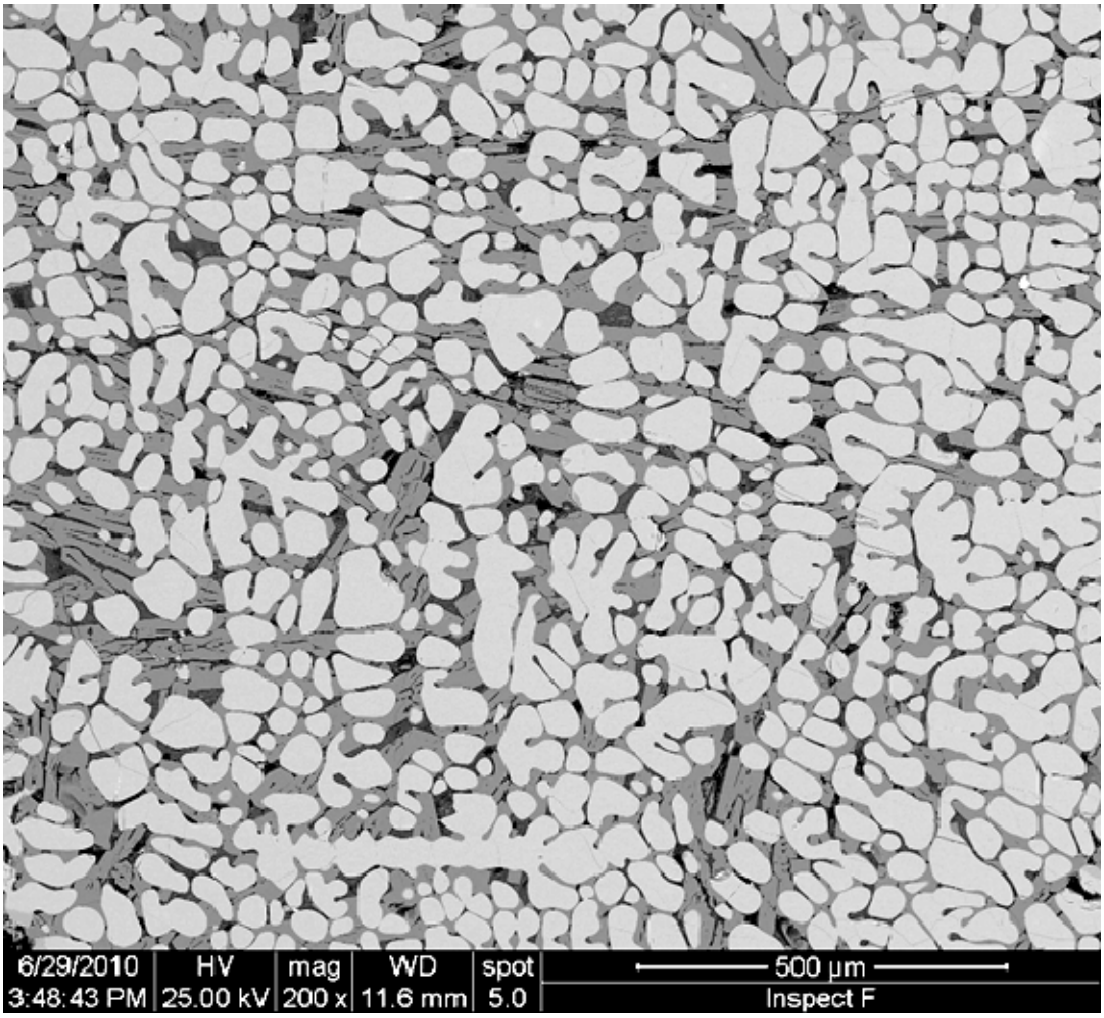

Fig 13: Globular wüstite and skeletal fayalite laths in sample SH1.1.

Table 5: Average area percentage of the micro-structural phases in each slag type

Slag Type (No of samples)	Fayalite %	Wüstite %	Glassy matrix %	Hercynite %
Slag Cake (8)	58.7	31.8	8.1	<1.6
Slag Block (5)	66.6	24.6	7.8	<1.4
Slag Tendril (5)	71.2	16.0	11.8	<1.4
Smithing (1)	28.0	62.0	10.0	Not Detected
All (19)	62.4	27.3	9.1	<1.4

Chemical Composition of Slags

The average chemical compositions for each slag type are shown below (Table 6). Apart from the possible smithing hearth all slag types have similar compositions. It suggests that they were the result of the same or very similar technology. The slags analysed in this study are typical of other iron smelting slag assemblages (Paynter 2006) with high levels of iron oxide, silica and a range of other oxides such as alumina, lime, potassium oxide, etc. However, the slags have a high percentage of manganese and such high levels (above 4wt%) are unusual in iron smelting slags. For the average compositions of each sample please refer to Appendix 3.

Table 6: Average chemical compositions of the different slag types.

Slag Type	No.	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	Fe_2O_3
Cake	8	<0.10	0.26	2.40	20.62	1.17	0.48	0.86	<0.10	4.28	69.78
Block	5	0.12	0.25	2.73	21.98	1.38	0.58	0.80	0.10	4.80	67.26
Tendril	5	0.15	0.23	3.43	22.74	1.45	0.70	0.93	0.12	4.12	66.14
Smithing	1	0.18	0.29	1.93	13.24	1.51	0.72	1.26	BDL	0.24	80.58
ALL	19	0.11	0.25	2.73	21.14	1.31	0.58	0.88	0.10	4.16	68.72

The possible smithing slag (SH1.1) differed in chemical composition to all the others. It had lower silica, lower manganese and higher iron oxide contents than the other slag types. McDonnell (1986, 184) identified that the most significant analytical attribute of smithing slags was their low manganese content. The possible smithing slag had 0.24wt% of manganese whereas the smelting slags had over 4wt%. This, with its morphological and micro-structural dissimilarities to other slags would confirm that it results from the smithing process.

Iron Inclusions

Iron inclusions (droplets or prills) were found in every sample. They are by majority very small (5–20 microns), irregular in shape and concentrated close to the natural edges or larger gas holes (Fig 14). There are very few prills in the centre of the samples examined and few have a characteristic dendritic shape (Fig 15).

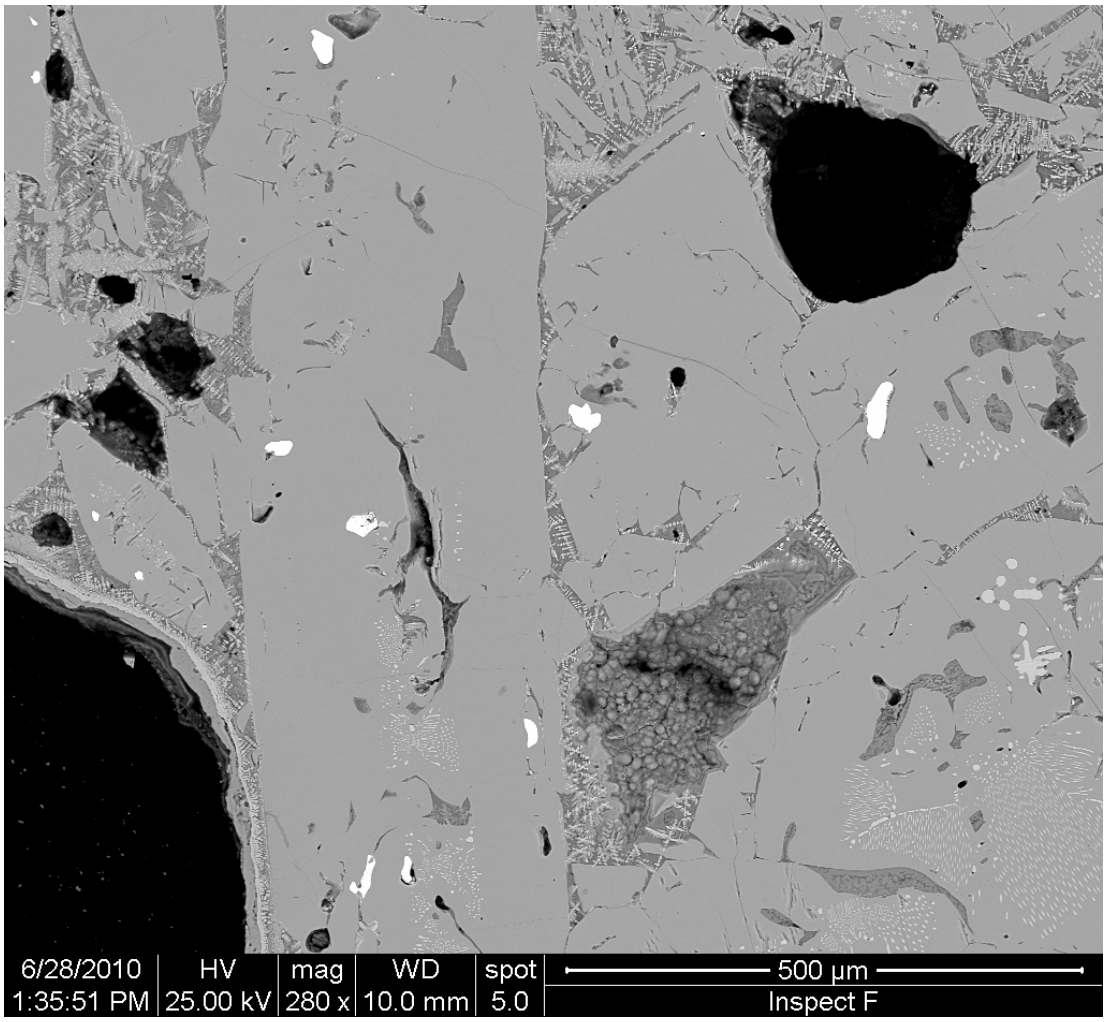

Fig 14: Irregular shaped metallic prills close to large hole in sample SB2.1.

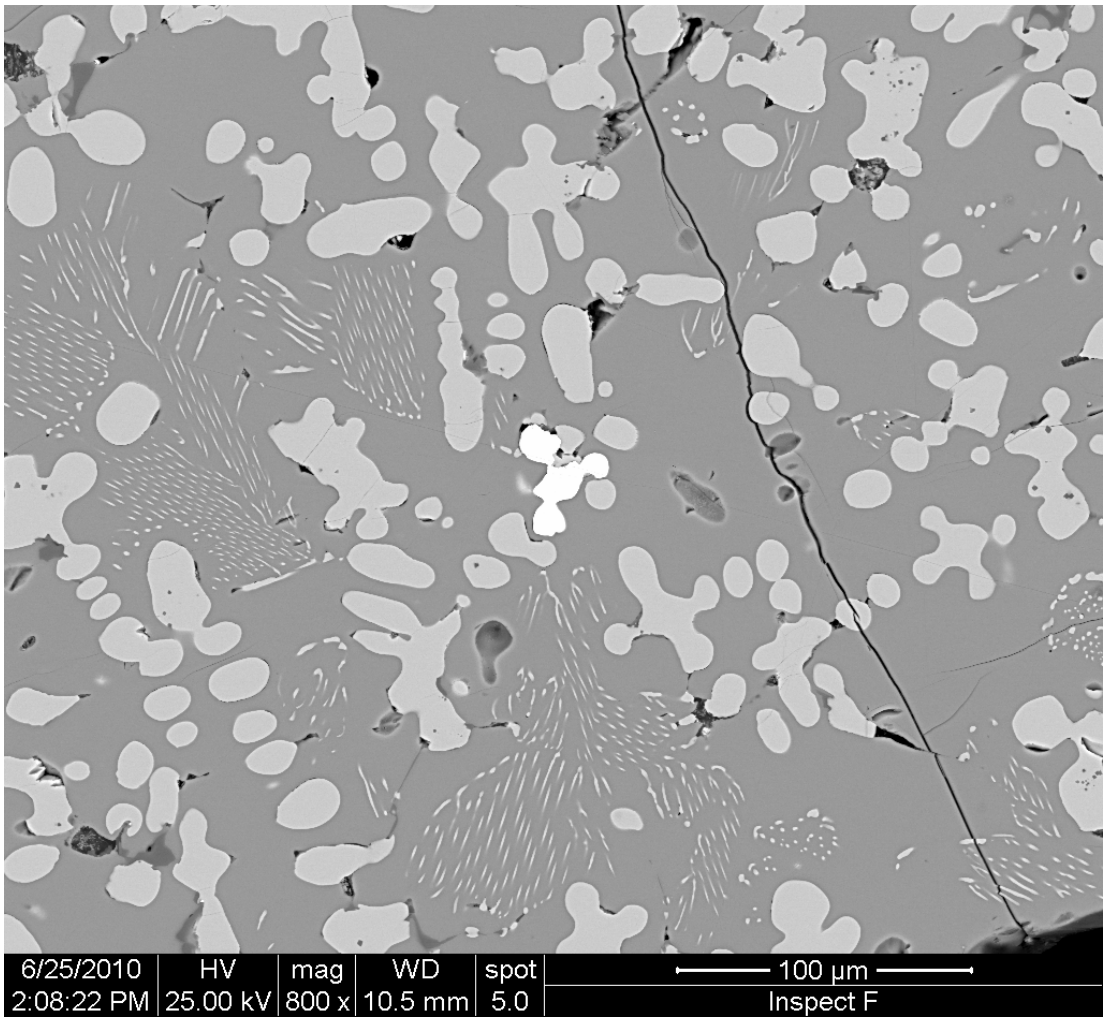

Fig 15: Dendritic shaped iron prill in sample SB1.1.

Three iron prills per sample were spot analysed and the results are reported in Table 7. The carbon content was not measured as it would be inaccurate due to the carbon coating of the slag samples. Instead a few samples were etched (2% Nital) to reveal the iron microstructure. Clear needle and equiaxed grain boundaries could be seen on some prills. However, due to the small size of the iron droplets it was hard to positively identify which phase was present (ferrite or cementite) but the lack of overall reaction to the etchant suggests that the iron was mainly ferritic. This does not necessarily imply that it was the type of iron produced as the iron present in the slags could have decarburised, and the possibility that steel was being made cannot be ruled out. Therefore one cannot determine what type of metal was produced. No phosphorous was detected.

The iron prills all have between 0.1 and 0.4wt% of manganese. This fits with the high levels of manganese oxide in the slags mentioned above. Some of the samples also had as much as 0.47wt% cobalt. This is unusual as very few iron artefacts contain detectable

levels of cobalt. Another point of interest is that the three samples (SC1.1, SC2.2 and ST2.1) with the highest contents of cobalt also have detectable nickel.

Table 7: Average chemical compositions of three iron prills per sample calibrated with three standards.

SAMPLE	Mn	Co	Ni
SC1.1	0.17	0.46	0.76
SC1.2	0.17	0.11	BDL
SC2.1	0.14	BDL	BDL
SC2.2	0.18	0.47	0.82
SC3.1	0.13	0.11	BDL
SC3.2	0.18	BDL	BDL
SC14.1	0.31	0.14	BDL
SC14.3	0.38	0.14	BDL
SB1.1	0.21	0.11	BDL
SB2.1	0.18	0.10	BDL
SB3.1	0.25	0.19	BDL
SB4.1	0.26	BDL	BDL
SB5.1	0.18	BDL	BDL
ST1.1	0.24	BDL	BDL
ST2.1	0.13	0.23	0.11
ST3.1	0.14	BDL	BDL
ST4.1	0.19	BDL	BDL
ST5.1	0.22	0.18	BDL
SH1.1	BDL	BDL	BDL

Clay

Due to the lack of suitable clay fragments that could be positively identified as furnace wall/lining, clay attached to the slag samples were analysed chemically in the SEM-EDS (Table 8). It is worth mentioning that the clay did not represent the complete width of furnace wall and only the most inner surviving layer was present. The clay in the majority of samples had highly reacted with the slag and although care was taken to analyse the least contaminated areas it is possible that this proximity with the slag had an effect on the chemical compositions (especially sample SC14.1). The compositions of the clays do reveal typical clay elements such a silica majority and high proportion of alumina. The high reaction with the slag visible at micro-structural level must mean that the slag made contact with the clay at high temperatures.

Table 8: Mean chemical composition of the clay in each sample.

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO	BaO
SC2.1	BDL	0.36	5.93	85.35	0.85	BDL	0.66	0.83	0.47	BDL	5.44	BDL
SC2.2	0.16	0.43	7.38	84.69	0.67	BDL	0.98	1.07	0.59	BDL	3.85	BDL
SC3.1	0.10	0.64	11.02	79.37	0.14	BDL	1.40	0.37	0.86	BDL	6.06	BDL
SC14.1	0.22	0.54	6.74	71.82	0.30	1.52	2.22	0.66	0.38	1.01	14.59	BDL

Ores

The XRD analysis of the ores revealed that they were all hematite. However, as mentioned earlier they showed signs of having been roasted making it likely that their crystalline structure was altered. Their compositions (Table 9 – for all spectra please refer to Appendix 4) show high levels of manganese and seem to be a good match for the slags analysed. This would indicate that these ores (or a similar type) may indeed have been the ones smelted but it cannot rule out that the ones found and analysed in this study could have been discarded by the smelters.

The cobalt and nickel are both below detection limit but are found in the iron prills. This could be because cobalt and nickel are preferentially reduced in the metal. A point which deserves mention are that two large inclusions with very high manganese content (nearly 60wt%) were present in sample MO3.1. They also had higher barium content and detectable levels of both cobalt and nickel. If these were present in the ore smelted at Michelmersh they could account for the very high manganese levels in the slags and the detectable cobalt and nickel in some iron prills. However, one would expect the barium concentrations present in the ores not to be reduced and therefore reflected in the slag compositions. The lack of barium in the slags is puzzling and could either mean that the fragments analysed were not those smelted (different source) or as mentioned above were intentionally discarded (lower quality).

Table 9: Mean chemical composition of the ores samples.

SAMPLE	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	MnO	FeO	ZnO	BaO
MO1.1	0.49	0.20	2.05	10.51	0.87	0.28	1.29	10.18	73.00	BDL	0.38
MO2.1	0.56	BDL	0.59	2.96	0.77	BDL	0.52	2.74	90.98	BDL	BDL
MO3.1	0.53	0.16	1.96	4.94	1.07	0.27	1.06	7.68	80.86	0.18	0.51
ALL	0.53	0.13	1.53	6.14	BDL	0.20	0.96	6.87	81.61	0.11	0.33

DISCUSSION

Morphological Analysis (Technology)

Through the visual examination of the assemblage several aspects of the technology were revealed. The morphology of the slag indicates that the debris must be from the production of iron in a non-tapping furnace, technologically characteristic of pre-Roman iron production in slag-pit furnaces (Paynter 2007). This type of furnace consisted of a pit under a super structure generally thought to be of the low-shaft kind – the pit was used to collect slag as it formed during the smelt (Paynter 2007). Due to the vertical flow of the slags this seems the most fitting theory and external/sloping pits can be ruled out (Jackson and Tylecote 1988). The size and curvatures of the slag cakes revealed an approximate internal furnace/pit diameter of 45–50cm. The technology correlates with the radio-carbon date (790–520 cal BC) retrieved from the pit (28039) where the majority of the industrial debris was found (personal communication Paul McCulloch 2010).

Several slag characteristics observed require further interpretation. All the slag cakes (apart from one) that have a complete (curved) side have burnt clay attached to it. As mentioned above, this would suggest that the cakes solidified against an enclosing clay (lined) structure. If indeed, like is proposed by many (Joosten 2004; Paynter 2007; Pleiner 2000), the slag accumulates in a purposely designed pit this would mean that it must be lined with clay. However, the slag cake from context 28070 (SC14) has a curve but no visible clay. It is also more consolidated with no flow like slag and there is chalk stuck to its flat underside. Its less viscous appearance and the fact that the local geology is chalk suggests that the slag ran straight down and solidified at the bottom. This would imply that the pit in this case was not entirely clay lined, with the lower parts left bare. However, the fact that the clay may not have survived (broke off) cannot be ruled out.

The rest of the slag cakes have flow features that do not appear to have been constricted on their undersides. This suggests that these cakes were not in contact with the bottom of the pit. Experimental studies by Mikkelsen (1997, 65) showed that the pit temperature could be around 500°C lower than the furnace temperature. It is therefore possible that the slag cooled forming a sort of plug before reaching the bottom of the pit. The organic fill may not have totally burnt before the slag started to cool (becoming more viscous) and perhaps solidifying above the fill, higher in the pit. It is also possible that the slag was more viscous in the early stages of the smelt and cooled reasonably fast forming the flow slag present on the bottom of the cake. This could have formed the start of a plug, to which subsequent slag added. The clay-slag reaction visible at micro-structural level must mean that the slag made contact with the clay at high temperatures. This supports the idea that the slag cake fragments may have solidified higher in the furnace structure, closer to the air supply where the temperature would be at its highest.

It is probable that all the slag in the furnace was part of a continuum whereby slag tendrils formed and consolidated into blocks while they in turn consolidated to make cakes. The flow slag tendrils may therefore be runs of slag that would have eventually fused to form a cake but somehow remained isolated and solidified (perhaps higher in the pit structure or at the edges). Another possibility is that the tendrils are drippings of slag that detached from the slag cake to penetrate/fall further into the pit. Further research and perhaps experimental studies would need to be carried out to ascertain morphological types of slag to specific areas of a furnace or indeed to specific phases of a single smelt.

The majority of the smelting slag was recovered from context 28048 (42.7kg out of 59kg) making a total of 49.6kg found in the same pit (28039). This would suggest that the metal production was in close proximity to this pit. Pit 28025 had about 8.4kg of slag of which 7.1kg was a slag cake fragment found in context 28070 discussed in detail above. The fact that this fragment differed so much (morphologically and micro-structurally) from any other may suggest that the material from this pit (or at least the context) was the result of a different technology. As slag was found in different contexts of the same pits it may mean that there were several depositional episodes, but the lack of timescale between each context limits interpretation. The similar morphological, micro-structural and compositional nature of most slag deposits (apart from context 28070) would suggest that they are the result of the same technology and may not have been temporally distant. There were very few other slag fragments recovered outside the two pits mentioned above (some in contexts 28035 and 28060) and the fact that these deposits were only small and lacking any significant slag cake would lead to suggest a random deposition (natural spread).

It is also important to mention that very few contexts contained both slag and clay, and that the majority of the clay (22.1kg out of 23.3kg) had no signs of vitrification suggesting that it does not represent the remains of furnaces. 1.1kg came out of pit 28030 which has no slag deposits. Context 28069 (pit 28039) yielded a smithing hearth bottom which proves that the manipulation of iron by smithing was also occurring on site. It was found in the bottom context of the pit with the subsequent top layers containing smelting slag. This means that the smithing hearth may pre-date the smelting slag but no further interpretation may be inferred without being too speculative. Considering the quantity of material recovered (about 60kg of slag) it is probable that it resulted from several smelting episodes, however, there are not enough remains to suggest that iron was produced on a large scale. It is therefore put forward here that it is most likely to have been a small sale production site, perhaps only to meet local needs. However, the possibility that more slag remains undiscovered cannot be ruled out.

Scientific Analysis (Archaeological Context/Provenance)

Paynter (2006) examined regional variation in the composition of iron-smelting slags linking slag composition to the type of ore smelted. Her study highlighted that smelting occurring in distinct geological areas produced distinct slag compositions. The slags analysed here are similar in composition to the Norfolk Lower Greensand group with low levels of lime, magnesia, potash and 1-2wt% phosphorous. However, they differ from any other by having very high levels of manganese (above 4wt% - Fig 16). This would suggest that they result from the smelting of a manganese-rich ore. Few iron smelting assemblages have such high levels of manganese but Berkhamsted in Hertfordshire (Tylecote 1986, 146) and Amersham Mantles Green in Buckinghamshire (McDonnell 1986, 95-100) have been reported to have as much as 9wt%. However, the Michelmersh slags have more iron oxide and less silica than the Amersham slags and higher levels of lime, potash and titania than the Berkhamsted assemblage.

These results are not surprising as Michelmersh lies on different geology than the sites in Paynter's study; mainly chalk and Tertiary deposits (Brackleshaw Beds with surrounding pockets of London Clay, Bagshot Sands and Plateau Gavel). According to Tylecote (1986, 125) the Tertiary strata of the Hampshire area yielded ore deposits worked in the Iron Age and 19th century. This could be the source exploited at Michelmersh. It may also be relevant that the area around Berkhamsted and Amersham have similar Tertiary strata. It is therefore probable that similar ore deposits (and other natural resources) were being exploited explaining the comparable levels of manganese found in the slags. Another interesting coincidence are the high levels of manganese (up to 3.3wt%) reported by McDonnell (1988) in the post-Roman smelting assemblage from Romsey. Romsey is only a few kilometres from Michelmersh and although they may have been using a different technology it is possible that the same (or very similar) ore source was exploited. This adds further credence to Paynter's research and the slag assemblage analysed in this study could be part of a new geological group.

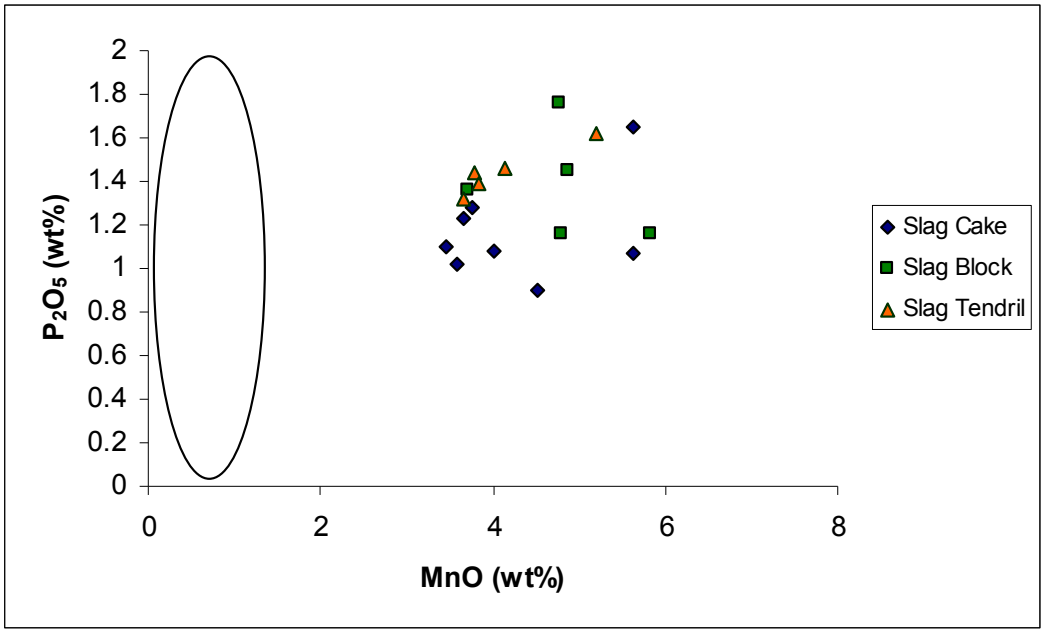

Fig 16: Concentrations of phosphorous and manganese oxides for the smelting slags (grouped by slag type) in this study. Data taken from Appendix 3. The circled area shows where the majority of smelting slags in Paynter's (2006) study lie clearly illustrating the higher manganese levels in the Michelmersh slags.

Where was the iron going?

Elemental comparisons of the Michelmersh slags with the Danebury iron currency bar slag inclusions do not reveal many similarities. This may be attributed to the fact that slag inclusions found in iron objects have been through more processes that may have altered their initial composition. Recent studies have tried to identify which element ratios remain unaffected (or partially) by smelting/forging processes. For example, Dillmann and L'Héritier (2007) and Blakelock *et al* (2009) concentrate upon major elements in particular those they claim not to be reduced (or less) during the smelting process (magnesia, alumina, silica, potash, lime and manganese oxide). It has been argued that the ratios of these elements should be constant throughout the processes and the slag inclusions within the finished artefacts should be representative of the slag produced in the smelt. Using this, one might expect the high manganese oxide content of the Michelmersh smelting slags to be reflected in the slag inclusions of the produced iron. The lack of it (average of 0.12wt%) in the Danebury currency bars (Hedges and Salter 1979, 171) would suggest they were not made in Michelmersh or indeed the Romsey area.

There are too few studies to date that have dealt with the dynamics of elemental compositions in smelting and smithing to fully rely on their results (Blakelock *et al* 2009; Buchwald and Wivel 1998; Coustures *et al* 2003; Desaulty *et al* 2009; Dillmann and

L'Héritier 2007; Salter 1982; Schwab *et al* 2006). Certain problems have to be considered like the high fragmentation of inclusions and their small size which may lead to local concentration effects. Additives (eg sand) used for forging as well as the prolonged periods of heating and effect of the fuel all alter the element compositions in the slags (Blakelock *et al* 2009; Dillmann and L'Héritier 2007). Several studies also reveal that more slag inclusions are introduced/made during smithing. Indeed, "slag inclusions coming from the smelting stage could be a small minority compared to those brought by forging" (Dillmann and L'Héritier 2007, 1815). Some elements favour certain micro-structural phases (eg barium oxide is always located in the glassy matrix of the slag) which has to be considered when the slag inclusions are analysed (Buschwald and Wivel 1998). All these factors have to be taken into account resulting in a lot of data manipulation making results often over complicated, unclear or unconvincing.

Another major problem is the limitation of the analytical techniques used. Studies by Coustures *et al* (2003) and Desaulty *et al* (2009) have concentrated upon trace elements to reveal possible ratios which may be of use for determining the origin of metal artefacts. Desaulty *et al* (2009, 2446) state that "comparing major element ratios in the slag inclusion allows distinguishing between different sources only in favourable cases and is limited by the limited number of elements". Certainly adding more elements to the equation may reveal wider aspects and enable more comparisons between smelting slag and inclusions. In particular, the high levels of chromium identified in the Danebury currency bars (Hedges and Salter 1979, 171; Paynter 2006, 290) would be of interest but cannot be probed for in this study due to the limitations of the equipment available. Nevertheless, it seems unlikely that Michelmersh is the source of the Danebury currency bars due to their comparatively low manganese oxide levels.

Salter (1982) analysed 80 iron objects from Danebury and highlights three distinctive elements which were present; cobalt and nickel in the metal and manganese in the slag inclusions. The published results in Cunliffe (1984, Table 120, fiche 13) show a correlation in a dozen samples between high levels of manganese in the slag inclusions (up to 12.98wt%) and high levels of cobalt (up to 3.31wt%) and nickel (up to 0.818wt%) in the metal. This group of objects are interesting as the majority of the other artefacts analysed in Salter's study had manganese levels below 0.4wt%, cobalt levels below the detectable limit and nickel levels below 0.05wt%. He suggests that the most likely sources of ore/manufacture (deposits containing high levels of those elements) would have been from the south-west peninsula of England, North Wales or the Weald of Sussex. However, it is clear that cobalt and nickel are present in the Michelmersh iron inclusions while there is a high concentration of manganese oxide in the slags analysed. Therefore, it may be possible that the source of manufacture is closer than previously anticipated and because there are few analyses of the uneconomic iron ore bodies (Cunliffe 1984, 436) a more local ore source cannot be eliminated. Indeed several sources (Cunliffe 1984, 436; Tylecote 1986, 125) state that the Tertiary basins of Hampshire are rich in iron while the analyses of the ore found on site revealed inclusions containing high levels of manganese oxide, cobalt oxide and nickel oxide (Appendix 4, sample MO3.1, spectrum 10).

CONCLUSION

Visual and scientific examinations of the Michelmersh slag assemblage have revealed several technological traits. The slags were typical of iron smelting in a non-tapping slag pit furnace (Paynter 2007). The furnaces were probably of a low shaft kind and about 40-50cm in diameter. It is hard to determine at what scale this was happening as not all the slag may have been recovered from the area and the lack of timescale between contexts makes the duration of smelting activity hard to discern. If one just takes into account the slags analysed here (about 60kg) then it is unlikely that more than 20 to 30kg of iron was produced (dependant on ore quality as well as technological efficiency) and may have satisfied only local needs. However, the possibility that more slag lies undiscovered is feasible and the production of iron for exportation cannot be ruled out.

The chemical compositions of the slag showed similar characteristics to Paynter's (2006) Norfolk Lower Greensand group but differed greatly to any other group by having very high manganese content. Slags recovered from Romsey (nearby) also displayed high manganese levels. In support of Paynter's study it is suggested here that the Michelmersh and Romsey slags form a new geological group distinct from any other by their high concentrations of manganese. Cunliffe (1984, 436) and Tylecote (1986, 125) state that the Tertiary strata of Hampshire were rich in iron and may have been the ore source(s) exploited.

Unfortunately it has not been possible to positively tie the provenance of the Danebury currency bars to Michelmersh. The low manganese oxide in the Danebury slag inclusions does not correlate with the much higher contents in the Michelmersh slags. Salter (1982) on the other hand, identified three distinctive elements (cobalt, nickel and manganese) in iron objects from Danebury. Due to the rarity of these elements possible ore and manufacture provenances as far as the south-west peninsula of England, North Wales and the Weald of Sussex were suggested. However, the published results in Cunliffe (1984) show that some artefacts have cobalt, nickel and manganese ratios comparable to the Michelmersh slags and their iron inclusions. Considering that the chemical dynamics of furnaces are yet to be fully understood one cannot prove or certify that objects found in Danebury have come from Michelmersh but it would suggest that those artefacts may have been manufactured closer than originally thought; perhaps in the Michelmersh area (amongst the new geological grouping).

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APPENDIX 1. SAMPLE LOCATIONS

Slag Cakes

Fragment SC1 (28048)

Fragment SC2 (28048)

Fragment SC3 (28048)

Fragment SC14 (28070)

Slag Blocks

Fragment SB1 (28048)

Fragment SB2 (28048)

Fragment SB4 (28048)

Fragment SB4 (28048)

Fragment SB5 (28067)

Slag Tendril

Fragment ST1 (28048)

Fragment ST2 (28048)

Fragment ST3 (28048)

Fragment ST4 (28048)

Fragment ST5 (28067)

Smithing Slag

Fragment SH1 (28069)

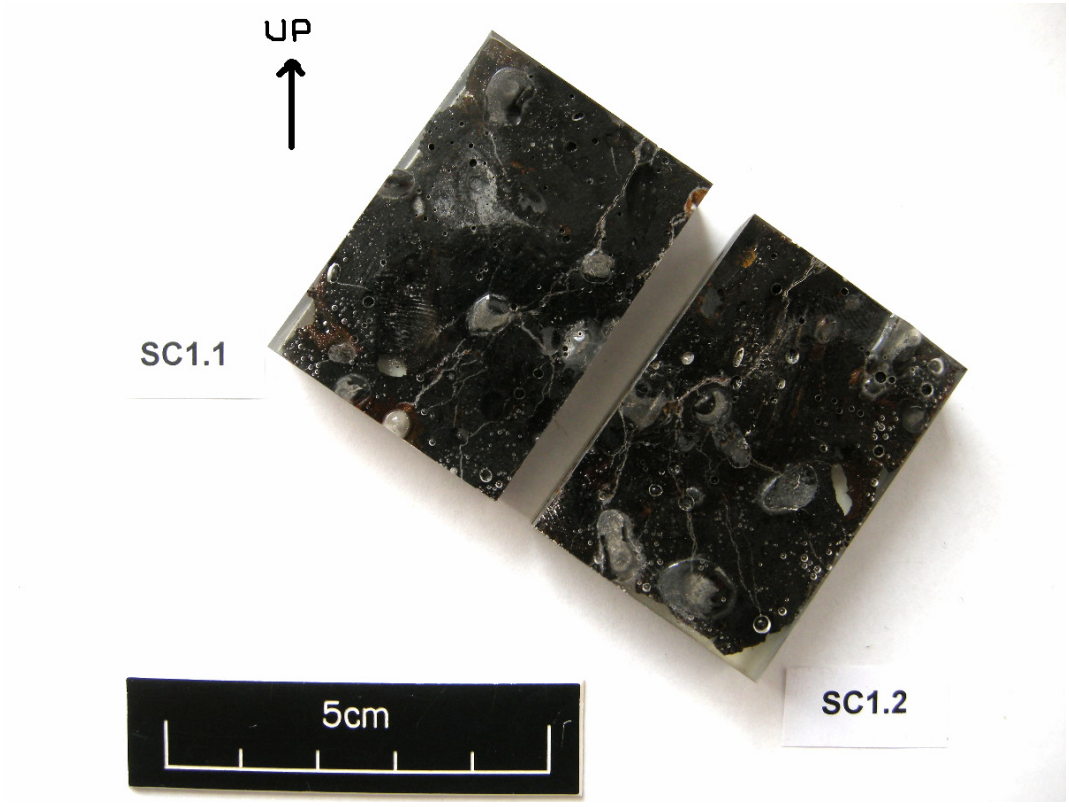
Ores

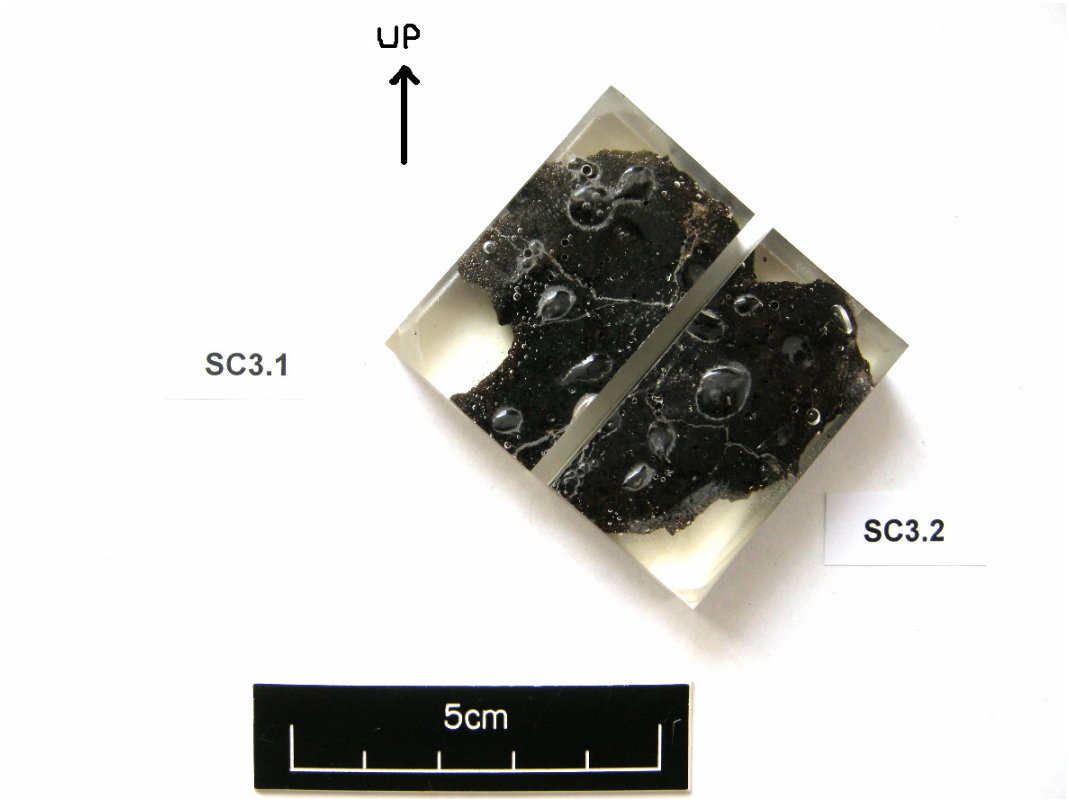
Fragment MO1 (28031)

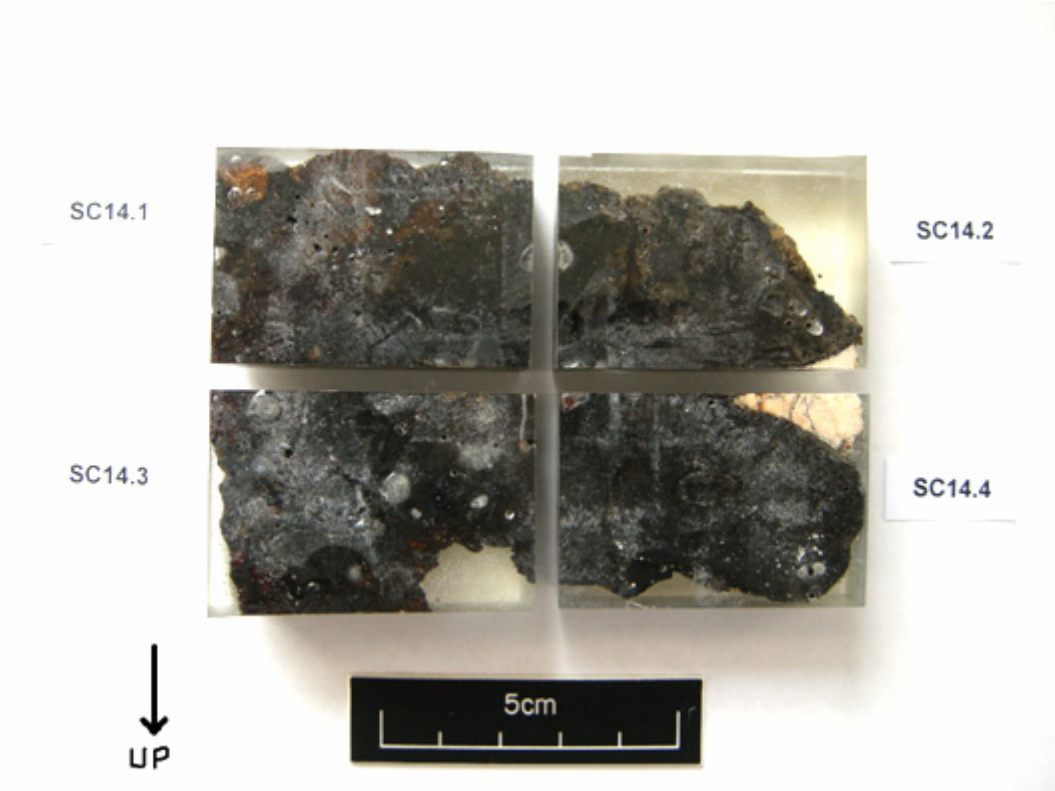
Fragment MO2 (28048)

Fragment MO3 (28068)

APPENDIX 2. ORIENTATION OF CUT SAMPLE LOCATIONS






SC14.1
SC14.2
SC14.3
SC14.4
5cm
UP

APPENDIX 3. AVERAGE CHEMICAL COMPOSITION OF THE SLAGS

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO
SC1.1	BDL	0.22	2.13	20.75	1.08	0.33	0.57	BDL	4.01	70.77
SC1.2	BDL	0.29	1.53	18.88	0.90	0.24	0.54	BDL	4.52	72.97
SC2.1	BDL	0.19	1.91	20.60	1.02	0.27	0.50	BDL	3.58	71.80
SC2.2	0.11	0.24	2.50	22.82	1.10	0.60	0.67	0.11	3.47	68.37
SC3.1	BDL	0.21	2.52	18.53	1.28	0.41	0.65	0.10	3.77	72.46
SC3.2	0.10	0.21	2.06	17.90	1.23	0.40	0.59	0.10	3.65	73.76
SC14.1	0.11	0.32	3.97	26.62	1.65	1.07	1.99	0.12	5.63	58.52
SC14.3	BDL	0.37	2.54	18.82	1.07	0.52	1.34	BDL	5.64	69.55
SB1.1	0.12	0.19	2.90	21.06	1.36	0.52	0.74	0.10	3.72	69.28
SB2.1	BDL	0.30	1.85	21.93	1.16	0.39	0.64	BDL	5.83	67.73
SB3.1	BDL	0.25	2.76	20.60	1.16	0.48	0.58	BDL	4.79	69.23
SB4.1	0.19	0.24	3.51	23.33	1.76	0.90	1.17	0.13	4.77	64.00
SB5.1	0.12	0.25	2.65	22.99	1.45	0.60	0.89	0.10	4.87	66.07
ST1.1	0.13	0.16	3.73	23.85	1.44	0.79	0.70	0.13	3.79	65.29
ST2.1	0.17	0.25	3.19	21.30	1.46	0.59	0.76	0.10	4.14	68.03
ST3.1	0.15	0.23	3.93	24.22	1.39	0.84	1.45	0.16	3.84	63.79
ST4.1	0.15	0.28	3.10	22.63	1.32	0.65	0.77	0.13	3.65	67.30
ST5.1	0.14	0.22	3.21	21.68	1.62	0.63	0.95	BDL	5.20	66.27
SH1.1	0.18	0.29	1.93	13.24	1.51	0.72	1.26	BDL	0.24	80.58

APPENDIX 4. CHEMICAL COMPOSITION OF THE ORE

MO1.1

Spectrum	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	MnO	FeO	ZnO	BaO	PbO
1	0.48	0.14	1.54	2.83	0.76	BDL	1.01	1.81	89.92	BDL	BDL	0.11
2	0.59	0.10	1.46	2.75	0.94	0.14	0.98	2.26	89.32	BDL	BDL	0.16
3	0.39	0.24	0.57	1.96	1.15	0.60	1.62	20.89	71.30	BDL	1.70	BDL
4	0.52	0.15	3.41	19.29	1.00	0.39	1.32	9.53	62.33	0.11	0.32	0.20
5	0.53	0.21	2.32	22.29	0.69	0.23	1.38	12.76	57.16	0.17	0.34	BDL
6	0.59	0.40	3.51	17.53	0.63	0.30	1.58	18.45	55.74	0.21	0.23	BDL
7	0.40	BDL	0.94	8.45	0.58	0.11	0.59	2.50	84.81	0.28	0.13	0.22
8	0.20	0.12	2.00	7.05	0.79	0.12	0.56	0.88	88.35	BDL	BDL	BDL
9	0.12	0.17	1.72	17.96	0.50	0.15	0.63	0.79	76.42	BDL	BDL	BDL
10	0.30	BDL	1.44	32.19	0.79	0.27	1.22	11.79	50.93	0.12	0.52	BDL
11	0.45	0.25	3.87	15.49	0.64	0.51	0.57	0.76	76.88	0.13	BDL	BDL
Mean	0.49	0.20	2.05	10.51	0.87	0.28	1.29	10.18	73.00	0.09	0.38	0.05
StDev	0.15	0.10	1.09	9.64	0.19	0.17	0.41	7.54	14.52	0.09	0.50	0.09

MO2.1

Spectrum	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	MnO	FeO	ZnO	BaO	PbO
1	0.51	BDL	0.46	3.06	0.91	BDL	0.66	4.17	88.92	0.03	BDL	0.19
2	0.55	0.12	0.63	3.86	0.89	BDL	0.64	3.59	89.56	0.03	0.15	BDL
3	0.56	BDL	0.43	2.12	0.68	BDL	0.57	4.15	90.98	0.17	BDL	BDL
4	0.63	BDL	1.04	4.31	0.58	0.12	0.59	3.17	87.39	0.10	BDL	BDL
5	0.53	BDL	0.66	2.91	0.87	BDL	0.37	0.82	92.57	BDL	0.17	BDL
6	0.52	BDL	0.33	1.93	0.74	BDL	0.38	1.8	94.02	BDL	0.21	BDL
7	0.61	BDL	0.55	2.47	0.74	BDL	0.45	1.43	91.93	0.12	BDL	BDL
Mean	0.56	0.03	0.59	2.96	0.77	0.04	0.52	2.74	90.98	0.07	0.09	0.05
StDev	0.05	0.05	0.23	0.88	0.12	0.04	0.12	1.37	2.29	0.06	0.09	0.07

MO3.1

Spectrum	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	MnO	FeO	CoO	NiO	ZnO	BaO	PbO
1	0.87	0.26	6.99	9.64	1.46	0.36	1.05	2.09	75.82	BDL	BDL	BDL	BDL	BDL
2	0.29	0.19	0.57	4.24	0.26	BDL	0.64	1.79	90.12	BDL	BDL	0.24	BDL	0.14
3	0.41	0.10	1.07	3.93	0.61	0.13	0.91	8.26	83.09	BDL	BDL	0.23	0.45	BDL
4	0.49	BDL	0.90	4.33	1.09	BDL	0.89	1.17	90.21	BDL	BDL	0.17	BDL	BDL
5	0.48	BDL	0.75	4.24	1.21	BDL	0.88	0.87	90.77	BDL	BDL	0.14	BDL	BDL
6	0.50	BDL	1.23	3.96	1.16	BDL	0.79	0.85	92.04	BDL	BDL	0.16	BDL	BDL
7	0.56	BDL	0.48	3.66	1.18	BDL	0.81	1.94	90.88	BDL	BDL	0.13	0.27	BDL
8	0.54	BDL	0.78	4.52	1.18	BDL	0.89	1.13	91.56	BDL	BDL	0.16	BDL	BDL
9	0.69	0.28	5.75	9.06	1.89	0.23	1.30	1.20	79.30	BDL	BDL	0.31	BDL	BDL
10	0.52	0.72	1.10	1.98	0.67	1.80	2.47	57.68	27.19	0.87	0.38	0.18	3.98	BDL
Mean	0.53	0.16	1.96	4.94	1.07	0.27	1.06	7.68	80.86	0.64	0.14	0.18	0.51	0.01
StDev	0.16	0.23	2.35	2.43	0.46	0.55	0.52	17.7	19.79	0.30	0.11	0.06	1.23	0.04






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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