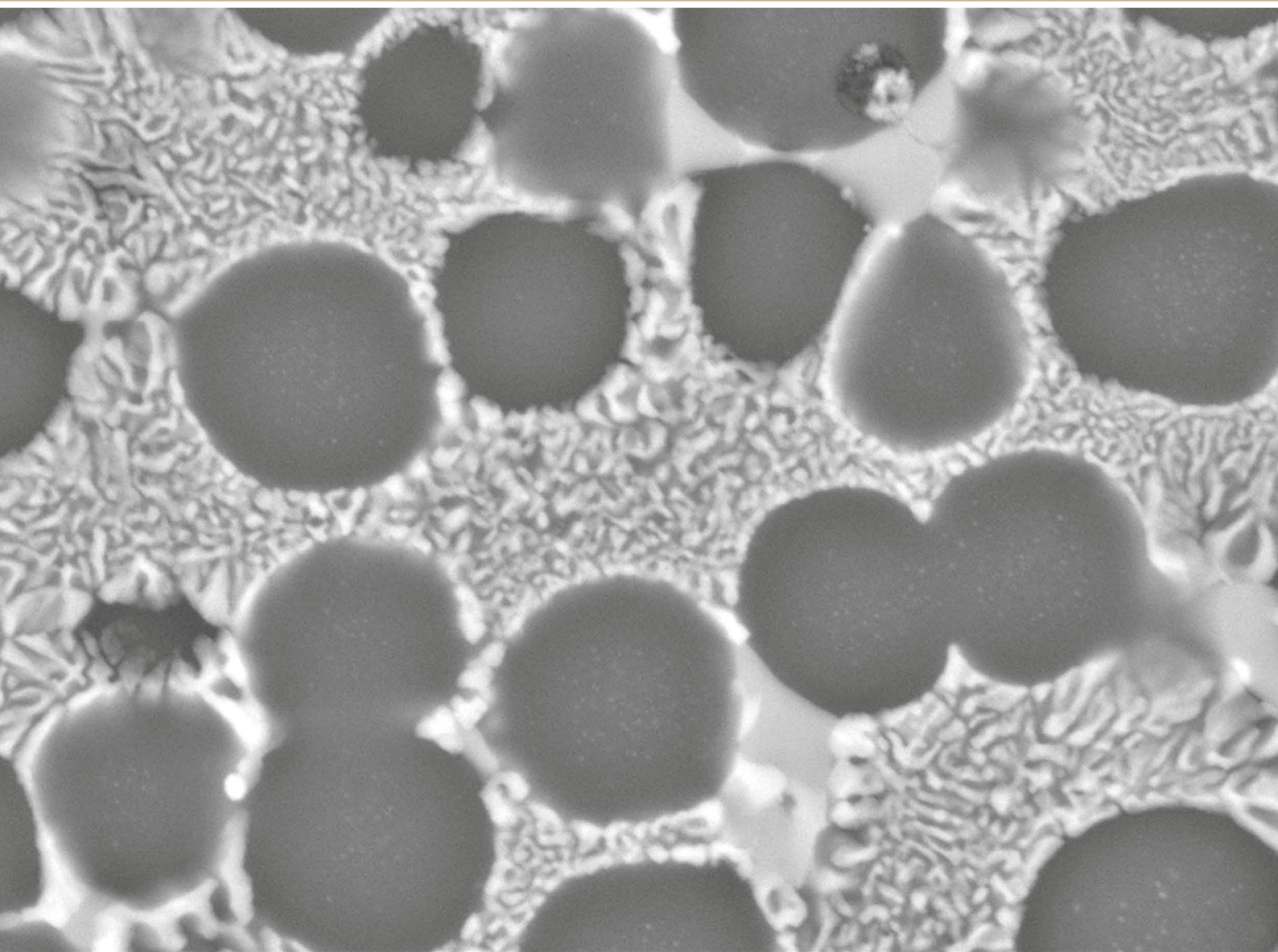# HECKFIELD, HAMPSHIRE
AN EXAMINATION OF MIDDLE IRON AGE SMELTING SLAGS

TECHNOLOGY REPORT

David Dungworth

Mag = 9.04 K X

EHT = 25.00 kV

10µm

Detector = QBSD

Date : 2 Apr 2007

ARCHAEOLOGICAL
SCIENCE

ENGLISH HERITAGE

Heckfield, Hampshire:
an examination of middle Iron Age smelting slags

D Dungworth

Heckfield, Hampshire:
an examination of middle Iron Age smelting slags

D Dungworth

Summary

The examination of a selection of ironworking slags from a prehistoric context demonstrates that they were produced during the smelting of iron ore. The slag lumps lack diagnostic morphological features which might allow a detailed reconstruction of the furnace and how it was operated. The chemical composition and microstructure of the slags show parallels with prehistoric material from the site of Thorpe Lea, Surrey.

Keywords

Technology
Prehistoric
Metal working Fe

Author's address

English Heritage, Fort Cumberland, Fort Cumberland Road, Eastney, Portsmouth, PO4 9LD.
Telephone: 02392 856783. Email: david.dungworth@english-heritage.org.uk

Introduction

The site of a Jacobean Manor House near the village of Heckfield (north-east Hampshire [approximate NGR SU7260]) has been the subject of archaeological excavations by the North East Hants Historical & Archaeological Society since 1990. In 2001, excavations revealed features containing prehistoric pottery and slag. This report contains a detailed examination of some of the slags. Pottery from the same contexts as the slag has been dated to the fourth century BC (Elaine Morris personal communication). Approximately 7kg of iron slag was recovered from Heckfield from trench 4A, context [2], of which approximately 2kg of the slag was submitted for examination and analysis.

Iron working is known in the area from the site of Riseley Farm, Berkshire (~3km to the north of Heckfield). 27kg of iron working slags were recovered from this Iron Age site (McDonnell 1984. There was evidence for iron smithing from the middle to late Iron Age through to the middle of the first century AD and for iron smelting during the first half of the first century AD.

Visual Examination

The size, colour, density, texture and surface morphology of fragments of slag can indicate the types of metal working processes carried out (Bayley *et al* 2001). In addition, the total weight of slag can provide an indication of which processes were carried out: iron smelting tends to produce larger quantities of slag than iron smithing.

The most common form of slag produced by the bloomery smelting of iron is 'tap slag' which has a surface morphology resembling lava flows. During the iron smelting the slag would be allowed to flow out of the base of the furnace into a small pit beside the furnace. Tap slag is common on iron smelting sites from the late Iron Age through to the late medieval period, however, it is rarely found on early to middle Iron Age iron smelting sites. Instead such sites tend to produce 'furnace bottoms' (large plano-convex blocks of slag), 'runs' (small lumps of slag showing signs of having been slightly fluid and often with charcoal impressions) and amorphous lumps (Crew 1986; 1988; Dungworth forthcoming; Halkon and Millett 1999; McDonnell 1984; 1988; Paynter 2007; Starley 1998).

The 2kg of iron slag submitted for examination consisted of 23 fragments. All of the slags are black to dark grey in colour (the colour of weathered surfaces is ignored). The colour and density of these slags are typical for iron working slags. The surfaces of the fragments are heavily abraded and weathered which obscures much of the original surface morphology of the slag (Figure 1). The slags fall into two morphological groups: amorphous lumps (Figure 2) and plano-convex lumps (Figure 1). The amorphous lumps occasionally bear charcoal impressions and often show areas which have been moderately fluid (drips). The amorphous lumps lack a sufficiently distinctive morphology to allow the identification of the ironworking process which produced them. The chemical analysis (see below) suggests that all of these amorphous slags were produced by iron smelting. The plano-convex lumps resemble smithing hearth bottoms (Bayley *et al* 2001, fig 21), but the chemical analysis suggests that at least two of these resulted from iron smelting. The assemblage includes no examples of tap slag (Bayley *et al* 2001, fig 14) but tap slag is rare in prehistoric contexts in Britain (Paynter forthcoming). A sample of soil from Trench 4A context [2] was also examined but this contained no slag and no hammerscale.

Figure 1. Heckfield slag (sample 6)

Figure 2. Heckfield slag (sample 7)

Chemical Analysis

Table 1. description of samples selected for examination and analysis

Sample	Description	Weight
1	Run	20g
2	Lump with charcoal impression	28g
3	Lump with drips	127g
4	Plano-convex lump	148g
5	Plano-convex lump	568g
6	Plano-convex lump	111g
7	Lump with drips	80g
8	Plano-convex lump	200g

In order to further investigate the possibility that some of the slag from Heckfield was produced during iron smelting, eight samples were selected for analysis. These were selected (Table 1) to represent the range of slag submitted (in terms of surface morphology, etc). Each of the eight samples was cut using a rock saw to remove a slice through the fragment (3–5mm thick). These slices were embedded in epoxy resin and then polished to a 1 micron finish. The samples were examined using an optical microscope at magnifications up to x500. This allowed the tentative identification of a range of crystalline phases (eg wüstite [FeO] and fayalite [Fe_2SiO_4]). The embedded samples were then coated in carbon and examined using a scanning electron microscope (SEM). The images were obtained using the back scattered electron detector, ie the brightness of each region is proportional to the average atomic number of that region. The chemical composition of each sample was determined using the energy dispersive X-ray spectrometer (with a germanium detector) attached to the SEM. This allowed the determination of bulk compositions (typically an area 0.5 by 0.2mm, see Table 2) and the determination of the composition of discrete crystalline phases. The average chemical composition was determined using several (3–6) different areas; more homogeneous samples required fewer areas to obtain a reliable average. Compositions were normalised to 100wt% to allow comparisons between samples with varying degrees of porosity. The Swedish Iron Slag standard (W:25-R) was analysed and showed that the data presented here is reliable (Table 2). The soda levels are higher than those reported by Kresten and Hjärthner-Holdar (2001), but analysis of glass reference materials suggests that the soda values are accurate.

Table 2. Six analyses of the Swedish Iron Slag standard (W:25-R) with the average reported value (Kresten and Hjärthner-Holdar 2001)

#	Na$_2$O	MgO	Al$_2$O$_3$	SiO$_2$	P$_2$O$_5$	SO$_3$	K$_2$O	CaO	TiO$_2$	MnO	FeO
1	1.41	0.35	7.63	21.17	0.13	0.22	1.07	1.47	0.35	3.55	62.64
2	1.60	0.50	7.79	22.96	0.19	0.31	1.11	1.37	0.36	3.26	60.55
3	1.98	0.46	8.59	23.43	0.32	0.39	1.41	1.64	0.42	3.62	57.76
4	1.53	0.49	8.30	22.86	0.23	0.36	1.19	1.56	0.37	3.44	59.68
5	1.48	0.49	8.23	22.48	0.11	0.23	1.15	1.52	0.26	3.23	60.82
6	1.65	0.41	8.09	23.48	0.19	0.32	1.15	1.70	0.34	3.06	59.59
reported	0.61	0.38	7.14	24.73	0.26	0.16	1.02	1.42	0.32	3.01	57.10

While the results of the chemical analyses of the Heckfield slags are discussed in more detail below, attention is drawn to the manganese oxide content of the slags (Table 3). Most of the Heckfield slags have relatively high levels of manganese oxide which indicates that they were produced by smelting rather than smithing (cf McDonnell 1986). The relatively high phosphorus content of the slags indicates that the ore used was probably a bog iron ore. Bog iron ores usually contain high levels of phosphorus (Pleiner 1999, 88) and this element 'enters both the slag and the metal' (Tylecote 1986, 127; see also Piakowski 1989).

Table 3. Chemical compositions (the average values based on the analysis of 3–6 areas). See Appendix for individual area and phase analyses

#	Na$_2$O	MgO	Al$_2$O$_3$	SiO$_2$	P$_2$O$_5$	K$_2$O	CaO	TiO$_2$	MnO	FeO	H
1	<0.5	0.2	3.7	21.6	5.9	0.7	1.1	<0.1	0.5	66.3	3.3
2	<0.5	0.6	3.0	31.4	1.4	0.4	1.5	0.3	0.5	60.9	1.7
3	<0.5	0.4	3.8	23.1	3.0	0.3	0.5	<0.1	0.3	68.6	1.8
4	<0.5	0.3	2.6	29.8	1.1	1.7	1.6	0.2	<0.1	62.7	2.2
5	<0.5	<0.2	1.4	13.6	5.1	0.5	0.7	<0.1	0.1	78.6	2.4
6	<0.5	0.4	2.6	24.5	1.3	1.5	2.3	<0.1	<0.1	67.4	3.1
7	<0.5	0.2	1.7	16.5	5.7	0.3	0.9	<0.1	0.8	73.9	0.9
8	0.8	<0.2	6.3	35.4	2.8	1.8	1.2	0.4	0.5	50.8	3.8

The degree of chemical homogeneity or heterogeneity may potentially be an indicator of the technological process. Slags which have been fully molten tend to be chemically very homogeneous while slags which have fused and sintered without full melting tend to be heterogeneous. A measure of the heterogeneity (H) for each sample has been calculated from the weighted sum of standard deviations for each element analysed,

Heterogeneity, $H = \sum \left(\dfrac{\sigma \times \overline{x}}{100} \right)$, $\overline{x}$ = average composition, σ = standard deviation

The heterogeneity of tap slags is generally very low (H = 1.2±0.5) reflecting the fact that they have been sufficiently molten to pass from inside the furnace to the tapping pit outside and so have become quite homogenous. Smithing slags have formed as the result of reactions between numerous components (eg hammerscale, fuel ash, hearth lining, etc, see McDonnell 1991) are highly heterogeneous (H = 6.7±4.1). Non-tapping smelting slags (eg Millbrook [McDonnell 1986] and Trevelgue Head [Dungworth forthcoming]) have intermediate H values (typically 2–4) which are comparable with the Heckfield slags (H = 2.4±1.0).

Description of microstructures

The samples of slag from Heckfield display a range of microstructures that are comparable with those previously observed in early bloomery smelting slags (eg Dungworth forthcoming; Starley 1998). In most cases, bloomery smelting slags contain iron oxide (wüstite) and iron silicate (fayalite) in a glassy matrix (McDonnell 1986; Morton and Wingrove 1969; Tylecote 1986, fig 73). The proportions of these phases varies widely both between different smelting sites and between different samples of slag from the same site (reflecting the nature of the early bloomery smelting process). The Heckfield slags, however, frequently contain a range of other phases (eg hercynite, $FeAl_2O_4$ and leucite $KAlSi_2O_6$ as well as iron phosphates and iron-potassium silicates). A selection of the Heckfield samples are illustrated and discussed in detail below. The closest parallel both in terms of microstructure and chemical composition can be found in the Iron Age smelting slags from Thorp Lea examined by Starley (1998).

Sample 1
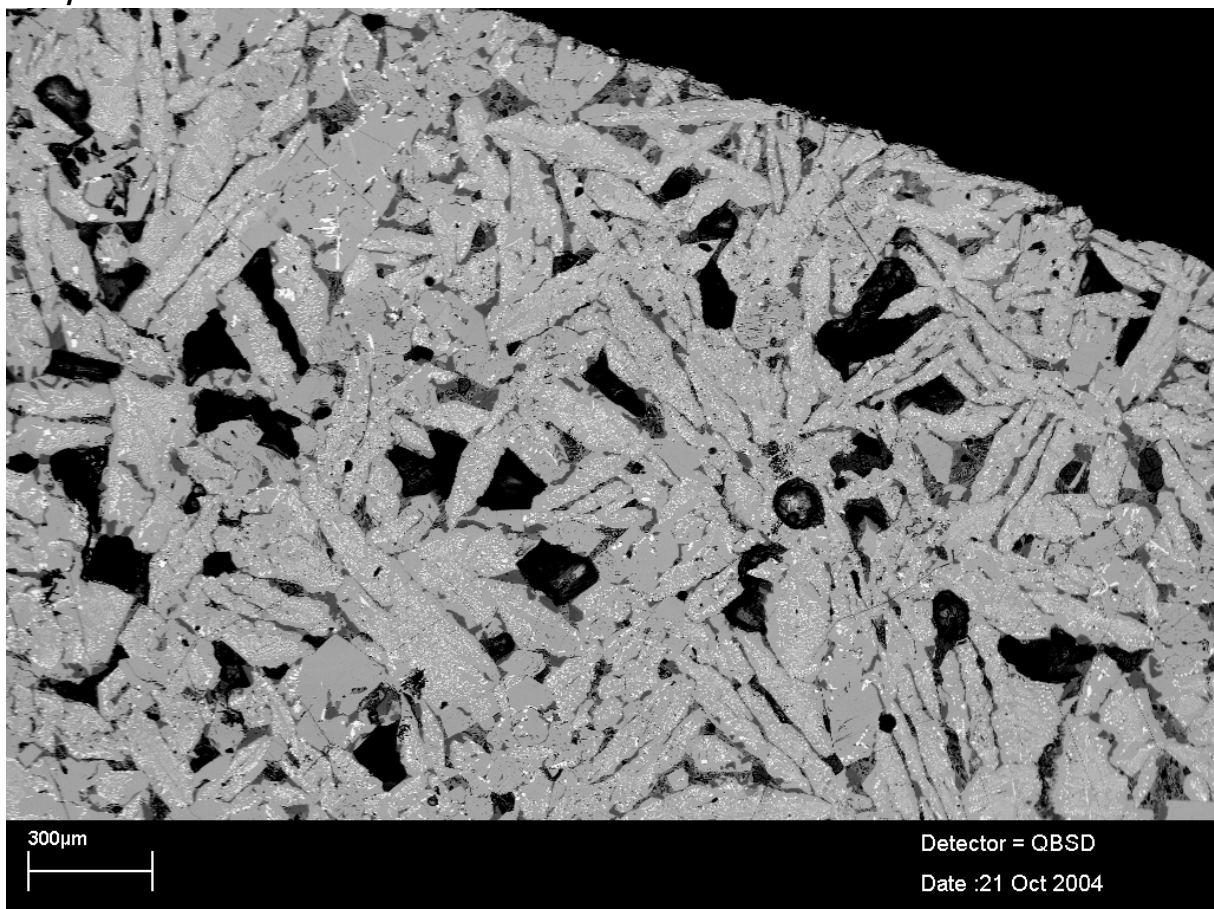
Figure 3. SEM image of sample 1 showing the presence of silicate laths (light grey) and porosity (black)

Sample 1 is from a small lump of slag which shows some evidence of having been moderately fluid at some stage. The sample has a microstructure which consists of largely of silicate laths (fayalite, Fe_2SiO_4) with moderate amounts of porosity (Figure 3). At a higher magnification, it is clear that most of the silicate laths contain finely dispersed wüstite (FeO, Figure 4). The solidification of the silicate has occurred as a fayalite-wüstite eutectic, which has a melting point of 1177±5ºC (Levin *et al* 1956, Fig 468). There is virtually no free wüstite present in this sample, although there are occasionally small crystals of hercynite ($FeAl_2O_4$). The distribution of the hercynite crystals suggests that they began to crystallise as the last of

fayalite formed and before the matrix had solidified. Hercynite crystallises from molten iron oxide and alumina mixtures at temperatures in excess of 1300ºC (Levin *et al* 1956, fig 73). This is much higher than the 1177ºC melting point of the fayalite-wüstite eutectic, however, in this case the hercynite has crystallised from a melt rich in phosphorus which would have a relatively low melting point (see below).
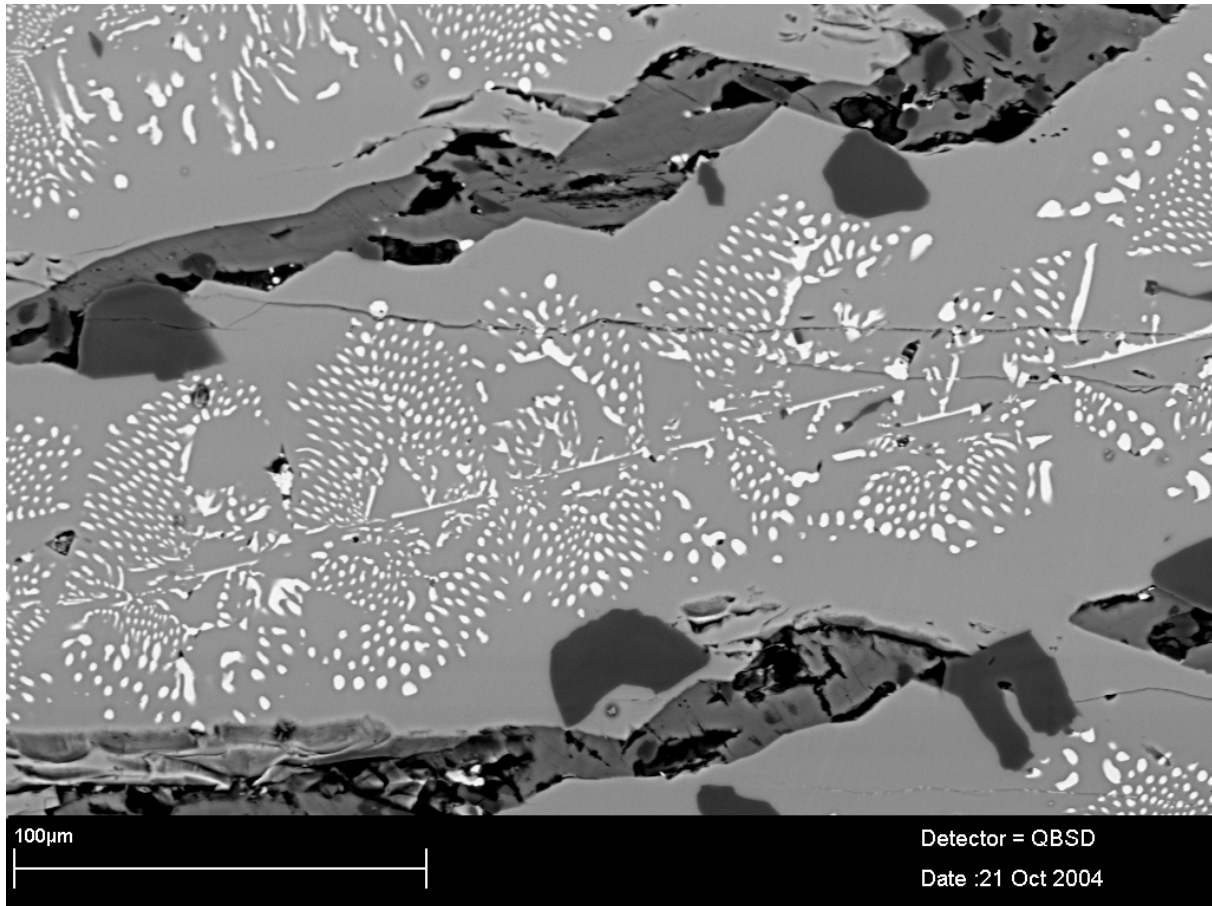
Figure 4. SEM image of sample 1 showing the finely dispersed wüstite (white) in the fayalite laths (light grey). The margins of the silicate laths contain dark grey crystals of hercynite. The material between the silicate laths (medium grey) is rich in iron and phosphorus oxide

The material in sample 1 from Heckfield which lies between the silicate laths is extraordinarily rich in phosphorus and iron oxides with moderate amounts of potassium and calcium oxide. The relative positions and distribution of the silicate laths and the matrix material indicate that the former solidified first and the latter last. From the P_2O_5–FeO phase diagram (Levin *et al* 1969, fig 2166) it can be inferred that the interstitial material would begin to solidify below 950ºC. It is likely that the presence of small amounts of potassium and calcium oxides in this material would further lower the melting temperature of this interstitial material. Therefore, it can be concluded that sample 1 would begin to solidify at approximately 1177ºC and remain at least slightly pasty until approximately 950ºC (the small proportion of interstitial material means that once the fayalite solidified the slag would be very viscous). The form of the silicate (laths) suggests fairly rapid cooling which is in agreement with their largely eutectoid microstructure.

Sample 4

Sample 4 is from a plano-convex lump of slag. This sample has a microstructure consisting of large euhedral grains of fayalite (Figure 5) surrounded by a complex interstitial groundmass. The interstitial groundmass is occasionally present as small bodies of leucite but is more commonly present as a mixture of wüstite, leucite, fayalite and an iron-potassium silicate (possibly iron-leucite or iron-feldspar). The first phase to have solidified would have been the fayalite (between 1177 and 1205ºC), followed by the interstitial ground mass.

Figure 5. SEM image of sample 4 showing fayalite (light grey) with a complex interstitial groundmass and some porosity (black)
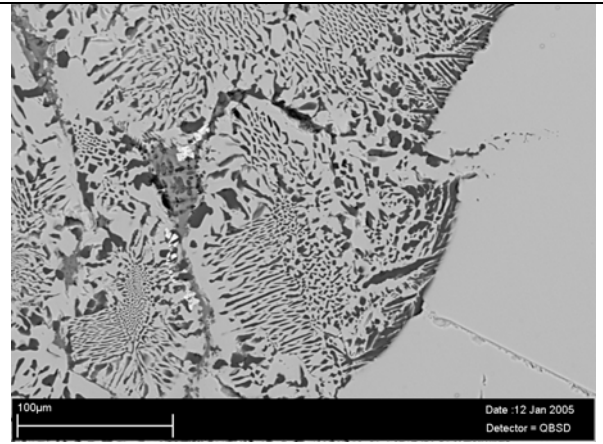
Figure 6. SEM image of sample 4 showing the interstitial groundmass. The dark grey is leucite, the medium grey is an iron-potassium silicate, the light grey is fayalite and the white is wüstite

The complex interstitial groundmass (Figure 5) contains four different phases (Figure 6). The first phase to have solidified would have been the wüstite, followed by a leucite-fayalite eutectic and solidification would end with the iron-potassium silicate. The complex nature of the interstitial groundmass in this case prevents any accurate estimation of the melting temperature of this material but it is certainly well below 1100ºC (Levin *et al* 1956, fig 425).

Sample 6

Sample 6 from is a plano-convex lump of slag. This sample has a microstructure consisting of wüstite dendrites superimposed on long, thin fayalite laths (Figure 7). The wüstite is present as fairly coarse dendrites which have solidified before the fayalite laths and as fine dendrites in the interstitial groundmass which have solidified after the fayalite laths. The microstructure lacks any of the more 'exotic' phases seen in the other samples.
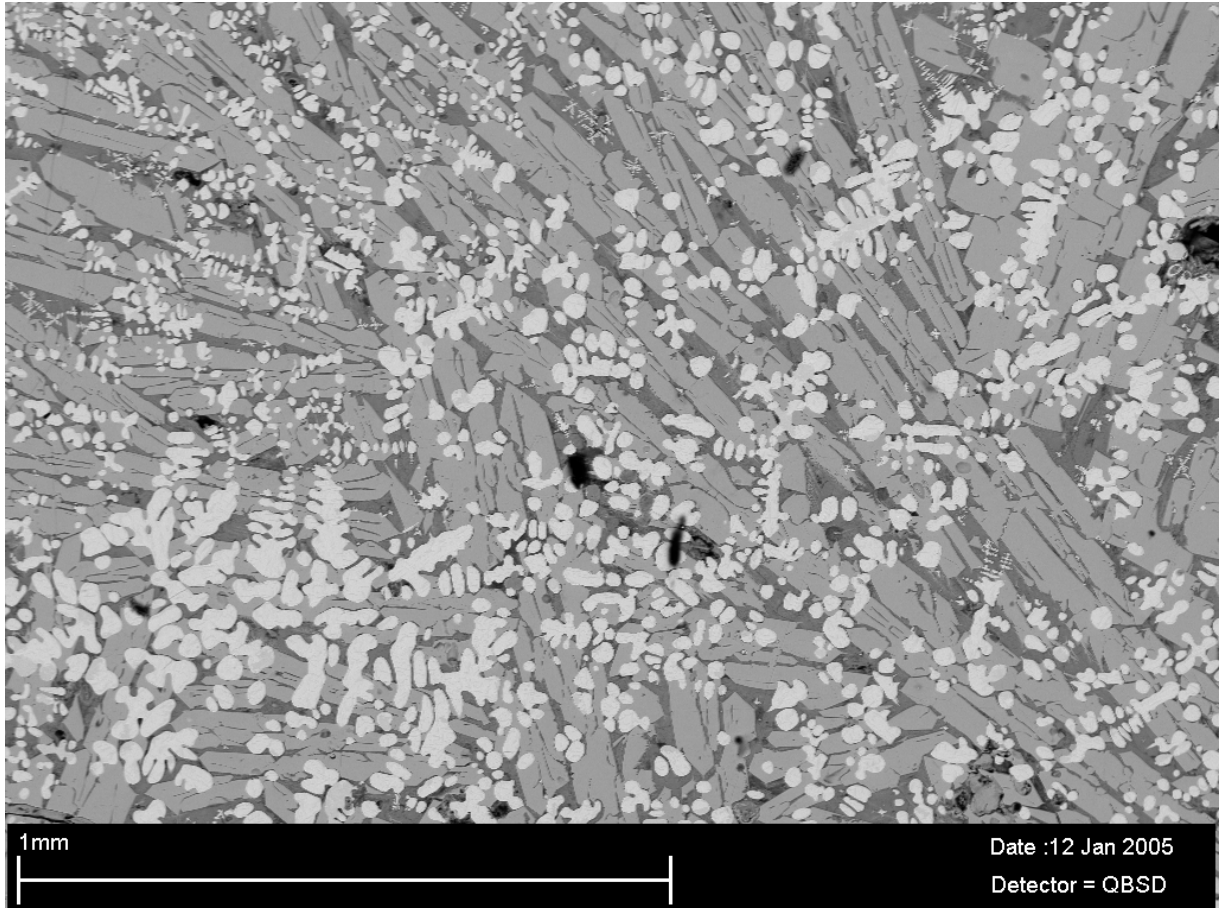
Figure 7. SEM image of sample 6 showing wüstite (white) and fayalite (light grey) in an interstitial glassy groundmass (darker grey)

Sample 8
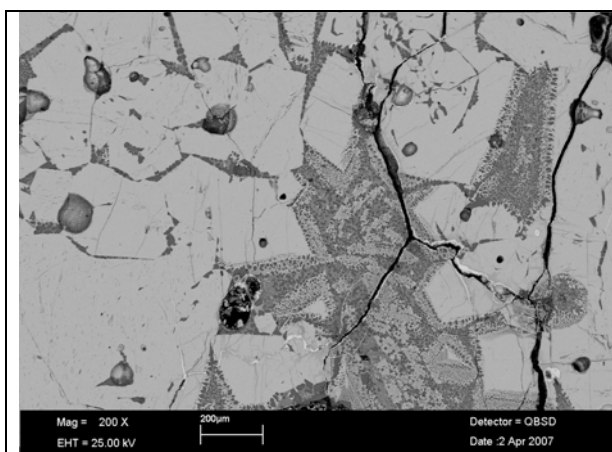
| Figure 7. SEM image of sample 8 showing fayalite (light grey) with a complex interstitial groundmass | Figure 8. SEM image of complex interstitial groundmass in sample 8 |
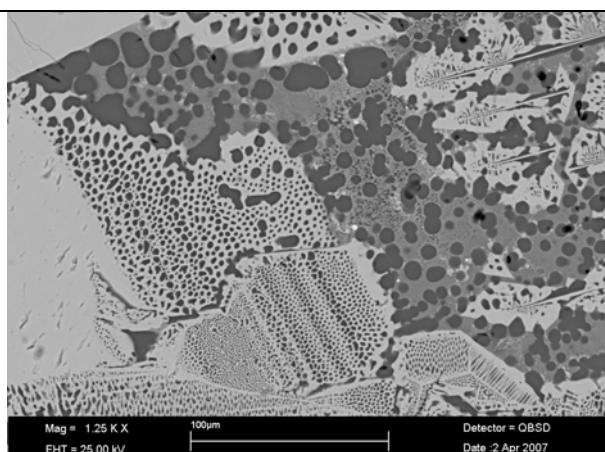
Sample 8 has a microstructure comprising abundant, large (up to 1mm) euhedral fayalite crystals in a complex groundmass (Figure 7). The interstitial groundmass, which contains several different phases (Figure 8), is probably a complex eutectic. The first phase to have solidified would have been the fayalite (between 1177 and 1205ºC), followed by the interstitial ground mass. Again the com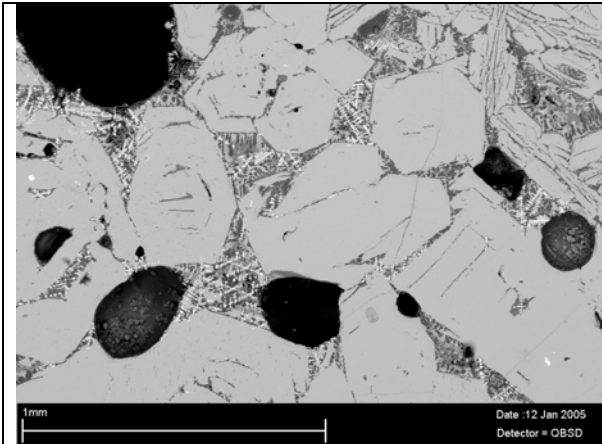plex nature of the interstitial groundmass prevents any accurate estimation of its melting temperature from phase diagrams. Nevertheless it is likely that the slag remained pasty well below 1100ºC.

Discussion

The Heckfield slags, which were probably produced during the middle Iron Age, are likely to have been produced during the smelting or iron ores. The manganese content of five of the slag samples are much higher than is normally seen in smithing slags (cf McDonnell 1986) but are comparable with some iron smelting slags (eg Thorpe Lea, Starley 1998). The three samples with low manganese contents do not have typical microstructures for smithing slags and are also likely to be smelting slags. The high phosphorus content of the slag suggests the use of a phosphorus-rich ore, such as bog ore (Piakowski 1989).

The morphology of the slag lumps provides very little information about how they formed. Indeed it is easier to say what they do not tell us: the slag was not tapped from the furnace or allowed to collect as a substantial furnace bottom (cf Paynter 2007). Parallels exist with other prehistoric iron smelting sites (eg North Cave, Thorpe Lea and Trevelgue Head) which lack morphologically distinct slags. In the absence of scientific techniques, such slags could easily be labelled non-diagnostic, ie iron working but not certainly smelting or smithing. The slag morphology, microstructure and chemical composition are similar to other prehistoric smelting sites in the region (ie Paynter's Surrey and Hampshire Tertiary Sands group).

References

Bayley, J, Dungworth, D and Paynter, S 2001 *Archaeometallurgy.* English Heritage: London

Crew, P 1986 'Bryn y Castell – a late prehistoric iron working settlement in north-west Wales'. *In* B G Scott & H Cleere (eds) *The Crafts of the Blacksmith.* Belfast: Ulster Museum, 91–100

Crew, 1988 'Bryn Y Castell hillfort, Gwynedd, North Wales: a preliminary analysis of the ironworking debris'. *In* J E Jones (ed) *Aspects of Ancient Mining and Metallurgy.* Bangor: University College of North Wales, 129–135

Crew, P 1991 'The experimental production of prehistoric bar iron'. *Historical Metallurgy* 25, 21–36

Dungworth, D forthcoming 'Examination of metalworking debris from the 1939 excavations at Trevelgue Head', *in* Nowakowski, J and Quinnell, H *Trevelgue Head, Cornwall – an Iron Age cliff-castle: the story of the 1939 excavations by the late C K Croft Andrew.* Truro: Cornwall County Council

Halkon, P & Millett, M 1999 *Rural Settlement and Industry: Studies in the Iron Age and Roman Archaeology of Lowland East Yorkshire.* Leeds: Yorkshire Archaeological Society

Levin, E M, McMurdie, H F and Hall, F P 1956 *Phase Diagrams for Ceramists.* Columbus: American Ceramic Society

McDonnell, J G 1984 *Interim report. Slags, Riseley Farm, Berkshire.* AML Report 4422. London: English Heritage

McDonnell, J G 1986 *The classification of early ironworking slags.* Unpublished PhD thesis. Birmingham: University of Aston

McDonnell, J G 1988 *The ironworking slags from North Cave, North Humberside.* AML Report 91/1988. London: English Heritage

McDonnell, J G 1991 'A model for the formation of smithing slag'. *Materialy Archeologiczne* 26, 23–26

Morton, G R and Wingrove, S 1969 'Constitution of bloomery slags: Part I: Roman'. *Journal of the Iron and Steel Industry* 1556–1564

Paynter, S 2006 'Regional variations in bloomery smelting slag of the Iron Age and Romano-British periods'. *Archaeometry* 48, 271–292

Paynter, S 2007 'Innovations in bloomery smelting in Iron Age and Romano-British England', *in* La Niece, S, Hook, D and Craddock, P (Eds) *Metals and Mines. Studies in Archaeometallurgy.* London: Archetype, 202–210

Piakowski, J 1989 'Phosphorus in iron ore and slag, and in bloomery iron'. *Archaeomaterials* 3, 47–59

Pleiner, R 2000 *Iron in Archaeology. The European bloomery smelters.* Prague: Archeologiký Ústav Avcr

Starley, D 1998 *Analysis of metalworking debris from Thorpe Lea Nurseries, near Egham, Surrey, 1990-1994.* AML Report 1/1998. London: English Heritage

Tylecote, R F 1986 *The Prehistory of Metallurgy in the British Isles.* London: Institute of Metals

Appendix: Chemical analyses

Sample	Area	Na$_2$O	MgO	Al$_2$O$_3$	SiO$_2$	P$_2$O$_5$	SO$_3$	K$_2$O	CaO	TiO$_2$	MnO	FeO
1	Bulk 1	<0.5	0.2	1.6	24.8	4.0	<0.2	0.4	0.8	<0.1	0.5	67.7
1	Bulk 2	<0.5	0.2	1.4	23.8	3.6	<0.2	0.4	0.7	<0.1	0.5	69.4
1	Bulk 3	<0.5	0.2	10.2	18.9	4.1	<0.2	0.4	0.8	<0.1	0.4	64.9
1	Bulk 4	<0.5	0.2	2.4	16.9	14.3	<0.2	1.9	2.5	<0.1	0.5	61.2
1	Bulk 5	<0.5	0.3	3.1	23.4	3.4	<0.2	0.3	0.7	0.2	0.6	68.1
1	Glass 1	1.1	<0.2	0.2	1.5	39.2	<0.2	7.1	7.0	<0.1	0.6	43.5
1	Glass 2	0.8	<0.2	0.2	1.5	39.7	<0.2	7.2	10.2	<0.1	0.6	39.8
1	Glass 3	0.9	0.2	0.2	2.0	39.0	<0.2	7.0	7.4	<0.1	0.7	42.6
1	Silicate 1	<0.5	0.3	0.5	28.2	1.2	<0.2	<0.1	0.2	<0.1	0.7	68.9
1	Silicate 2	<0.5	0.6	0.5	29.1	0.6	<0.2	<0.1	0.1	<0.1	0.7	68.4
1	Silicate 3	<0.5	0.6	0.4	28.7	1.3	<0.2	<0.1	0.2	<0.1	0.6	68.2
1	Spinel 1	<0.5	0.5	46.3	0.6	<0.2	<0.2	<0.1	<0.1	1.0	0.2	51.5
1	Spinel 2	<0.5	0.3	46.7	0.5	<0.2	<0.2	<0.1	<0.1	1.0	0.1	51.5

Sample	Area	Na$_2$O	MgO	Al$_2$O$_3$	SiO$_2$	P$_2$O$_5$	SO$_3$	K$_2$O	CaO	TiO$_2$	MnO	FeO
2	Bulk 1	<0.5	0.6	3.0	31.4	1.4	<0.2	0.4	1.5	0.3	0.5	61.0
2	Bulk 2	<0.5	0.6	2.6	28.2	1.4	<0.2	0.5	2.0	0.1	0.5	64.1
2	Bulk 3	<0.5	1.0	2.9	27.4	1.6	<0.2	0.6	1.7	0.2	0.6	64.0
2	Glass 1	<0.5	0.2	20.8	52.4	<0.2	<0.2	16.5	<0.1	<0.1	<0.1	9.8
2	Glass 2	0.7	<0.2	16.9	44.9	5.3	0.5	4.7	7.8	1.0	0.3	17.7
2	Glass 3	1.0	<0.2	15.8	39.6	5.1	0.5	3.5	8.3	1.0	0.4	24.9
2	Silicate 1	<0.5	0.8	0.3	33.3	0.5	<0.2	<0.1	0.9	<0.1	0.6	63.7
2	Silicate 2	<0.5	1.4	0.4	29.9	0.4	<0.2	<0.1	0.2	<0.1	1.0	66.8
2	Spinel 1	<0.5	0.3	49.6	0.3	<0.2	<0.2	<0.1	<0.1	0.7	0.2	48.9
2	Spinel 2	<0.5	0.4	46.7	0.8	<0.2	<0.2	0.6	0.1	1.2	0.2	50.0

Sample	Area	Na$_2$O	MgO	Al$_2$O$_3$	SiO$_2$	P$_2$O$_5$	SO$_3$	K$_2$O	CaO	TiO$_2$	MnO	FeO
3	Bulk 1	<0.5	0.4	0.8	24.9	1.8	<0.2	0.1	0.3	<0.1	0.3	71.1
3	Bulk 2	<0.5	0.3	1.2	23.2	4.7	<0.2	0.5	0.7	<0.1	0.3	69.1
3	Bulk 3	<0.5	0.5	5.4	22.7	2.9	<0.2	0.3	0.4	<0.1	0.3	67.5
3	Bulk 4	<0.5	0.3	7.6	21.5	2.6	<0.2	0.3	0.4	0.1	0.2	66.9
3	Glass 1	1.2	<0.2	0.2	1.4	39.3	<0.2	7.1	7.2	<0.1	0.3	43.3
3	Glass 2	1.4	<0.2	0.3	1.5	39.3	<0.2	7.3	7.2	0.2	0.5	42.3
3	Glass 3	1.7	<0.2	0.2	1.4	39.0	<0.2	7.5	7.5	0.3	0.2	42.1
3	Iron oxide 1	<0.5	<0.2	0.7	0.5	<0.2	<0.2	<0.1	<0.1	0.3	<0.1	98.5
3	Iron oxide 2	<0.5	<0.2	1.2	0.5	<0.2	<0.2	<0.1	<0.1	0.4	<0.1	97.9
3	Iron oxide 3	<0.5	<0.2	0.7	0.6	<0.2	<0.2	<0.1	<0.1	0.3	<0.1	98.4
3	Silicate 1	<0.5	0.6	0.5	27.8	1.3	<0.2	<0.1	0.1	<0.1	0.5	69.0
3	Silicate 2	<0.5	<0.2	0.6	27.3	1.8	<0.2	<0.1	0.2	<0.1	0.4	69.8
3	Spinel 1	<0.5	0.7	52.0	0.4	<0.2	<0.2	<0.1	<0.1	0.3	0.2	46.5
3	Spinel 2	<0.5	0.4	47.7	0.5	<0.2	<0.2	<0.1	<0.1	0.4	0.1	50.9

Sample	Area	Na$_2$O	MgO	Al$_2$O$_3$	SiO$_2$	P$_2$O$_5$	SO$_3$	K$_2$O	CaO	TiO$_2$	MnO	FeO
4	Bulk 1	<0.5	0.2	2.8	30.2	1.1	<0.2	1.8	1.7	0.1	<0.1	62.0
4	Bulk 2	<0.5	0.3	2.0	30.1	0.9	<0.2	1.2	1.1	0.1	<0.1	64.2
4	Bulk 3	<0.5	0.3	3.0	28.9	1.4	<0.2	2.2	2.0	0.2	<0.1	62.1
4	Bulk 4	<0.5	<0.2	4.7	31.8	1.1	<0.2	3.0	1.7	0.1	<0.1	57.4
4	Glass 1	0.6	<0.2	2.1	47.1	2.5	2.1	12.5	4.1	1.6	<0.1	27.4
4	Glass 2	<0.5	<0.2	20.3	54.3	0.7	0.2	19.4	0.2	0.2	<0.1	4.6
4	Glass 3	1.8	<0.2	2.6	45.2	2.7	1.8	12.5	2.4	0.6	<0.1	30.4
4	Glass 4	<0.5	<0.2	21.0	55.1	<0.2	<0.2	20.3	<0.1	<0.1	<0.1	3.4
4	Glass 5	2.0	<0.2	2.6	44.3	2.4	1.9	15.3	2.3	0.7	<0.1	28.4
4	Glass 6	<0.5	0.2	20.7	53.3	0.9	<0.2	20.8	0.5	<0.1	<0.1	3.5
4	Iron oxide 1	<0.5	<0.2	0.3	0.4	<0.2	<0.2	0.2	<0.1	0.3	<0.1	98.7
4	Iron oxide 2	<0.5	<0.2	0.4	0.3	<0.2	<0.2	<0.1	<0.1	<0.1	<0.1	99.3
4	Iron oxide 3	<0.5	<0.2	<0.1	0.6	<0.2	<0.2	<0.1	<0.1	0.4	<0.1	99.0
4	Silicate 1	<0.5	0.4	0.3	29.1	0.2	<0.2	<0.1	0.4	<0.1	<0.1	69.6
4	Silicate 2	<0.5	0.4	0.2	29.3	0.3	<0.2	<0.1	0.4	<0.1	<0.1	69.3
4	Silicate 3	<0.5	0.3	0.2	29.7	0.2	<0.2	<0.1	0.5	<0.1	<0.1	69.2

Sample	Area	Na$_2$O	MgO	Al$_2$O$_3$	SiO$_2$	P$_2$O$_5$	SO$_3$	K$_2$O	CaO	TiO$_2$	MnO	FeO
5	Bulk 1	<0.5	<0.2	0.9	12.9	4.7	<0.2	0.5	0.7	<0.1	0.2	80.1
5	Bulk 2	<0.5	<0.2	2.8	11.4	8.6	<0.2	1.0	1.3	<0.1	0.1	74.9
5	Bulk 3	<0.5	0.3	1.0	15.8	2.3	<0.2	0.1	0.2	<0.1	0.1	80.1
5	Bulk 4	<0.5	<0.2	0.9	14.3	4.6	<0.2	0.5	0.6	<0.1	<0.1	79.0
5	Glass 1	<0.5	<0.2	0.3	1.9	38.7	<0.2	6.4	6.8	<0.1	0.3	45.6
5	Glass 2	<0.5	<0.2	0.4	2.9	33.8	0.6	0.4	2.8	<0.1	<0.1	59.2
5	Glass 3	<0.5	<0.2	0.2	1.9	38.6	<0.2	6.8	7.6	<0.1	0.3	44.7
5	Iron oxide 1	<0.5	<0.2	0.8	0.6	<0.2	<0.2	<0.1	<0.1	<0.1	<0.1	98.5
5	Iron oxide 2	<0.5	<0.2	0.8	0.5	<0.2	<0.2	<0.1	<0.1	<0.1	<0.1	98.7
5	Silicate 1	<0.5	0.3	0.4	31.2	1.7	<0.2	<0.1	0.1	<0.1	0.2	66.0
5	Silicate 2	<0.5	0.6	0.2	27.8	1.4	<0.2	<0.1	0.1	<0.1	0.2	69.7
5	Silicate 3	<0.5	0.3	0.5	28.9	1.9	<0.2	<0.1	0.1	<0.1	0.2	68.0
5	Silicate 4	<0.5	<0.2	0.5	27.8	1.5	<0.2	<0.1	0.1	<0.1	0.2	69.9
5	Silicate 5	<0.5	<0.2	0.6	29.2	2.6	<0.2	<0.1	0.2	<0.1	0.2	67.2
5	Spinel 1	<0.5	0.4	48.1	0.6	<0.2	<0.2	<0.1	<0.1	0.4	<0.1	50.5
5	Spinel 2	<0.5	0.3	49.8	0.3	<0.2	<0.2	<0.1	<0.1	0.5	<0.1	49.1
5	Spinel 3	<0.5	0.3	48.8	0.4	<0.2	<0.2	<0.1	<0.1	0.3	<0.1	50.2

Sample	Area	Na$_2$O	MgO	Al$_2$O$_3$	SiO$_2$	P$_2$O$_5$	SO$_3$	K$_2$O	CaO	TiO$_2$	MnO	FeO
6	Bulk 1	<0.5	0.5	2.2	24.6	1.1	<0.2	1.1	1.9	0.1	<0.1	68.4
6	Bulk 2	<0.5	0.3	3.3	24.5	1.7	<0.2	1.8	2.7	<0.1	0.1	65.4
6	Bulk 3	<0.5	0.3	2.6	25.9	1.5	<0.2	1.7	2.6	0.1	<0.1	65.3
6	Bulk 4	<0.5	0.4	2.3	22.8	1.1	<0.2	1.3	2.0	<0.1	<0.1	70.2
6	Bulk 5	<0.5	0.7	3.0	30.1	1.7	<0.2	1.4	2.3	0.1	<0.1	60.8
6	Glass 1	1.1	<0.2	8.1	34.5	6.0	1.3	7.3	10.3	0.2	<0.1	31.2
6	Glass 2	1.1	<0.2	7.3	36.3	4.5	0.7	6.4	10.9	0.2	<0.1	32.7
6	Glass 3	1.3	<0.2	6.9	38.4	4.7	1.1	8.4	9.8	0.2	<0.1	29.2
6	Glass 4	<0.5	<0.2	6.4	32.2	5.3	<0.2	6.7	6.0	<0.1	0.1	43.2
6	Iron oxide 1	<0.5	<0.2	0.3	0.4	<0.2	<0.2	<0.1	<0.1	<0.1	<0.1	99.2
6	Iron oxide 2	<0.5	<0.2	0.3	0.4	<0.2	<0.2	<0.1	<0.1	0.1	<0.1	99.1
6	Iron oxide 3	<0.5	<0.2	0.5	0.4	<0.2	<0.2	<0.1	<0.1	0.2	<0.1	99.0
6	Silicate 1	<0.5	0.9	0.2	29.2	0.4	<0.2	<0.1	0.8	<0.1	<0.1	68.4
6	Silicate 2	<0.5	0.8	0.3	29.2	0.5	<0.2	<0.1	0.9	<0.1	0.1	68.1
6	Silicate 3	<0.5	0.8	0.3	29.3	0.3	<0.2	<0.1	0.9	<0.1	0.1	68.3
6	Silicate 4	<0.5	0.8	0.2	29.7	0.2	<0.2	<0.1	0.8	<0.1	<0.1	68.0

Sample	Area	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
7	Bulk 1	<0.5	0.2	2.0	16.0	6.2	<0.2	0.4	1.0	<0.1	0.8	73.3
7	Bulk 2	<0.5	0.2	1.4	16.9	5.1	0.3	0.3	0.8	<0.1	0.9	74.0
7	Bulk 3	<0.5	<0.2	2.1	15.0	6.8	<0.2	0.5	0.9	<0.1	0.8	73.8
7	Bulk 4	<0.5	<0.2	2.7	17.2	5.8	<0.2	0.4	0.9	0.1	0.9	72.1
7	Glass 1	1.3	0.4	0.3	1.7	38.3	<0.2	6.2	7.7	0.3	1.7	42.2
7	Glass 2	1.2	<0.2	0.2	1.2	39.5	<0.2	6.7	7.5	0.2	1.9	41.3
7	Glass 3	1.1	<0.2	0.2	1.8	38.2	0.5	6.1	7.1	0.3	1.7	43.0
7	Iron oxide 1	<0.5	<0.2	0.5	0.4	<0.2	<0.2	<0.1	<0.1	<0.1	0.2	98.9
7	Iron oxide 2	<0.5	<0.2	0.6	0.5	<0.2	<0.2	<0.1	<0.1	<0.1	0.3	98.6
7	Iron oxide 3	<0.5	<0.2	0.6	0.5	<0.2	<0.2	<0.1	<0.1	<0.1	0.3	98.6
7	Odd phase 1	<0.5	<0.2	0.8	2.8	7.5	<0.2	<0.1	<0.1	0.3	0.4	88.4
7	Odd phase 2	<0.5	<0.2	0.7	1.6	8.4	<0.2	<0.1	<0.1	0.2	0.4	88.6
7	Odd phase 3	<0.5	<0.2	0.8	2.3	7.6	<0.2	<0.1	<0.1	0.1	0.3	88.9
7	Silicate 1	<0.5	0.4	0.5	26.6	3.1	<0.2	<0.1	0.2	<0.1	1.0	68.2
7	Silicate 2	<0.5	0.3	0.6	27.7	1.4	<0.2	<0.1	0.1	<0.1	1.0	68.9
7	Silicate 3	<0.5	0.4	0.7	26.7	3.3	<0.2	<0.1	0.2	<0.1	1.1	67.7
7	Spinel 1	<0.5	0.3	47.4	0.7	<0.2	<0.2	<0.1	<0.1	0.5	0.3	50.8
7	Spinel 2	<0.5	0.4	48.2	0.6	0.2	<0.2	<0.1	0.1	0.3	0.4	49.8
7	Spinel 3	<0.5	0.3	47.7	0.9	<0.2	<0.2	<0.1	<0.1	0.3	0.2	50.5

Sample	Area	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
8	Bulk 1	<0.5	0.4	3.5	32.1	1.8	<0.2	1.0	0.5	0.1	0.6	59.9
8	Bulk 2	0.7	<0.2	7.7	37.0	3.7	<0.2	2.4	1.8	0.6	0.4	45.7
8	Bulk 3	0.8	0.4	5.0	33.7	1.8	<0.2	1.2	0.6	0.1	0.6	55.8
8	Bulk 4	<0.5	0.4	3.5	31.7	1.9	<0.2	0.9	0.6	0.2	0.6	60.3
8	Bulk 5	0.5	0.4	5.0	31.8	3.4	<0.2	1.2	1.5	0.3	0.6	55.4
8	Bulk 6	0.5	0.3	3.8	32.2	2.0	<0.2	0.9	0.7	0.2	0.6	58.7
8	Glass 1	1.2	<0.2	15.6	59.3	2.7	<0.2	6.6	1.2	0.3	0.2	13.0
8	Glass 2	<0.5	<0.2	13.8	27.1	15.7	<0.2	2.9	8.5	2.1	0.4	29.5
8	Glass 3	0.8	<0.2	15.7	60.9	2.2	<0.2	6.0	1.7	0.4	0.1	12.2
8	Glass 4	<0.5	<0.2	13.9	26.7	15.5	<0.2	3.1	7.9	2.3	0.4	30.2
8	Glass 5	<0.5	<0.2	12.9	27.9	14.1	0.4	2.3	7.9	2.8	0.4	31.3
8	Silicate 1	<0.5	0.4	0.3	29.3	0.4	<0.2	<0.1	<0.1	<0.1	0.7	68.8
8	Silicate 2	<0.5	0.6	0.2	29.1	0.7	<0.2	<0.1	<0.1	<0.1	0.7	68.7