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Archaeometallurgical residues from  
the South Hook LNG terminal

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# Archaeometallurgical residues and associated materials from the South Hook LNG terminal

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## Abstract

*The site yielded approximately 53kg of iron slag. Metallurgical activities on the site included both iron smelting and smithing of the raw blooms. Smelting was undertaken in a pair of furnaces in Complex 1. The layout of the Complex 1 workshop can best be paralleled in SW Ireland. There is no evidence from the metallurgical residues for metallurgical activities in any of the other complexes.*

*The smelting furnaces were slag-tapping furnaces of a slightly unusual form, with the basal preserved sections apparently rectangular of "D"-shaped in plan, with a straight blowing wall reinforced with vertical slabs of stone. The base of the furnace was constructed as a pit, extending externally as a tapping pit. Further stonework in the western furnace suggests the partial survival of a collapsed tapping arch. Inclined stones within the fill of the furnaces appear to be attempts to re-floor the furnace pit during refurbishment. Based on the internal slag distribution, the furnaces appear to have been blown axially, from the uphill, northern side, contrasting with the more usual arrangement of blowing from a direction perpendicular to the tapping arch. Although the superstructure is missing, the basal parts of the furnaces resemble that of the last of the middle Saxon furnaces at Ramsbury, Wiltshire.*

*The evidence for refurbishment and the construction of a pair of similar furnaces indicates that this was a sustained attempt to make iron on a significant scale. The amount of slag and other waste from the iron-making operation is, however, rather small. The area around the furnaces in Complex 1 appears to have been rather clean, with most of the recovered slag probably representing material reworked into the hollow after abandonment, presumably from waste dumps in areas outside the hollows containing the preserved archaeology.*

*It is suggested that two distinct sources of iron ore were employed, but it is possible that only one of these was actually smelted at South Hook. Tapped smelting slags from c1038 (fill of pit c1039) and c1887 (fill of furnace c1081) were produced by the smelting of a manganese-rich ore, possibly a bog iron ore or a Carboniferous claystone ironstone. A second suite of materials, represented by bloomsmithing slags and possibly furnace slags from several contexts, also shows strong manganese enrichment, but also markedly elevated zirconium contents. The source of this second group was probably a bog ore deposit, possibly in a location influenced by a zircon-rich rhyolitic unit within the Skomer Volcanic Group which crops out from the St Ishmaels area (three kilometres west of South Hook) westwards to Skomer. This suggests that the South Hook site may have been involved with the refining of blooms produced elsewhere, in addition to its own smelting operation. Centralised smithing of blooms smelted close to ore sources or to charcoal-producing woodlands is a common feature in early iron production.*

*A small piece of manganese-rich iron ore recovered from c1038 did not prove to be a good match for either suite of slags. Its rare earth element profile was, however, somewhat similar to (unprovenanced) manganese ores probably recovered during excavation of the Palaeolithic burial at Paviland Cave, Gower.*

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## Methods

All materials were examined visually with a low powered binocular microscope as part of the evaluation (Young 2006a). The evaluation identified this assemblage as being slags and associated residues produced in the processes of iron smelting and smithing. A catalogue of the material is presented in Table 1. A follow-up programme of analysis was designed to investigate the residues in more detail. These materials are reported on here separately from the fuel ash slags from the same site (Young 2010a) which are interpreted as being non-metallurgical and produced with corn-drying kilns.

Thirteen samples of slags, two furnace lining samples and an iron ore sample were selected for detailed analysis (Table 2). Four samples (two slags and two ores) from the nearby smelting site at Brownslade were also examined, to extend the range of possible provenancing data, but have been reported upon separately (Young 2010b).

Electron microscopy was undertaken on the LEO S360 analytical electron microscope in the School of Earth, Ocean and Planetary Sciences, Cardiff University. Microanalysis was undertaken using the system's Oxford Instruments INCA ENERGY energy-dispersive x-ray analysis system (EDX). All petrographic images presented in this report are backscattered electron photomicrographs. The polished blocks for investigation on the SEM were prepared in the Earth Science Department, The Open University. Chemical analysis was undertaken using two techniques. The major elements (Si, Al, Fe, Mn, Mg, Ca, Na, K, Ti, and P) were determined by X-Ray Fluorescence using fused beads, on the Open University Earth Science

Department's Wavelength-Dispersive X-Ray Fluorescence (WD-XRF) system. Whole-specimen chemical analysis for minor and trace elements was undertaken using samples in solution on the ThermoElemental X-series Inductively-Coupled Plasma Mass Spectrometer (ICP-MS) in the School of Earth, Ocean and Planetary Sciences, Cardiff University.

Whole-specimen bulk chemical analyses are presented in Table 3 and EDS microanalyses in Table 4.

The convention adopted in this report is to describe olivine bearing Fe, Mg, Ca and Mn in terms of an olivine on the forsterite-fayalite join (using the notation for instance of Fa95 for an olivine that is 95% fayalite and 5% forsterite; where  $Fe/(Fe+Mg) = 0.95$ ) plus figures for the overall percentage replacement by calcium and manganese.

This project was undertaken for the Dyfed Archaeological Trust Ltd.

## Results

### Description of samples

#### Tapped smelting slags

##### *General*

The tapped slags accumulated in thin flows (usually <40mm), at least some of which were moderately wide (<0.2m) and on the evidence of the flows left in-situ in the furnaces, many were moderately long (<0.60m?).

Samples SHL4, 5, and 6 all provide evidence for the nature of the tapping channel. SHL4 has a strongly hooked shape to the flows in profile, showing that the flows had dropped sharply over a fall in the floor. Such a drop is provided by the distal ends of the stone slabs placed onto the floors of both furnaces during their refurbishment. A similar flow morphology is shown in the section of Ramsbury Furnace 4 (Haslam 1980), where slag flows that were not fully cleared from the furnace produced similar rises in furnace floor level and falls over their distal (fractured?) ends.

SHL 5 shows a narrow "runner", with the flow constricted into a channel only 50mm wide. This flow solidified in the channel, with its proximal end (represented by conjoined piece SHL6) grading inwards into the charcoal-rich furnace fill.

Sample SHL3 is from an early, flat-topped flow well within the furnace base itself.

The samples show some variety in composition, but in general are characterised by primary wustite dendrites, which are extensive and delicate in the tapped slags, but more stocky in the less quenched materials. The wustite shows some Al substitution and often quite high levels of Mn substitution. The wustite is followed by elongate olivine, typically with high levels of manganese substitution. Interstitial areas of typical textures are mainly glassy.

In contrast, the samples which solidified inside the furnace (SHL3 and SHL6) both show extensive development of a leucite-wustite cotectic, particularly around vesicle margins, in association with an olivine which bears small quantities of calcium. Such areas

have coarse-grained olivine and are typically poor in primary wustite.

#### Details

**SHL1 (Plate 1):** SHL1 shows multiple flow lobes with thin iron oxide veneers marking the chilled lobe surfaces (Plate 1a, c). The individual lobes vary in microstructure in detail, particularly in the degree of vesicularity. The primary wustite forms delicate dendrites with coherency over distances of about 300µm (Plate 1d). The wustite shows about 1-2% Al and 5-6% Mn substitution.

The elongate fayalite has lengths of around 600-800µm (Plate 1d). The cores have compositions of Fa96 with 20% Mn substitution and margins of Fa98 with 20% Mn substitution. The fayalite bears inclusions (presumably as a cotectic) of hercynite, which has a variable composition, recorded as having 15-16% magnetite and 12% galaxite in one analysed area, but as much as 17-21% magnetite and 12-17% galaxite in another.

**SHL2 (Plate 2):** This specimen shows multiple flow lobes (Plate 2a, b). The flow lobes are marked by particularly well marked iron oxide crusts. Internally the primary phase is a delicate dendritic array of wustite, with individual dendrites approximately 300-400µm across (Plate 2c). The wustite shows 1-2% Al and 7-8% Mn substitution.

The subsequent olivine is present as elongate crystals probably up to about 1mm in length. These can be seen to radiate from nucleation centres on the margin of the flow lobes (Plate 2b) and within each lobe occur as oriented blocks or sheaves (Plate 2c). The cores of the olivine are typically Fa92 with 27-28% Mn substitution. The margins are more variable at approximately Fa95 with 1% Ca and 24-28% Mn substitution. The interstitial areas are apparently mainly glass, locally with trains of small iron blebs.

**SHL3 (Plate 3):** This sample is much more heterogeneous than more flow-lobed slags. The structure includes arcuate zones of quite different microstructure, but it is unclear if these are flow lobes, or perhaps infills of large voids. From lower left to upper right Plate 3c shows five zones: a) skeletal texture with elongate olivine crystals defining voids, b) elongate olivine crystals with arcuate boundary with above zone, gradational into c) coarse grained equant olivine containing large vesicles with leucite-rich peripheries particularly towards the border with d) which is marked by large complex fayalite-hercynite-leucite-wustite intergrowths, beyond which the olivine becomes elongate (to 700µm) and the wustite dendrites become larger and more delicate and finally e) in which the equant olivine is again developed.

The primary wustite is restricted in its distribution and comprises mainly rather small blebby linear dendrites where the olivine is equant and more delicate, larger dendrites where the olivine is elongate (right hand side of Plate 3c).

Interstitial material is mainly a leucite-wustite cotectic, but some areas show a glass with a wide variety of crystallites (Plate 3e).

Where the olivine is fairly simple, its core is of Fa94-95 with 8-9% Mn substitution and this grades out to margins of Fa97-100 with 8-9% Mn and up to 1% Ca substitution. The associated complex olivine is typically Fa100 with 1% Ca and 8% Mn substitution.

Hercynite is associated with the interface between the complex olivine and the leucite-wustite cotectic mixture. The hercynite shows 8-22% magnetite (some of this variation may well be a function of an impure analysis) and 4-7% galaxite.

**SHL4 (Plate 4):** This flow lobed structure shows large delicate primary wustite dendrites (up to about 800µm across; Plate 4a), which are followed by particularly thin elongate olivine crystals, aligned in sweeping arrays across the lobes (Plate 4a, b). Interstitial materials are not well preserved, but appear to be mainly glass.

The wustite shows 9% Mn substitution. The olivine is relatively calcic (compared with the almost calcium-free olivines that are characteristic of the South Hook slags), having cores of Fa88, with 1% Ca and 29-30% Mn substitution. The margins are up to Fa96 with up to 3% Ca and 27% Mn substitution.

**SHL5 (Plate 5):** This sample is dominated by wustite, with some areas of the specimen (e.g. Plate 5a) very close to 100% wustite. In this area the wustite is in the form of rounded stout but elongate dendrites. In other areas the wustite development is less (e.g. lower part of view in Plate 5c) and elongate olivine is visible. The largest wustite dendrites are about 2mm long (Plate 5d). Analysed wustite had 6-7% Mn and 1% Al substitution.

The olivine has cores of Fa95 with 1% Ca and 23% Mn substitution, which grade to margins of Fa99 with similar levels of substitution. Interstitial areas are dominantly glassy.

**SHL6 (Plate 6):** This specimen is very heterogeneous, with zones of wustite dominated textures, similar to those of SHL5 (a contiguous part of the same flow). The wustite doesn't achieve quite such high proportions as in SHL5 however (Plate 6a, e). The wustite is in stout dendrites with rounded elements and shows 1% Al and 7-8% Mn substitution.

The olivine in these wustite rich areas has cores of Fa95 with 0-1% Ca and 24% Mn substitution, grading out to margins of Fa96, with 1% Ca and 27% Mn substitution.

In other areas, around large vesicles, the slag is poor in primary wustite and has textures dominated by a large equant olivine and a complex olivine intergrown with a leucite-wustite cotectic (Plate 6b, c, e, g). The main olivine in these areas has compositions very close to those described above, and even the complex olivine is little different at Fa94-95 with 1% Ca and 24-25% Mn substitution.

**SHL 7 (Plate 7):** This is a relatively coarse-textured slag, with primary wustite in stout linear dendrites up to 700µm in length, followed by elongate olivine (Plate 7a), probably slightly greater in length than the wustite. Interstitial areas are of glass with fine olivine crystals and iron blebs.

The wustite shows 3% Mn and 1% Al substitution. The main phase olivine ranges from cores of Fa96 with 12% Mn substitution grading to margins of Fa98 with 1% Ca and 13% Mn substitution. Similar analyses have been obtained for the small interstitial olivine.

## Furnace and smithing slags

### General

This section deals with material identified as being smithing hearth cakes (SHCs) as well as with material identified as being furnace slags (i.e. slags which solidified within the smelting furnaces). Both classes of material include much slag that is very rich in charcoal inclusions, and their certain differentiation in hand specimen is not always possible.

The site produced a small number of smithing hearth cakes (SHCs). The SHCs are all large, with all five cakes identified as possibly being complete SHCs weighing over 700g. The specimens did not, in general, have a classic SHC morphology; only the SHC sampled as SHL10 was of a typical compact form with a dense lower crust. Most of the other specimens contained a high proportion of charcoal-rich slag. The SHC sampled as SHL9 was a very wide cake, with a dense upper layer and low density charcoal-rich material below.

The SHCs were extensively sampled, in order to develop an understanding of the smithing being undertaken on site. Seven slag cakes were identified as probably or possibly being SHCs (or part of SHCs) during the assessment. Of these five were sampled for further analysis:

C901, possible SHC, 704g	(SHL18)
C1003, probable SHC, 1115g	(SHL9)
C1004, probable SHC, 776g	(SHL10)
C1005, possible SHC fragment, 264g	
C1033, possible SHC fragment, 334g	(SHL16)
C1037, probable SHC, 756g	
C1043, possible SHC, 1440g	(SHL17)

In addition to the material isolated in the assessment phase as probably being from SHCs, a block of charcoal-rich slag from C1038, tentatively identified as furnace slag, with a slightly lobate upper surface, weighing 536g was sampled as SHL8.

In both Britain (Crew, 1996) and Ireland (Young, forthcoming) SHCs from blacksmithing (the use of iron in making or repairing artefacts) mainly seem to weight in the range of 100-600g, although heavier cakes may appear in the later medieval period. SHCs heavier than 600g are mainly associated with the smithing of blooms down to usable iron. In Britain, SHCs from early medieval bloomsmithing (a general term for the refining of blooms from the raw state down to usable iron) range up to about 2kg (Crew 1996), but in Ireland SHCs can be much larger, as much as 11kg on some sites (Young forthcoming). That all five possible complete SHCs from this site weigh over 700g is strongly suggestive that they are from bloom refining rather than artefact manufacture. It also, despite the rather small assemblage, suggests that the bloomsmithing is not being undertaken within an Irish tradition.

For the specimens which were firmly identifiable as being SHCs (SHL9 and SHL10) the key microstructural features are an extremely heterogeneous primary wustite distribution, ranging from zones of densely-packed blebs (suggestive of an original iron ore or iron particle) through to well marked zones (early vesicles?) with no primary wustite. In SHL10 the primary wustite overgrew pieces (now highly altered) of metallic iron (Plate 10) and small enclaves may represent similar altered iron in SHL9 (Plate 9a), SHL17 (Plate 12a, b) and SHL18 (Plate 13a). In some of these specimens the olivine which follows the wustite is relatively

magnesian, with values as low as Fa83 being recorded in SHL10. Levels of Mn substitution were relatively low (up to a maximum of 9%, but typically much less) in agreement with the modest bulk Mn content of these samples.

Samples SHL17 and SHL18 were considered less certainly SHCs on a morphological basis, and although the presence of iron does not confirm the identification of these slags as SHCs, it does strengthen the link between the group of samples.

SHL8 shows a different microstructure from the other members of this group (Plate 8). The primary wustite is rather sparse and forms well developed, but fine dendrites. The rather coarse elongate olivine is cotectic with hercynite and the material shows an interstitial leucite-wustite cotectic, which locally approaches 50%. This difference may support the original interpretation of this piece as a furnace slag.

The microstructures seen in SHL16 are rather similar to the bulk of SHL8. The primary wustite forms well developed fine dendrites, which are followed by quite coarse grained fayalite (although without a hercynite cotectic). The interstitial areas are poorly preserved, but are rich in rods of probable wustite, but it is unclear if they are within leucite or glass.

### Details

**SHL8 (Plate 8):** This specimen shows primary wustite, in dendrites of up to about 400µm, with a very heterogeneous distribution (compare Plates 8a and b) which does not reach a particularly high proportion. The wustite shows about 1% Al and 4% Mn substitution. The subsequent olivine shows analyses in its core of Fa93 with 19% Mn substitution. Olivine margins range up to Fa97 with 19% Mn and 1% Ca substitution. These outer parts of the olivine are cotectic with a spinel mineral of approximate composition 73% hercynite, 12-15% magnetite, 11-12% galaxite and up to 3% spinel.

In some relatively primary wustite-rich areas the olivine is elongate (Plate 8b), but in some primary wustite-poor areas the olivine is more equant (Plate 8a). In both areas there is an interstitial leucite-wustite cotectic, but in the primary wustite-poor areas the leucite-wustite may compose up to 50% of the material. In these extreme textures the leucite-wustite cotectic may be surrounded by subhedral leucite rims.

In some areas the outer margins of the olivine bear small rounded inclusions rich in Fe, Ca, Mn and P (Plate 8c). These are presumably a phosphate mineral, given the lack of silica, but it not certain that they are crystalline.

**SHL9 (Plate 9):** This sample shows an extremely inhomogeneous distribution of coarse primary wustite (Plate 9a, b). This varies from moderately tightly packed aggregates (Plate 9b) to coarse rounded dendritic masses, locally exceeding 1mm in size (Plate 9a). The wustite shows up to 1% Mn and 1% Mg substitution. The olivine is typically in small elongate crystals up to 600µm in length with a composition of Fa91 with 1% Ca and 6-7% Mn substitution. The olivine is most clearly seen in gaps in the wustite growth, but may be finer grained in those gaps than within the wustite-rich areas.

Some rounded zones of secondary iron oxides with slightly cusped margins may represent badly decomposed blebs of iron metal (left side of Plate 9a). The interstitial glass to the fayalite is also badly altered

in many areas and contains rounded hollow iron oxide(?) bodies that may possibly also represent decomposed iron blebs.

**SHL10 (Plate 10, Plate 11a):** This sample is dominated by substantial irregular, porous, pieces of highly altered iron, the largest of which is at least 5mm across within the plane of the section (Plate 10a). No surviving iron was observed. The iron showed a thin rim of wustite (Plate 10b, g), which shows bulbous outgrowths sometimes forming the roots of dendrites. Away from the iron, the texture had a heterogeneous, but locally dominant primary wustite in rounded crude coarse dendrites, locally much larger than 1mm across. The arms of the wustite dendrites are locally intermingled with abundant similarly-sized irregularly blebby altered iron. The wustite shows up to about 1% substitution of each of Mn, Mg and Al.

The olivine has a variable crystal size, but mainly shows an elongate (probable lath-like) morphology, which is locally skeletal. Within the voids of the iron lump there is no interstitial material so the morphology of the olivine is particularly clear (Plate 10b). Close to the iron, the olivine was observed to be Fa90-93 with 4-5% Mn substitution and 1-2% Ca substitution. Further from the iron, even more magnesian compositions of Fa83-86 with 2-3% Ca and 8-9% Mn substitution. In this area the wustite is more heavily substituted too, with 1% Mg and 3% Mn substitution.

**SHL16 (Plate 11 b,c):** This specimen shows primary wustite dendrites (with 5% Mn and 1% Al substitution) typically of around 0.5mm across. The second phase is an olivine with complex elongate crystals of at least 2.5mm length. The olivine ranges from inner zones of Fa87 with 1% Ca and 18-19% Mn substitution, through to outer zones of Fa95 with 2% Ca and 18% Mn substitution. The interstitial areas show fine rod-like crystals of possible wustite, embedded in a glass.

**SHL17 (Plate 12):** This sample shows a large void, partially filled with acicular cements, with external radiating tubular structures of iron oxide (Plate 12a, b). These features are similar to the altered iron in parts of SHL10, and show a similar overgrowth of wustite outgrowths. Away from the altered textures around the iron a blebby wustite is the dominant phase and this shows 1% Al and 4% Mn substitution. Olivine appears preferentially oriented perpendicular to the iron fragment. It forms elongate crystals similar to, but much finer than, some of the other specimens. The longest observed crystal is only about 100µm. The olivine cores are Fa95-96, with 13% Mn substitution, grading out to margins of Fa96 with 1% Ca and 14% Mn substitution.

**SHL18 (Plate 13):** SHL18 shows a porous texture with an extremely heterogeneous distribution of coarse wustite. The wustite elements are coarse (to 100µm) and rounded, making recognition of dendrite size difficult. Many of the former voids are filled with secondary oxides. Some of the voids are clearly locations of charcoal (right hand side of Plate 13a), but others show textures similar to some of the altered iron fragments in SHL10 and 17. There are also similarly – sized altered blebs amongst the wustite blebs (left side of Plate 13c), which have a similar style of secondary oxides and may also be altered iron. The coarse wustite shows major gaps, within which there is either no primary wustite, or very delicate dendrites.

Olivine forms elongate crystals of up to about 400µm in length. The cores show a composition of around Fa95 with 33% Mn substitution, which grades out to

margins of Fa97 with 34% Mn substitution. The wustite is similarly very heavily (up to 11%) Mn-substituted and also has approximately 1% Al substitution.

The interstitial regions show either a glass with tiny blebs, probably of native iron (upper left Plate 13b), or fine dendritic intergrowths, possibly of wustite and fayalite (lower right Plate 13b). Some of the late dendrites show a hollow form (centre of Plate 13c), that may be related to the circular-sectioned shells seen in some of the other samples in this group.

## Iron ore

A single small (2g) sample of bog iron ore (SHL19) from C1038 was examined. This small piece was selected because it derived from the same context as much of the slag examined and therefore there was a reasonable possibility of a genetic link between them.

The specimen is very porous (Plate 14f) and shows well marked zones of varying density (Plate 14a, b). In some areas there was a marked contrast between dense areas, often with a botryoidal texture (e.g. left side Plate 14e) and less dense, more porous areas, also having a lower electron density (and therefore appearing darker on the backscattered electron images; e.g. right side of Plate 14e). The dense areas are composed of a manganese mineral, probably cryptomelane and the porous areas are dominantly iron oxides (probably hydrated iron oxides).

One area (Plate 19g) showed several moderately large (250-300µm) euhedral potassium feldspar crystals.

## Chemical composition of the residues

The bulk analyses of the slags fall into two distinct groups:

### Group 1 (SHL1-7):

These samples show an Upper Crust-normalised (Taylor & McLennan 1981) REE profile inclined with progressive LREE depletion with respect to Upper Crust, with superimposed elevated MREE and a negative cerium anomaly (Figure 1). The degree of elevation of the MREE results in quite a wide dispersion of data-points when  $Gd_N/Lu_N$  is plotted against  $Gd_N/La_N$  (Figure 5; where  $X_N$  is the Upper Crust-normalised value for X), a diagram allowing discrimination of many of the local ores (Young 2000a; Young & Thomas 1998, 1999).

The group is also characterised by (Figure 6) high U/Th ratios, moderately low concentrations of U and Th, together with high manganese contents (giving a high MnO:U ratio), and a low Nb:TiO<sub>2</sub> ratio.

### Group 2 (SHL8-10, 16-18):

This group includes samples with a more gently inclined Upper Crust-normalised REE profile with progressive depletion of the LREE (with a variable negative cerium anomaly), but with a virtually horizontal profile for the HREE (Figure 2). The profiles are very similar in shape, leading to tight clustering on the  $Gd_N/Lu_N$  against  $Gd_N/La_N$  diagram (Figure 5)

Other properties (Figure 6) of this group include high U, Th, and Zr contents, a lower MnO:U ratio than for Group1 and a higher Nb:TiO<sub>2</sub> ratio. The "Fe-free" figures used on some of these plots are concentrations normalised excluding the iron oxide from the analysis,

in order to examine elemental abundancies with the silicate component of the slag.

The two groups show no difference in silica:alumina ratio.

The Group 2 residues can be further differentiated into those samples with elevated levels of the siderophile elements cobalt, molybdenum and nickel (Group 2a) and those samples with low levels of these elements (Group 2b). The presence of these elements in elevated quantities is strongly correlated with the presence of altered fragments of iron in the slag. The iron fragments were observed in SHL9, SHL10 (where they were a significant proportion of the slag) and SHL18. Iron fragments were only identified rather tentatively in SHL17, which shows only very slightly elevated levels of this group of elements.

Group 2a samples show an elevated Zr:Al<sub>2</sub>O<sub>3</sub> ratio of up to  $73 \times 10^{-5}$ , reflecting a Zr content for these samples of 126 – 152 ppm, equivalent to 646 – 945 ppm re-calculated on an iron-free basis.

Group 2b samples show higher values of U and Zr than the Group 1 smelting slags, but with a similar U:Zr ratio. They have similar levels of the siderophile elements to the Group 1 slags. They show a significantly different Nb/TiO<sub>2</sub> ratio to the Group 1 slags, but which is similar to local ore samples and moderately close to that of the furnace lining samples.

The correlation between the siderophile elements and with phosphorus is shown in Figure 7. These diagrams suggest the Group 2a samples are the result of mixing of a slag phase (of composition close to that of the Group 2b samples) with an iron-dominated component with extremely elevated levels of Co, Mo and Ni, but with a lower P<sub>2</sub>O<sub>5</sub> content than the slag and little or no Mn. Detailed calculations of the mixing are hindered by the alteration of the iron and hence potential mobility (and non-conservation) of the elements contained within the iron. It seems reasonable to suggest, however, that the iron had very highly elevated levels of Co, Mo and Ni and that the iron pieces were mixed with a slag of a composition close to that of Group 2b. If such high levels of these elements is characteristic of the finished iron, it would be an unusual signature for the metal produced here.

A small piece of manganese-rich bog ore (SHL19) recovered from c1038 did not prove to be a good match for either suite of slags (Compare Figure 3 with figures 1 and 2; figures 6, 7). Despite its overall lack of chemical similarity to the slags, the presence of large potassium feldspar crystals may provide a link to acidic igneous rocks and thus perhaps to a similar source area to the zirconium-enhanced Group 2. Its rare earth element profile was fairly similar to (unprovenanced) manganese ores (wad) probably recovered during excavation of the Palaeolithic burial at Paviland Cave, Gower (Figure 3; Young 2000a), despite having a cerium anomaly of opposite sense.

The specimens of furnace lining (SHL10 and SHL11) had Upper Crust-normalised REE profiles that are almost flat and close to parity.

## Distribution of the residues

The iron slags and associated residues were concentrated in Complex 1. The upper fills over the structures of this complex (1002, 1003, 1004, 1028,

1042, 1054) yielded 22.7kg of residues and waste (?) pit 1039 produced 12.7kg of slag. Fills of the furnaces themselves (1033, 1853, 1886, 1887) contained 6.5kg of residues, mainly representing part of the slag produced during the last use of the furnaces and the last use before refurbishment, together with debris from degradation of the shaft. Only a few contexts (1044, 1048, 1049, 1056) elsewhere in the complex yielded any residues, with the total from those contexts being only 414g (21 pieces).

Outside Complex 1, only Complex 4 produced any significant quantity of metallurgical residue, with 10.4kg from upper fill 1037. This material was of similar make-up to the slag deposits filling Complex 1 and it is suggested that both groups of material derive from directly or indirectly from the waste produced by the operations in Complex 1.

Complex 2 yielded just one piece of slag (264g), Complex 6 two pieces (324g) and Complex 8 four pieces (121g). These quantities are too insignificant to provide support for proposals of metalworking activity having been undertaken in any of these other areas.

This distribution is in marked to that of the pale fuel ash slags from the site, which are interpreted as having been generated in the corn drying kilns and have been recorded from Complex 4 (2g), Complex 6 (13g), Complex 7 (1115g) and Complex 8 (13g).

## Description of furnaces 1071/1081

The furnaces present in the northern end of Complex 1 are similar, although not identical. At their NE terminations both incorporate vertical blocks of stone associated with *in-situ* slag. These blocks appear to be attempts to provide a firm blowing wall for the furnace pit and other blocks have been used to make a firm floor for the pit. In the case of the horizontal stones, they are clearly seen to overlie earlier slag flows and would therefore seem to represent refurbishment. This refurbishment is apparent in both furnaces. In both cases the slag attached to walls of the pit are suggestive of axial blowing from the NE. It is not clear whether the vertical stones forming the straight blowing wall are original, or whether they too are refurbishment. The blowing wall is adjacent to the hottest part of the furnace, so tends to suffer most damage – not only through direct erosion by the chemical reactions between iron-rich materials in the furnace and the silica-rich wall, but also mechanical damage from clearance of the slag from the furnace after smelting.

The SW limit of the base of the furnace is only suggest in 1081 by a change in angle of the base of the pit, but in 1071 a series of large stones suggests a collapse tapping arch (and indeed bury a flow beneath).

In furnace 1071 the *in-situ* slag formed part of c1886 and included a significant quantity (91 pieces, 1700g) of flowed slags in small horizontal flows and prills, as well as a smaller quantity (86 pieces, 734g) of highly fragmented vesicular slag. This assemblage is strongly suggestive of a "within-furnace" assemblage, but without the photographs of the material prior to lifting, could not have been demonstrated to be certainly *in-situ* (such assemblages may be raked out through the furnace arch and deposited in the tapping pit).

In furnace 1081 the NE termination of the pit was associated with slag deposit 1887, which contained

slag flows fused to the underlying stone and so more conclusively *in-situ*. In this instance the flows comprise small tapped slag-like flows (6 pieces, 376g) and some pieces of particularly broad, flat-topped flows (5 pieces, 500g; probably forming the flow visible in the photographs lying below the possible refurbished stone floor). One of the fragments of the flat-topped flow was sampled (as sample SHL3) and proved to be chemically related to the tapped slag recovered from pit 1039 (samples SHL1,2 and 4-7). In particular, there were textural and compositional similarities with SHL6, the within-furnace slag attached to the end of a flow which had solidified in the tapping channel. Both samples showed complex slag textures associated with the margins of vesicles, which involve the formation of leucite-rich areas, indicative of slag interaction with, and capture of, potassium volatilised from burning fuel. Such textures are not normally seen in tapped slag, but occur in furnace and hearth slags (from smelting and smithing respectively) where permitted by a more constant environment.

For both furnaces 1071 and 1081 the blowing wall of the furnace appears to have been opposite to the tapping arch. The blowing wall was straight and formed of vertical stone slabs (at least in the final form of the furnaces) in both cases. In furnace 1081 the stone slabs were preserved up to the height of the blowhole (as suggested by the shape of the slag mass adhering to the wall). A scatter of small features to the NE of the furnaces suggests the possible location of the bellows mountings.

The pits continued SW outside the tapping arch to form tapping pits. That for furnace 1081 extends approximately 1m outside the likely line of the furnace arch; that for furnace 1071 is cut by pit 1039, but appears to have continued SW as cut1079, giving an overall length of 1.7m outside the furnace arch. Pit 1039 appears to contain general waste, including 12.7kg of mixed slag including both SHCs and smelting slags.

## Interpretation

The analyses of slags described above show a marked differentiation into two groups. The analyses which were taken from samples identifiable morphologically as tapped bloomery slags show REE profiles in Group 1 (profile inclined with progressive LREE depletion with respect to Upper Crust, with superimposed elevated MREE and a negative cerium anomaly). Manganese contents are typically very high. The chemical characteristics of the Group1 slags are similar to, although not identical with, a sample of iron ore from Brownslade (BS4; figures 1 and 6).

Those samples morphologically identifiable as SHCs and other hearth/furnace slags show a more gently inclined profile with depletion of the LREE (with a variable negative cerium anomaly), but with a virtually horizontal profile for the HREE (Group 2).

A direct trace element similarity between the two groups of residues would have been expected, but there is little sign, particularly in the evidence from the REE, of material identifiable as being smelting slag being carried forward into the smithing stage. On the other hand, the smithing slags show an unusual chemical composition with an exceptionally high uranium content, a high manganese content and with Upper Crust-normalised REE profiles largely well above parity.

The interpretation of the chemical composition of the residues therefore has to address the problem of the smithing slags having a chemical signature quite distinct from that of the smelting slags. Such a situation might arise if:

1. the source of the iron ore was different – i.e. the smithing slags were produced during the working of iron from a different source than that being smelted.
2. the smithing process entailed the chemical signature of the ore being diluted by another input – such as the lining of the smithing hearth or a smithing flux.
3. the smithing residues are not from bloomsmithing, but from the smithing of finished iron, they therefore inherited no significant silicate component from the workpiece and the chemical signature is that of the smithing hearth.
4. The smithing slags are misidentified and are actually smelting slags, working a different ore from the tapped slags.

Option 4 is unlikely, given the clear morphological evidence for at least some of these samples being from smithing in conjunction with their chemical homogeneity as a group. One member of Group 2 (SHL8) shows significantly different microstructures from the rest of the group and may be a smelting slag.

Options 2 and 3 are equally unlikely given that zirconium and manganese are not likely to be dominant elements in any potential smithing flux or smithing hearth ceramic.

This leaves the most likely interpretation of Option 1: the smithing residues were the result of the working of iron produced from a different ore source from that employed in the smelting operation in Complex 1 (the presumed origin of the tapped slags analysed from the complex). The origin of the smithing residues is also problematic because very little smithing debris was recognised, there was no structural evidence for a smithing hearth and, although there was no concerted programme of sampling for hammerscale, none was recognised in the field nor was any found attached to the submitted specimens. This may suggest that the smithing undertaken on the site was separate from the smelting in Complex 1 and the small amount of material recovered and analysed from Complex 1 may not have been representative of the smithing undertaken on the site as a whole.

Both the slags with Group 1 and those with Group 2 REE patterns are typically manganese-rich, with elevated levels of uranium. However, they are distinguished by their U and Zr contents together with their Nb/TiO<sub>2</sub> and U/Th ratios (Figure 7) as well as by their REE profiles (Figures 1, 2, 6). The evidence from the smithing slags is also that the iron being worked was particularly rich in Co, Mo and Ni. These factors all suggest that the two iron sources were chemically quite distinct:

Group 1 – REE profile with MREE enrichment; high U:Th ratio; low Nb:TiO<sub>2</sub> ratio; low U, Th, Zr contents; high Mn content.

Group 2 – gently inclined REE profile; lower U:Th ratio; higher Nb:TiO<sub>2</sub> ratio; high U, Th, Zr contents; lower Mn content.

Group 1, as mentioned above shows some chemical similarities with a block of ore from Brownslade (Young 2010b; BS4). The origin of that block is uncertain. It is not something that would have occurred naturally on the Brownslade site, it has a geochemical composition quite close to some bog iron ores, but has a texture suggestive of that of the Carboniferous claystone ironstones. If it is a Carboniferous ore then it may have been moved to Brownslade by human agency, but such nodules also occur in the Quaternary drift deposits, derived by glacial and fluvio-glacial activity from the Carboniferous outcrops to the north and northwest of South Hook.

The high Zr content of the Group 2 materials requires further investigation. The extreme values shown in the "iron-free" calculations (Figure 6) are only a real measure of Zr in the silicate fraction if the Zr does not actually occur in the iron to any great extent (which would be the normal expectation). Analyses of the iron-bearing SHCs (Group 2a) do not appear, however, to show a marked dilution of the Zr content. The high Zr content may suggest a relationship with the high-Zr rhyolitic rocks within the Skomer Volcanic Group (Thorpe *et al.* 1989) which outcrop to the west of South Hook – either because the iron ore was sourced in this area, or because the iron was smelted in furnaces formed of Zr-rich materials. In either case it suggests that the South Hook site was smithing blooms produced west of Sandy Haven Pill, as well as smelting ores from another, perhaps more local, source.

## Discussion

The South Hook assemblage is of enormous significance for there are extremely few other iron smelting sites known from this period (8-10<sup>th</sup> century) in Britain and no confirmed examples in this part of the country, although there are three other sites in South Wales which may include smelting of early medieval date.

In SW Wales recent excavations at Brownslade (8km S of South Hook) have produced mostly unstratified slag (Young 2006b, 2010b) from an early medieval cemetery site with both tapslag and possible flow slag (from a non-tapping furnace). The excavations produced numerous examples of goethite-rich veins and crusts, probably the result of iron ore being released from a limestone host through dissolution. Slag samples and goethite veins share a common chemical signature (figures 5, 6) which is similar to some other ores of the Bristol Channel Orefield (Young & Thomas 1998, 1999; Young 2000a), so it is likely that ores from the site were being smelted. The smelting may well be contemporary with the cemetery, but is currently undated.

Current work at Robeston Wathen (22km ENE of South Hook) has also revealed traces of bloomery iron-making with tapped slags. There is currently no evidence to date this smelting, nor yet any geochemical data to assess the ore source.

On the outskirts of Cardiff a substantial iron production site at Rhiwbina (Young 2000b) is again of uncertain age and characterised by tapped slags. It lies adjacent to the Twmpath motte and arguably close to a location "Cincenn's kiln" on one of the Llandaff charters. There is thus circumstantial evidence hinting that the site might be of earlier medieval age.

Early medieval iron smelting sites in the broader area of SW Britain are known at Ramsbury, Wiltshire (8<sup>th</sup> century; Haslam 1980), Burlescombe, Devon (8-10<sup>th</sup> century; Reed *et al.* 2006), Carhampton, Somerset and probably at Cheddar (late 10<sup>th</sup>-11<sup>th</sup> century; Rahtz 1979). Slightly further east are Gillingham (Heaton 1992) and Worgret (Hinton 1992) in Dorset. Additional evidence is provided, for instance, by the 3 manors in Gloucestershire and 6 in Somerset that are given as paying revenue in iron in Domesday.

In contrast, very many iron-smelting sites of the early medieval period are now being recognised in Ireland (e.g. Young 2003a,b, 2005a,b), but these differ in technology from South Hook, being non-slag tapping slagpit furnaces.

Of the British examples, it appears from published evidence that the earlier furnaces at Ramsbury, together with those at Burlescombe and Carhampton, were non-slag tapping furnaces too, although the precise morphology of these furnaces remains rather controversial. The later furnace at Ramsbury, Furnace 4, appears, however, to have been a fully slag-tapping furnace, but unfortunately the slag assemblages were not fully published.

The two furnaces at South Hook are rather poorly preserved, but do allow comparison with the published examples. The closest comparison is with Furnace 4 at Ramsbury. Although Furnace 4 at Ramsbury appears very different to the South Hook examples, particularly in the evidence for its massively relined, inverted "bell-shaped" superstructure, there is a similarity at a lower level:

- Furnace 4 shows a relatively straight rear wall, with large slag accumulations at its foot, although the excavator preferred to envisage blowing from other three sides.

- Slag accumulations on the floor of Furnace 4 had not always been cleared after smelting; instead the furnace has been raised to accommodate the raised floor

- The tapping pit for Furnace 4 is deepest immediately outside the tap arch and shallower at its distal end

- The markedly sloping sides of the pit below the furnace give the structure a transversely elongated plan.

A largely unmodelled aspect of Ramsbury Furnace 4 is the lateral splaying of the lining from about 0.4m above the base of the cut. This implies, if the record is correct, that initial form of the furnace cannot have supported a shaft, although later phases of the furnace become more constricted and tubular.

The earlier non-slag tapping furnaces at Ramsbury are remarkable for including bowl-like cuts of very large diameter and relatively shallow depth (Furnace 2: 0.85 x 0.9 x 0.35m deep, Furnace 3: 1.1 x 1.0 x 0.3m). These seem to have produced large low-density "furnace bottoms" (up to 0.5 x 0.2 x 0.2m) which were oriented transversely in the furnaces. In contrast, the non-tapping furnaces at Burlescombe were deep (Furnace 539: cut 0.75 x 0.84 x 0.65 m deep, Furnace 529 0.78 x 1.10 x 0.75m, Furnace 535 0.80 x 0.45 x 0.60m) and produced much more vertically oriented "furnace bottoms".

The use of these two quite distinct furnace styles in the 8<sup>th</sup>-9<sup>th</sup> centuries remains a subject requiring further work. Slag-tapping furnaces may be derived from Roman period techniques (either by survival or reintroduction), whereas the non-tapping furnaces reflect a tradition widespread in pre-Roman Europe, which may have survived in S Britain (an Iron Age example from SW England was described by Young 2008a), or been reintroduced from either the east (northern Europe) or west (Ireland).

Understanding of the situation in Ireland in the 8<sup>th</sup>-10<sup>th</sup> centuries is also made problematic by a lack of well-preserved early medieval furnaces. Iron-making was being undertaken on a large scale at this period, but much of the evidence derives from settlement sites with bloomsmithing, but little primary smelting. The Iron Age tradition current in the first half of the first millennium AD seems to be for small non-slag-tapping furnaces (with cut diameters of <0.5m). These Iron Age furnaces employed a careful pit packing of large split wood (as also seen for instance at Burlescombe) and probably had a low shaft or bottle-shaped superstructure. They show a great deal of variation in detail, including some examples with a furnace arch (for clearing the furnace rather than tapping) being seen throughout this period (e.g. Derrinsallagh 4, Young 2008g).

By the 9-10<sup>th</sup> centuries a few examples with slightly larger pit diameter are known. Arched furnaces are rare (but see the two examples below), but for the following centuries several sites are providing evidence that furnaces with an arch (although probably not for tapping) were being built on the ground surface, with adjacent pits used to receive the furnace rakings (e.g. Ballynamorohan, Young 2009b; Derrinsallagh 1, Young 2008a). The pits employed in conjunction with the non-slag tapping furnaces are either rather shallow, often irregular in form and adjacent to the arch or are more substantial pits but separated from the furnace structure.

Despite this diversity of furnace design, the style of construction at South Hook with the furnace superstructure built at one end of a trench, seen in Britain in many Roman examples, Ramsbury Furnace 4 and many later medieval examples (e.g. Stanley Grange), is currently unknown in Ireland.

Although the vast majority of Irish smelting sites were clearly not tapping the slag, there are two early medieval examples where the evidence is rather stronger.

The first of these is Woodstown, Co. Waterford (Young 2009a), where a small furnace was constructed in the butt-end of one of the enclosure ditches (and thus being somewhat similar to the use of the slope at South Hook). This furnace is poorly-understood because of its closure, or possible conversion into a hearth, by having a packing of large stones rammed into the truncated basal section of its shaft. These stones sealed a dense accumulation of lobed slags, which appeared to have flowed from the furnace base on one side, suggesting the former presence of a tapping arch. Identical slag textures, probably tap slags were recovered from a later excavation in a different area of the same site, suggesting that this furnace may not have been an isolated example. The date of this furnace is likely to be late 9<sup>th</sup> century.

A second early medieval site with a claim for slag-tapping is a site at Knockbrack, Co. Kerry. This site had two furnace pits, each 0.36m in diameter, with <sup>14</sup>C

dates on oak of cal. AD 110-380 and cal. AD 260-290/320-450, but with a date from hazel of cal. AD 570-670 (Hull & Taylor 2006). These furnaces appear to have been carefully constructed with a clay lining added to the excavated pits and with a large stone placed as the floor. They were interpreted as slag-tapping furnaces by the excavators, and must at very least have employed a furnace arch for the clearance of hot waste and possibly the bloom. The pairing of furnaces is an apparently common feature in the first half of the first millennium AD (e.g. Clonrud 4, Derrivorrigan 1, Derrinsallagh 4; Young 2008 d, e, f), although paired furnaces may possibly be confused in some instances with a furnace plus external working hollow.

The Knockbrack site is significant, therefore, on several grounds: it has a similar overall plan to Complex 1, with paired furnaces about 1m apart facing into a working area, it may, unusually for early medieval Ireland, have undertaken slag tapping and, like Complex 1 it seems, again rather unusually, to have used flat stones to provide a firm floor for the furnace. The layout of smelting sites elsewhere seems more irregular. Postholes at Ramsbury suggested the presence of a structure associated with the furnaces, but there was no indication of the plan of the structure and the furnaces may have lain outside it. There were no indications of enclosing structures at Burlescombe.

The surprising discovery that the smithing slags from Complex 1 had a different chemical signature (Group 2) to the smelting slags (Group 1) suggests that South Hook may have been a focal point for iron-making in the area. Just one specimen with a Group 2 analysis may be possibly be a smelting slag, but the evidence is inconclusive. No tapped slags showed a Group 2 analysis. Smelting may, therefore, have been undertaken not only at South Hook itself but possibly at outlying locations closer to the ore sources (or woodlands?), with the smithing debris analysed here being waste from smithing of blooms that were produced to the west of Sandy Haven Pill (on the evidence of their high zirconium contents).

In summary, bearing in mind the paucity of comparative sites, the style of site layout in Complex 1 can best be paralleled in SW Ireland (Knockbrack) and to a lesser extent at the Viking site of Woodstown. The structure of the furnaces themselves can probably be paralleled best in the later phase at Ramsbury, although the superstructure at Ramsbury is unusual. Thus the similarities are to be found in sites which are respectively Irish, Viking and Saxon; a situation which probably reflects the lack of present understanding of early medieval iron-making rather than real cultural influences. South Hook appears to have smelted iron from one source, whilst apparently processing iron originally smelted from a different source, probably several kilometres to the west. Neither source is yet located, but this arrangement hints at a fairly sophisticated operation with South Hook acting as focal point for iron production.

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## Illustration Captions

Figure 1. Upper Crust-normalised (Taylor and McLennan 1981) REE profiles, Group 1.

Figure 2. Upper Crust-normalised (Taylor and McLennan 1981) REE profiles, Group 2.

Figure 3. Upper Crust-normalised (Taylor and McLennan 1981) REE profiles, bog ore sample SHL19, with sample from Paviland (Young 200a) for comparison..

Figure 4. Upper Crust-normalised (Taylor and McLennan 1981) REE profiles, furnace linings.

Figure 5. Plot of descriptors of Upper Crust-normalised (Taylor and McLennan 1981) REE profile shape, showing differentiation of residue groups.

Figure 6. Bivariate plots showing discrimination of residue groups. Variables are plotted where appropriate on an iron-free basis (i.e. components are normalised excluding iron oxide from the total), which allows a better visibility of trends within the silicate component without the variation caused by variable amounts of iron.

Figure 7. Bivariate plots showing the distribution of the siderophile elements cobalt, molybdenum and nickel in the various residue classes, together with the variation in iron and phosphate.

Plate 1  
Backscattered electron photomicrographs: SHL1

- a. area 1. Scale bar 1mm.
- b. area 2. Scale bar 100 $\mu$ m
- c. area 3. Scale bar 3mm
- d. area 4. Scale bar 300 $\mu$ m
- e. area 5. Scale bar 60 $\mu$ m
- f. area 6. Scale bar 60 $\mu$ m

Plate 2  
Backscattered electron photomicrographs: SHL2

- a. area 1. Scale bar 600 $\mu$ m
- b. area 2. Scale bar 600 $\mu$ m
- c. area 3. Scale bar 300 $\mu$ m
- d. area 4. Scale bar 60 $\mu$ m
- e. area 5. Scale bar 50 $\mu$ m

Plate 3  
Backscattered electron photomicrographs: SHL3

- a. area 1. Scale bar 300 $\mu$ m
- b. area 2. Scale bar 100 $\mu$ m
- c. area 3. Scale bar 1mm
- d. area 4. Scale bar 200 $\mu$ m
- e. area 5. Scale bar 50 $\mu$ m
- f. area 6. Scale bar 100 $\mu$ m

Plate 4  
Backscattered electron photomicrographs: SHL4

- a. area 1. Scale bar 1mm
- b. area 2. Scale bar 100 $\mu$ m
- c. area 3. Scale bar 50 $\mu$ m

d. area 4. Scale bar 60 $\mu$ m  
Plate 5  
Backscattered electron photomicrographs: SHL5

- a. area 1. Scale bar 600 $\mu$ m
- b. area 2. Scale bar 60 $\mu$ m
- c. area 3. Scale bar 1mm
- d. area 4. Scale bar 1mm

Plate 6  
Backscattered electron photomicrographs: SHL6

- a. area 1. Scale bar 600 $\mu$ m
- b. area 2. Scale bar 600 $\mu$ m
- c. area 3. Scale bar 800 $\mu$ m
- d. area 4. Scale bar 800 $\mu$ m
- e. area 5. Scale bar 800 $\mu$ m
- f. area 6. Scale bar 60 $\mu$ m
- g. area 7. Scale bar 100 $\mu$ m

Plate 7  
Backscattered electron photomicrographs: SHL7

- a. area 1. Scale bar 600 $\mu$ m
- b. area 2. Scale bar 60 $\mu$ m
- c. area 3. Scale bar 80 $\mu$ m
- d. area 4. Scale bar 90 $\mu$ m

Plate 8  
Backscattered electron photomicrographs: SHL8

- a. area 1. Scale bar 400 $\mu$ m.
- b. area 2. Scale bar 1mm
- c. area 3. Scale bar 60 $\mu$ m
- d. area 4. Scale bar 100 $\mu$ m

Plate 9  
Backscattered electron photomicrographs: SHL9

- a. area 1. Scale bar 600 $\mu$ m
- b. area 2. Scale bar 1mm
- c. area 3. Scale bar 60 $\mu$ m

Plate 10  
Backscattered electron photomicrographs: SHL10

- a. area 1. Scale bar 2mm
- b. area 2. Scale bar 100 $\mu$ m
- c. area 3. Scale bar 600 $\mu$ m
- d. area 4. Scale bar 300 $\mu$ m
- e. area 5. Scale bar 300 $\mu$ m
- f. area 6. Scale bar 200 $\mu$ m
- g. area 7. Scale bar 60 $\mu$ m
- h. area 8. Scale bar 70 $\mu$ m

Plate 11  
Backscattered electron photomicrographs: SHL10

a. area 1. Scale bar 60 $\mu$ m  
Backscattered electron photomicrographs: SHL16

- b. area 2. Scale bar 1mm
- c. area 3. Scale bar 100 $\mu$ m

Plate 12  
Backscattered electron photomicrographs: SHL17

- a. area 1. Scale bar 900 $\mu$ m
- b. area 2. Scale bar 300 $\mu$ m
- c. area 3. Scale bar 60 $\mu$ m

Plate 13

Backscattered electron photomicrographs: SHL18

- a. area 1. Scale bar 800 $\mu$ m
- b. area 2. Scale bar 60 $\mu$ m
- c. area 3. Scale bar 100 $\mu$ m

Plate 14

Backscattered electron photomicrographs: SHL19

- a. area 1. Scale bar 2mm
- b. area 2. Scale bar 2mm
- c. area 3. Scale bar 2mm
- d. area 4. Scale bar 2mm
- e. area 5. Scale bar 200 $\mu$ m
- f. area 6. Scale bar 6mm
- g. area 7. Scale bar 600 $\mu$ m

Context	Sample	Weight	Description
102		30.62	small fragment of tapslag with high-lobed flows
		2.33	low-density highly vesicular lining slag fragment
112		20.76	dense tapped lobe
119		11.06	corrosion around small iron pieces, in c.7 pieces
		8.24	larger piece of probably corrosion (not certain) attached to stone
127		0.16	low-density highly vesicular green lining slag
127		52	broken hollow bleb/flow lobe of dense slag - presumably a tapslag bleb but not classic tapslag
132		1.43	3 low-density highly vesicular lining slag pieces, greenish externally but black internally
137		1.1	melted greenish glass, probably not metallurgical
139		5.47	small dense prill
139		42	small tapslag fragment
		15.7	2 small stone pieces with buff coloured concretion, natural
139		0.58	1 grey-green low-density highly vesicular lining slag piece
168		17.4	small tapslag fragment
188		5.19	disintegrated lump of low-density highly vesicular lining slag
197		14.74	11 pieces of low-density highly vesicular greenish lining slag and vitrified lining material
		11.45	brick like reddish fired clay
197		2.82	green low-density highly vesicular lining slag
		1.1	4 pieces of burnt bone
		7.63	iron rich stone? in 2 pieces
198		124	c.40 pieces of green low-density highly vesicular lining slag in charcoal rich soil
508		1.47	2 rounded lumps of grey low-density highly vesicular lining slag
511		30.3	c.13 pieces of greenish low-density highly vesicular lining slag

Context	Sample	Weight	Description
513		78	small pieces of green low-density highly vesicular lining slag mixed with soil
515		1.63	green low-density highly vesicular lining slag fragment
516		362	pale greenish lining slags - mainly the low-density highly vesicular kind in crude sheets, but also some completely altered pebbles and at least perfect green slag sphere
516		182	63 pieces of pale low-density highly vesicular green lining slag. Some very shiny spheroidal aggregates included here
517		2.02	c.10 pieces of low-density highly vesicular green low density lining slag
517		98	complicated descending flow of tap lobes - possibly from drip area?
543		7.98	small irregular spiky bleb of low-density highly vesicular green lining slag
		226	dense block of slag, irregular in shape but has some small lobes so may be partially flowed furnace slag or very thick tapped flow
623		1.13	3 low-density highly vesicular pale lining slag fragments
629		320	large quantity of very friable lining type slag
737		3.53	greenish low-density highly vesicular lining slag in >6 pieces
901		704	dense bun shaped slag block, possibly part/all of SHC?
901	(unstratified)	424	34 pieces of tapslag
		8	slagged lining
		27	2 pieces of claystone ironstone
		128	tapslag fragment
		124	42 small pieces of iron slag indet
		116	4 lumps of rusty slag - not clear if smithing slags or not
962		352	large block of bog ore
969		130	4 stones

Context	Sample	Weight	Description
1002	1250		large block of charcoal rich slag with lobate top - probably a furnace slag
	284		vesicular slag with irregular lobate projections - contorted furnace slag?
	228		charcoal rich furnace slag
	112		fractured pebble
	12		6 fragments of flint
	42		fractured flint/chert pebble
	22		fired pebble - possibly ore?
	14		2 flints
	6235		tapped slag -195 pieces
	962		small slag debris
	70		stones
	28		boxstone claystone ironstone fragment
	724		51 pieces of extremely corroded slag and iron - most probably iron rich slags, but at least one appears to be iron fragment - not practical to separate
	494		11 pieces of charcoal rich furnace slag
	346		curved slab of slag with charcoal on one side and smooth on other - probably a crust from with the furnace
1002	220		30 pieces of lining, some vitrified
	722		15 pieces of tapslag, up to 30mm thick, mainly thin flows, some wrinkly, lots of shale clasts on base
1002	86		4 pieces of lower density vesicular iron slag indet
	328		14 pieces of tapslag
1002	196		11 other pieces of dense slag
	46		6 pieces of fired lining
	22		iron-mottled soil
	10		iron concretion - rusted material?
1003	find416	1115	SHC, platy dished top up to 15 thick, below which hangs finely prilly material with a small area of almost thin crust like margin. 140x150x80
		28	small fragment - possibly from lip of the above or a similar cake?
1003		332	three pieces of dense slags, 2 smaller are tapped, large block also has flowed top but seems internally massive at first inspection

Context	Sample	Weight	Description
1003			charcoal stick
		24	tapslag fragment
		158	2 small pieces of dense slag which is finely vesicular with small charcoal - could be SHC or furnace bottom
		6	2 indet iron slag fragments
1004		776	105x125x55, medium sized bun like SHC with dished top. Details obscured by corrosion, lots of charcoal adhering to base
		5305	87 pieces of tapslag, largest c.700g, thickest c.35mm, mainly fairly narrow flows, base mainly rough some adhering stone fragments
		408	42 small pieces of indet low density vesicular slags
		48	7 pieces of vitrified lining
		680	5 lumps of charcoal rich furnace slags
		514	two pieces including furnace slag like material but with flow lobed top, one is a large block from throat showing flow lobed surface cutting down across finely charcoal rich material and turning towards a tapslag. Length 110, 60 thick on furnace side, 30mm thick towards outside
		126	irregular dense slag fragment
		78	3 stones
		106	7 rusty concretionary lumps which may have contained iron
	1005		264
		116	26 pieces of broken slag, mainly or entirely from a broken piece of tapslag
1005		64	5 pieces of tapslag
1028		542	95 small pieces of very rusty material, probably mainly slag
		64	5 pieces of rusty material formed around corroded iron
		132	11 pieces of flowed slag, largest certainly tapslag, smaller prills probably so
1033		334	part of an irregular thin crust style cake. Crust to about 5mm, inside charcoal rich or hollow, slightly rusty top, not clear if this is an SHC (v odd for Britain) or part of a furnace bottom deposit (more likely?). Mainly c40 thick but with protrusion to 60.
		210	5 pieces of tap sag, single lobe thickness, grey particles on base
		54	5 vesicular slag pieces indet
		20	fired clay with smoothed grey surface
		54	vitrified lining block?
		80	vitrified surface of lining including large stone clast

Context	Sample	Weight	Description
1034		130	3 pieces of tapslag, to 30mm thick, shale rich bases
		14	4 tiny pieces of rusty probably furnace material
1037		756	140x115x75 SHC, (bowl 60mm deep), very charcoal rich throughout, smooth top with raised lump, has no real lower crust
		5610	109 pieces of tapslag, largest about 700g
		1090	small iron slag pieces, undifferentiated
		1580	19 pieces of mainly brown fine furnace accumulation, but grading into more normal charcoal rich slag
		210	3 stones
		36	2 pieces of vitrified lining
1037		564	79 pieces of vitrified lining - mostly with orange ceramic but a few pieces are just the slag layer
		236	stone
		88	25 small iron slag pieces indet
		518	15 pieces of tapslag and prill, largest piece 256g, shows base resting on charcoal rich ashy deposit
		182	4 large lumps of amorphous slag, mostly slightly rusty, mostly charcoal bearing, one has some lobes
1037		20.79	tapslag fragment
1038	1039	1450	large block of tapslag - but probably only half cake at most, 160x110x40, narrow lobes, typically 10mm
		424	smaller tapslag block with strongly wrinkled lobes
		772	contorted flow lobed block, not all dense - so may be a tap arch piece, but probably secondarily folded
		1820	42 pieces of tapslag and prills
		146	dense slag piece, rounded cross section with possible flow lobed top - probably a taping channel runner
		498	dense possible furnace floor piece, attaches to the above runner, suggest channel 40 deep by 30 wide
		1115	3 large blocks of dominantly charcoal rich material with some slightly lobed surfaces - furnace slag
		14	3 stones
		1435	c.200 small indet slag pieces
20	5 pieces of vitrified lining		
2	possible bog ore fragment		

Context	Sample	Weight	Description
1042		82 38 148	4 lumps of ferruginous as on fired clay base - could be with cleaning later dense iron slag indet, has very large vesicles so may be a tapslag block of dense slag composed of a complicated mass of prills and lobes
1043		792	mixed ferruginous material in ashy matrix- may be determinable after washing, but matrix interesting in own right!
1043	1039	2020 1440 962	slab of stone with small attached area of fine furnace accumulation - probably c.100g object like a charcoal rich SHC, 150x110x75, 127 pieces of similar furnace accumulation, rusty fine charcoal rich, some containing slag blebs, others fragments of stone
		260 42 470 144 18	block of charcoal rich slag with rusty contact surface, medium sized charcoal 15 pieces of fired or vitrified lining 7 pieces of dense tapslag 30 small or indet pieces of slag charcoal stick 2 stones
1044		248	curious block with smooth flown lip above (?) zone of contact with hard substrate. Possibly the lip of a large SHC, but could just be tap arch material. Dense dark vesicular slag
1048		28	11 tiny slag pieces including at least two apparently fragments of tapslag
1049		56	5 brown lumps of material (ash?) cemented by "rust"
1054	(=1003?)	34 2.49 42	7 fragments of slag cooled between charcoal moulds fired clay 4 stones
1056		28 54	tapslag lobe 3 lumps of amorphous iron slag
1083		13.91	5 pieces of non- slag material, 1 stone with attached charcoal, 2 pieces of broken iron-rich stone, 1 small pebble, 1 iron-rich lump of concretionary? Origin
1098		66	3 pieces of tapslag plus debris
1609		2.33	2 pieces of greenish low-density highly vesicular lining slag

Context	Sample	Weight	Description
1853		528	iron cemented ashy soil with abundant charcoal and a few lobes of both very and horizontal prilly material. Presumably some sort of furnace bottom accumulation?
1853	1071	8.79 2.07	prill in 3 pieces ferruginous ash?
1886	furnace 1071	644 734 146 1700	234 stones 86 pieces of indet grey slag - mainly vesicular fragments 53 pieces of fired lining 91 small pieces of tapslag- mainly from small flows and prills
1887	1081 fuel ash and slag run-off see section 1780	338 76 528 958 278 500 376 100	c150 small indet slag pieces 31 small local stones 37 pieces of slagged lining, variably reduced or oxidised fired 43 pieces of broken grey vesicular slags of medium density 9 blocks of dark lining slag, variable density (not the pale low-density highly vesicular type) 5 pieces of thin tapped flow, rubbly bases with attached stone, top unusually flat - might just be flowed bit almost looks like base of obstruction. Max about 25 thick 6 pieces from more normal, but probably small tapped flows stone
1889		150	small block from 35mm thick tapslag flow

*Table 1. Summary catalogue of all pyrotechnological residues from South Hook, including both the iron slags described in this report and the fuel ash slags described separately.*

Sample	context	description
SHL1	1038	1450g block of tapslag, 160x110x40mm, probably only half of cake at most, narrow lobes- typically 10mm
SHL2	1038	424g block, smaller tapslag block with strongly wrinkled lobes
SHL3	1887	174g piece of plano-convex smooth topped flow - flow has unusually flat top
SHL4	1038	claw-shaped block - flown over obstacle
SHL5	1038	146g dense slag piece, rounded section with lobed top - runner (conjoins #6)
SHL6	1038	498g piece suggesting channel 40 wide by 30 deep, furnace floor slags (conjoins #5)
SHL7	1038	772g contorted flow lobed block, not at all dense, may be from tap arch, but probably secondarily folded
SHL8	1038	536g furnace slag block or SHC fragment, charcoal-rich with slightly lobed surface
SHL9	1003	1115g SHC, platy dished top, up to 15mm thick, below which hangs finely prilly material with a small area of "crust-like" margin, 140x150x80mm
SHL10	1004	776g, medium sized bun-like SHC, dished top, details obscured by corrosion
SHL11	1883	furnace ceramic
SHL12	1033	furnace ceramic
SHL16	1033	334g piece of thin crust cake/furnace bottom shell
SHL17	1043	1140g - block like a charcoal-rich SHC
SHL18	901	704g bun-shaped block - possibly part/all of SHC (unstratified)
SHL19	1038	2g bog ore fragment

*Table 2. Material selected for detailed analysis*

sample	context	SiO <sub>2</sub>	Al <sub>2</sub> O <sub>3</sub>	Fe <sub>2</sub> O <sub>3</sub>	FeO (*)	MnO	MgO	CaO	Na <sub>2</sub> O	K <sub>2</sub> O	TiO <sub>2</sub>	P <sub>2</sub> O <sub>5</sub>	LOI	LOI (*)	Total	Ba ppm	Cr ppm	S%
SHL1	1038	15.55	3.99	73.91	66.51	7.04	0.49	0.26	0.38	1.52	0.20	0.95	-6.98	0.42	97.31	242	140	0.14
SHL2	1038	21.38	5.01	59.56	53.59	10.70	0.97	0.51	0.59	2.32	0.27	1.37	-5.51	0.46	97.17	399	144	0.17
SHL3	1887	21.75	4.13	68.94	62.04	3.54	0.69	0.29	0.44	1.50	0.26	0.75	-5.25	1.66	97.04	128	115	0.18
SHL4	1038	13.61	3.55	67.10	60.38	10.34	1.06	0.77	0.50	2.74	0.17	1.36	-5.94	0.78	95.26	522	158	0.30
SHL5	1038	9.53	2.50	78.34	70.49	7.77	0.54	0.29	0.40	1.33	0.13	0.99	-7.08	0.77	94.73	252	116	0.16
SHL6	1038	15.46	3.38	71.94	64.73	7.88	0.63	0.36	0.46	1.62	0.17	1.48	-5.41	1.80	97.98	378	94	0.15
SHL7	1038	15.82	3.33	74.96	67.45	4.87	0.57	0.31	0.43	1.29	0.17	1.00	-4.69	2.82	98.07	259	96	0.23
SHL8	1038	19.25	4.75	66.27	59.63	7.27	0.90	0.43	0.37	1.88	0.25	0.90	-4.71	1.93	97.55	365	158	0.23
SHL9	1003	10.38	1.84	82.98	74.67	2.61	1.23	0.64	0.36	1.14	0.14	0.90	-4.24	4.07	97.98	189	84	0.07
SHL10	1004	9.17	1.83	83.18	74.85	1.05	0.75	0.28	0.22	0.44	0.13	0.56	1.66	9.99	99.27	93	51	0.10
SHL11	1883	71.15	14.77	5.91	5.32	0.07	1.03	0.18	0.33	2.96	0.82	0.24	2.83	3.42	100.28	298	96	0.02
SHL12	1033	65.16	14.18	12.01	10.81	0.11	1.45	0.32	0.49	2.42	0.92	0.56	2.53	3.73	100.16	272	113	0.03
SHL16	1033	18.87	3.99	69.37	62.42	6.88	1.24	0.91	0.53	1.60	0.21	1.11	-4.86	2.09	99.87	359	117	0.17
SHL17	1043	14.29	3.08	75.07	67.55	3.53	0.50	0.20	0.30	0.90	0.18	0.79	-0.81	6.71	98.03	197	115	0.22
SHL18	901	7.43	1.91	77.53	69.76	5.44	0.32	0.11	0.16	0.37	0.10	0.71	2.31	10.08	96.40	185	93	0.15

Table 3a. Major elements determined by XRF, expressed as wt% oxides except where stated. Columns in grey (\*) are alternative calculations with iron expressed as FeII instead of FeIII. LOI = loss on ignition

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	TiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	P <sub>2</sub> O <sub>5</sub>
	wt%	wt%	wt%	wt%
SHL1	0.22	71.72	7.98	0.93
SHL2	0.28	58.50	12.93	1.42
SHL3	0.32	80.47	4.57	0.84
SHL4	0.22	75.54	14.33	1.59
SHL5	0.16	75.89	8.80	0.95
SHL6	0.22	79.88	10.43	1.68
SHL7	0.22	83.83	6.22	1.11
SHL8	0.28	69.25	8.99	0.96
SHL9	0.17	83.42	2.87	0.89
SHL10	0.16	86.57	1.15	0.56
SHL11	0.83	5.81	0.08	0.22
SHL12	0.94	12.43	0.12	0.55
SHL16	0.26	71.37	8.19	1.11
SHL17	0.24	78.61	4.10	0.81
SHL18	0.14	80.50	6.43	0.76
SHL19	0.11	50.88	22.39	0.72

Table 3b. Major elements determined by ICP-MS expressed as wt% oxides

	Sc	V	Cr	Co	Ni	Cu	Zn	Ga	Rb	Sr	Y	Zr	Nb	Mo	Sn	Cs	Ba
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
SHL1	6.6	133.4	155.3	14.7	17.5	27.8	92.1	23.2	40.2	92.5	102.5	16.7	0.50	1.93	0.71	3.56	246.6
SHL2	7.9	133.3	124.0	23.0	17.3	58.7	134.2	29.9	50.2	134.6	105.4	19.2	0.78	2.28	1.52	3.40	356.6
SHL3	7.0	145.7	115.6	20.9	67.4	45.3	154.5	11.1	40.9	79.1	136.9	44.0	1.57	1.85	1.89	2.24	323.0
SHL4	6.7	158.2	149.9	12.0	114.5	51.2	122.3	13.2	25.1	227.4	255.4	44.4	1.39	2.98	1.68	1.28	614.0
SHL5	4.9	121.3	96.0	12.4	9.4	41.3	119.4	23.4	25.8	83.8	97.8	13.5	0.37	3.01	0.42	1.85	256.8
SHL6	5.2	114.9	68.7	15.3	4.0	23.4	107.6	13.4	32.3	98.7	137.0	36.9	1.18	4.50	1.03	2.11	434.9
SHL7	5.9	140.3	96.6	14.4	15.4	21.9	145.9	16.5	31.8	66.8	132.8	21.0	0.70	2.48	0.80	1.97	287.3
SHL8	13.7	142.8	125.6	4.0	5.7	13.1	62.6	6.9	23.8	89.1	151.2	148.1	4.48	2.55	1.73	1.33	440.4
SHL9	2.9	44.8	68.0	105.2	82.5	23.9	71.5	2.9	9.5	86.6	31.8	134.2	3.23	14.03	2.33	0.33	203.6
SHL10	3.0	29.8	41.6	280.9	640.8	47.6	72.4	3.4	7.1	39.0	22.2	126.9	3.22	20.49	3.19	0.35	152.8
SHL11	12.6	129.0	125.2	9.5	52.9	18.8	69.0	17.9	98.4	30.2	29.1	331.2	14.03	1.21	5.56	5.26	277.9
SHL12	13.9	128.2	123.9	17.6	35.6	9.6	243.4	18.7	87.5	39.2	32.1	336.8	13.96	1.73	5.38	4.45	271.5
SHL16	5.9	116.5	88.6	36.2	12.4	8.5	81.9	5.5	16.6	181.6	155.8	160.0	5.16	5.74	3.42	0.77	409.3
SHL17	5.4	114.4	97.0	42.0	53.5	11.6	82.0	4.6	16.5	39.7	91.1	158.0	4.61	8.40	3.50	0.97	225.1
SHL18	3.9	127.3	80.4	274.2	224.6	44.0	78.1	3.9	6.1	43.7	53.7	126.0	2.79	17.11	2.89	0.59	203.5
SHL19	1.7	139.5	43.7	692.9	370.3	33.4	1193.0	6.0	11.7	312.6	211.2	106.0	2.46	15.60	4.05	0.59	3143.2

Table 3c. Trace elements determined by ICP-MS in ppm

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Pb	Th	U
	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm
SHL1	2.91	3.42	1.20	7.27	4.11	4.58	20.41	2.10	3.13	0.62	2.52	0.36	3.17	0.46	0.72	0.07	0.55	0.20	1.87
SHL2	3.30	4.47	1.40	8.27	5.04	6.24	25.30	2.48	3.62	0.71	3.07	0.43	3.82	0.54	0.81	0.10	5.09	0.24	1.89
SHL3	9.50	8.27	2.74	15.95	7.42	4.37	25.18	2.65	5.90	1.22	3.78	0.65	4.50	0.76	1.35	0.14	6.28	0.56	3.75
SHL4	12.78	11.38	4.87	28.47	12.88	7.44	38.57	4.44	11.27	2.28	6.40	1.08	7.16	1.27	1.48	0.13	5.33	0.57	6.87
SHL5	2.53	2.81	1.09	6.59	3.96	5.00	19.99	2.08	2.92	0.61	2.53	0.35	3.25	0.47	0.61	0.07	4.37	0.14	1.59
SHL6	7.39	8.93	2.98	18.36	8.56	5.45	28.35	3.12	6.89	1.42	4.22	0.69	4.74	0.80	1.22	0.11	3.42	0.45	4.84
SHL7	3.83	4.39	1.64	10.34	5.81	4.86	24.66	2.62	4.14	0.84	3.31	0.51	4.24	0.62	0.85	0.10	2.53	0.24	2.63
SHL8	36.44	54.77	12.94	57.55	16.00	3.85	18.93	2.96	16.66	3.38	10.85	1.56	10.56	1.69	3.80	0.32	4.89	4.06	21.40
SHL9	13.12	17.51	3.26	13.77	3.38	0.82	3.67	0.56	3.46	0.70	2.07	0.30	1.77	0.33	3.50	0.21	1.48	2.06	6.82
SHL10	9.99	16.00	2.86	11.57	2.74	0.65	2.81	0.43	2.80	0.57	1.69	0.25	1.52	0.27	3.29	0.20	3.06	1.93	3.57
SHL11	35.85	79.21	9.72	33.86	6.17	1.09	4.65	0.78	4.83	0.93	2.87	0.44	2.93	0.49	8.46	1.14	20.79	13.68	4.00
SHL12	37.00	81.37	10.06	35.29	6.62	1.19	5.12	0.86	5.27	1.03	3.13	0.49	3.17	0.55	8.62	1.17	16.50	14.00	4.92
SHL16	39.85	40.53	9.95	43.55	11.40	3.04	13.39	2.19	12.97	2.68	7.94	1.09	6.29	1.19	4.14	0.32	1.49	4.16	21.65
SHL17	25.16	30.04	6.73	29.02	7.63	1.95	8.61	1.42	8.80	1.81	5.47	0.78	4.70	0.89	3.92	0.28	2.53	3.35	19.24
SHL18	16.93	20.24	4.44	19.09	4.86	1.24	5.59	0.88	5.43	1.11	3.31	0.46	2.67	0.50	3.10	0.16	2.52	1.83	12.43
SHL19	68.26	25.34	11.77	57.51	16.26	4.78	17.32	2.70	14.85	2.86	7.58	0.90	4.45	0.83	2.28	0.13	33.61	1.23	6.10

Table 3d. Trace elements determined by ICP-MS in ppm (continued)

Sample	Area	#		Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	Co	Ni	As	Zr	Ba	O
1	5	1	outer fayalite		0.73		13.93	0.26						5.77	22.15						57.16
1	5	2	hercynite			24.32	0.20						0.26	1.72	17.19						56.31
1	5	3	hercynite			24.45	0.25						0.23	1.74	16.98						56.35
1	5	4	inner fayalite		0.93	0.34	13.69	0.33						5.79	21.73						57.18
1	5	5	fayalite margin		0.52	1.18	13.56	0.15				0.14		5.48	21.78						57.19
1	5	6	fayalite margin		0.77	0.26	13.92	0.16				0.10		5.75	21.89						57.14
1	5	7	wustite			0.90	0.21						0.15	2.75	45.57						50.41
1	5	8	wustite			0.90	0.29						0.16	2.79	45.41						50.45
1	5	9	leucite?	0.66		11.27	17.03	1.23			6.38			0.31	2.63						60.50
1	5	10	glass	2.54		12.82	8.65	0.97	0.16		0.41	0.63		0.95	15.18						57.68
1	6	1	fayalite core		0.86	0.32	13.76	0.27						5.78	21.84						57.17
1	6	2	fayalite outer		0.53	0.49	14.28	0.16			0.23	0.12		5.59	21.28						57.32
1	6	3	hercynite			21.60	2.24						0.14	2.28	17.15						56.59
1	6	4	hercynite		0.36	24.13	0.18						0.16	1.76	17.21						56.20
1	6	5	fayalite core		0.85	0.35	13.77	0.30						5.92	21.62						57.20
1	6	6	interstitial mixture	2.68		8.49	13.10	2.19	0.99		5.58	0.58		1.25	5.92						59.24
1	6	7	interstitial mixture	2.15		8.50	13.76	2.14	0.88		6.35	0.49		1.15	5.21						59.36
1	6	8	wustite			0.79	0.28						0.12	2.42	46.00						50.40
2	4	1	olivine core		1.27		13.77	0.27				0.13		8.05	19.42						57.09
2	4	2	olivine margin		1.03	0.83	13.77	0.38			0.22	0.17		7.60	18.69						57.32
2	4	3	olivine core		1.57	0.52	13.71	0.38			0.26	0.13		7.70	18.52						57.20
2	4	4	olivine margin	0.32	0.66	1.04	13.67	0.45			0.34	0.17		7.35	18.73						57.27
2	4	5	interstitial mixture	2.87		8.66	14.18	1.78	0.44		5.04	0.71	0.09	1.52	5.60						59.10
2	4	6	interstitial dark, even	0.94		12.39	16.41	0.22			9.74			0.28	1.24						58.79
2	4	7	bright interstitial	1.49		7.31	13.83	1.25	0.32		5.20	0.53		2.91	8.84						58.33
2	4	8	wustite			0.38	0.22						0.14	4.10	44.89						50.27
2	4	9	wustite			2.06	1.66				0.60		0.21	3.39	40.79						51.30
2	4	10	bright interstitial	0.74	0.52	3.21	14.05	0.69	0.12		2.09	0.39		5.59	14.84						57.75
2	5	1	interstitial glass	2.01		9.41	13.12	1.63	0.83		4.97	0.74		1.64	6.43						59.22
2	5	2	interstitial bright	2.03		7.62	8.99	1.07	0.16		3.08	0.42	0.08	2.22	18.21						56.12

Sample	Area	#		Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	Co	Ni	As	Zr	Ba	O	
2	5	3	interstitial glass	2.27		9.88	13.88	1.76	0.25		5.43	0.74		1.55	5.20							59.06
2	5	4	wustite			0.97							0.19	3.98	44.53							50.34
2	5	5	olivine core		1.57	0.29	13.72	0.21				0.11		7.62	19.39							57.09
2	5	6	interstitial outer		1.16	0.73	13.35	0.25			0.20	0.16		6.91	20.25							56.99
2	5	7	olivine core		1.53	0.39	13.55	0.29				0.12		7.64	19.39							57.09
2	5	8	olivine margin	0.49	0.92	0.90	14.26	0.22			0.20	0.19		7.08	18.38							57.35
2	5	9	olivine core		1.37		13.94	0.25				0.11		7.72	19.45							57.15
2	5	10	olivine margin	0.53	0.83	1.95	13.79	0.36			0.54	0.20		6.71	17.69							57.39
3	4	1	olivine core		0.61	0.34	13.47							2.56	26.20							56.82
3	4	2	olivine core		0.52		14.05							2.42	25.98							57.03
3	4	3	olivine margin			0.35	13.51	0.28				0.10		2.43	26.28							57.05
3	4	4	complex olivine	0.29		7.00	13.60	0.12			5.22		0.09	0.45	15.92							57.31
3	4	5	complex olivine			11.92	10.13	0.60	0.14		0.73		0.49	0.72	16.57							58.70
3	4	6	complex olivine			0.23	13.47	0.51				0.16		2.37	26.09							57.17
3	4	7	leucite	0.43		9.21	18.09	0.15			8.72				4.22							59.18
3	4	8	hercynite?			13.38	12.11	0.64	0.17		1.66		0.22	0.54	11.54							59.74
3	4	9	olivine core		1.49	0.29	13.78	0.23						2.47	24.59							57.14
3	4	10	olivine outer		1.14		13.86	0.13						2.60	25.24							57.03
3	4	11	olivine margin	0.41		9.31	17.71				7.65			0.13	5.62							59.17
3	4	12	olivine margin	0.28		9.27	17.84	0.80			7.31			0.24	4.32							59.94
3	5	1	olivine core		0.32	0.36	13.47	0.25				0.09		2.49	26.01							57.01
3	5	2	main olivine margin			0.33	13.16	0.69				0.19		2.40	26.06							57.18
3	5	3	hercynite			23.45	1.26				0.24		0.65	0.72	16.94							56.75
3	5	4	hercynite			5.71	10.67	0.30				0.09	0.12	1.90	24.14							57.05
3	5	5	interstitial dark			11.31	17.18	0.36			8.83				2.83							59.48
3	5	6	hercynite?	0.32		21.67	4.62	0.16			1.01		0.64	0.51	13.24							57.84
3	5	7	complex olivine			0.28	13.44	0.52				0.23		2.37	25.97							57.18
3	5	8	interstitial glass	5.52		10.15	14.28	1.90	0.21		2.33	0.81	0.07	0.41	4.93							59.39
3	5	9	interstitial dark	3.87		8.54	13.74	2.48	0.46		1.58	1.84	0.08	0.46	6.94							60.01
3	5	10	interstitial dark	5.14		8.53	12.45	2.36	0.58		1.76	1.89	0.15	0.46	7.63							59.06
3	5	11	interstitial dark	5.19		7.76	12.05	4.44	0.35		1.86	3.36		0.46	4.65							59.88
3	6	1	fine l/w - altered	0.40		9.00	17.43				6.40			0.17	7.33							59.27

Sample	Area	#		Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	Co	Ni	As	Zr	Ba	O
3	6	2	leucite	0.24		10.50	19.46	0.35			8.01				0.76					0.11	60.56
3	6	3	leucite	0.56		9.98	19.77				7.96				1.48						60.24
3	6	4	complex olivine core		0.36		13.58	0.31				0.12		2.52	26.09						57.02
3	6	5	complex olivine margin			0.36	13.53	0.45				0.13		2.44	25.90						57.19
3	6	6	hercynite?			23.39	0.56						0.78	0.70	18.05						56.52
3	6	7	hercynite?			21.51	1.39						0.72	0.95	18.99						56.44
3	6	8	main olivine core		1.25		14.09							2.43	25.18						57.05
3	6	9	main olivine core		1.42	0.20	13.91							2.52	24.96						57.00
3	6	10	main olivine outer		0.91	0.21	13.78	0.18						2.51	25.33						57.08
3	6	11	main olivine outer		1.24	0.23	13.93							2.64	24.94						57.02
4	3	1	interstitial intermediate - glass?	8.29	0.25	3.34	4.71	9.31	0.58		4.52	5.26		2.66	3.29					0.24	57.55
4	3	2	olivine		2.22	0.32	13.72	0.35			0.13	0.35		8.33	17.40						57.17
4	3	3	interstitial dark	1.17		11.19	13.29	1.40	0.51		9.32	0.68		0.99	3.06						58.38
4	3	4	interstitial dark	0.92		10.98	12.55	1.80	0.93		8.58	0.73		1.01	3.57						58.92
4	3	5	interstitial intermediate - glass?	8.12	0.25	3.45	5.21	9.33			3.35	5.45		3.03	4.00					0.22	57.60
4	3	6	olivine		1.98	0.24	13.98	0.14			0.08	0.38		8.37	17.69						57.14
4	3	7	wustite										0.12	4.74	45.08						50.06
4	3	8	olivine		1.83		14.17	0.15			0.09	0.50		8.42	17.66						57.18
4	3	9	interstitial dark	1.20		13.19	15.22	0.19			10.40			0.24	1.43						58.15
4	4	1	olivine centre		2.31	0.40	13.93	0.23			0.10	0.38		8.37	17.06						57.21
4	4	2	olivine centre		2.43	0.17	13.84	0.26				0.28		8.46	17.41						57.16
4	4	3	wustite								0.12		0.11	4.69	45.06						50.03
4	4	4	olivine		1.72	0.18	13.96	0.22				0.44		8.66	17.63						57.19
4	4	5	interstitial intermediate - glass?	8.32		0.78	2.07	12.73			2.32	7.45		3.30	4.41					0.51	58.12
4	4	6	interstitial dark rounded	1.15		10.97	14.79	0.75	0.19		9.39			0.79	3.73						58.25
4	4	7	interstitial dark rounded	0.96		11.74	16.11	0.39			10.67			0.33	1.44						58.37
4	4	8	olivine	0.43	0.84	0.16	13.86	0.39			0.12	0.50		7.66	18.93						57.12
5	2	1	olivine outer		0.30	0.43	14.27	0.20				0.24		6.15	20.84						57.39
5	2	2	olivine inner		0.35	0.19	13.71	0.31				0.18		6.39	21.55						57.13
5	2	3	olivine core		0.62	0.22	13.74	0.22				0.12		6.60	21.39						57.09
5	2	4	olivine core		1.09	0.28	13.56	0.27				0.16		6.49	20.92						57.09

Sample	Area	#		Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	Co	Ni	As	Zr	Ba	O	
5	2	5	olivine outer		0.77	0.28	13.52	0.39				0.17		6.57	21.17							57.12
5	2	6	olivine outer		0.55	0.26	13.93	0.25				0.14		6.47	21.20							57.21
5	2	7	interstitial mixed	2.84		7.29	13.03	2.62	0.54		4.51	0.93		1.68	7.22							59.17
5	2	8	interstitial mixed	2.18		7.50	13.25	2.33	0.58		5.18	0.92		1.83	7.12							59.03
5	2	9	wustite			0.33							0.11	3.24	46.17							50.14
5	2	10	wustite			0.52								3.27	46.08							50.13
5	2	11	interstitial dark rounded	2.10		8.98	12.90	2.56	0.96		3.65	0.90		1.30	6.51							60.14
6	6	1	olivine		1.02	0.28	13.42	0.41				0.15		6.92	20.72							57.09
6	6	2	olivine		1.05		13.89	0.19				0.11		7.03	20.64							57.09
6	6	3	dark interstitial	1.88		11.73	15.34	0.86			8.62	0.34		0.75	1.85							58.63
6	6	4	olivine		1.04	0.23	13.59	0.27				0.17		6.86	20.79							57.05
6	6	5	interstitial bright - ol?	1.39	0.69	1.51	11.03	3.01			0.62	0.17		7.23	16.72							57.65
6	6	6	wustite/iron?			0.39							0.11	3.67	45.68							50.15
6	6	7	wustite			0.36								3.50	46.04							50.09
6	6	8	dark interstitial	0.38		20.94	6.54	1.16	0.17	0.50	1.40	0.48		0.78	8.80							58.85
6	6	9	olivine margin	1.56	0.55	3.81	12.32	1.99			2.54	0.18		5.41	14.07							57.58
6	6	10	dark interstitial	2.31		11.64	14.80	1.50			8.65			0.67	1.73							58.70
6	7	1	olivine mrgin		0.95	0.26	13.63	0.24				0.19		7.15	20.53							57.06
6	7	2	olivine core		1.16	0.25	13.49	0.44				0.17		7.06	20.29							57.14
6	7	3	olivine		0.92		13.79	0.25				0.29		7.18	20.49							57.08
6	7	4	complex olivine		1.22	0.22	13.42	0.50				0.17		7.11	20.23							57.14
6	7	5	complex olivine		0.98	0.19	13.68	0.31				0.25		7.12	20.36							57.12
6	7	6	complex olivine		1.27	0.21	13.52	0.33				0.19		7.00	20.41							57.06
6	7	7	complex olivine		1.18	0.24	13.61	0.37				0.17		7.03	20.24							57.15
6	7	8	complex olivine		1.37		13.65	0.43				0.13		6.62	20.66							57.14
6	7	9	olivine (in w zone)		1.19		13.75	0.21				0.11		6.66	21.03							57.04
6	7	10	olivine (in w zone)		1.28	0.24	13.93	0.13						6.52	20.77							57.12
6	7	11	olivine (in w zone)		1.07		13.80	0.36				0.17		6.88	20.55							57.17
6	7	12	wustite			0.33								3.79	45.79							50.08
7	2	1	olivine margin	0.35	0.77	0.91	13.67	0.40			0.24	0.20		3.45	22.81							57.21
7	2	2	olivine core		1.05	0.28	13.38	0.45						3.58	24.16							57.10
7	2	3	olivine margin		1.01	0.31	13.52	0.23				0.10		3.51	24.30							57.01

Sample	Area	#		Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	Co	Ni	As	Zr	Ba	O
7	2	4	olivine inner		1.04	0.36	13.43	0.29						3.52	24.36						57.02
7	2	5	olivine margin	0.40	1.04	0.80	13.64	0.29			0.13	0.10		3.46	23.04						57.10
7	2	6	olivine core		0.92	0.24	13.84	0.15						3.54	24.24						57.09
7	2	7	olivine margin		0.60	0.21	13.88	0.13				0.15		3.58	24.34						57.09
7	2	8	interstitial glass (with Fe blebs)	2.82		9.20	14.86	1.59	0.23		4.42	0.94		0.73	5.87						59.35
7	2	9	wustite			0.74								1.63	47.44						50.19
7	2	10	interstitial bright	1.66		8.95	13.78	1.44	0.19		5.75	0.63		1.13	7.93						58.54
7	2	11	interstitial dark	2.23		9.66	14.60	1.80	0.22		5.47	1.01		0.88	4.77						59.36
7	4	1	olivine core		1.07	0.28	13.75	0.21				0.11		3.79	23.69						57.10
7	4	2	olivine inner		1.06		14.00	0.19				0.11		3.71	23.79						57.14
7	4	3	olivine inner		0.98	0.30	13.56	0.20				0.11		3.81	23.78						57.06
7	4	4	olivine outer		0.83		13.77	0.39				0.13		3.76	23.85						57.09
7	4	5	late olivine	0.34	0.53	1.07	14.00	0.40			0.41	0.25		3.37	22.25						57.38
7	4	6	late olivine	0.39	0.35	1.04	13.70	0.48			0.49	0.27		3.45	22.60						57.25
7	4	7	olivine overgrowth		0.66	0.45	13.57	0.44			0.11	0.20		3.78	23.59						57.20
7	4	8	wustite			0.71							0.12	1.62	47.31						50.24
7	4	9	interstitial glass	2.96		10.13	15.44	1.43	0.20		4.91	0.72		0.45	4.20						59.56
7	4	10	late olivine on W		0.53	0.40	10.89	0.32				0.18		3.30	28.61						55.78
7	4	11	interstitial glass	3.04		9.49	14.60	1.84	0.22		4.75	0.99		0.57	5.17						59.32
8	3	1	leucite	0.22		10.58	19.32	0.18			8.34		0.07	0.14	0.81						60.34
8	3	2	hercynite			24.17	0.50						0.50	1.69	16.60						56.54
8	3	3	olivine outer		0.65	0.23	14.01					0.16		5.39	22.49						57.07
8	3	4	olivine core		1.61	0.34	13.74	0.15				0.11		5.45	21.53						57.07
8	3	5	hercynite			23.68	0.33						0.64	1.56	17.39						56.41
8	3	6	inclusion in olivine margin			0.90	1.91	11.92			0.10	10.35		4.43	10.06						60.14
8	3	7	wustite			0.36							0.23	2.19	47.02						50.20
8	3	8	olivine core		1.51	0.29	13.90	0.15						5.42	21.60						57.13
8	3	9	hercynite			24.27	0.38						0.55	1.75	16.52						56.53
8	4	1	olivine core		1.70		13.85	0.12				0.09		5.65	21.56						57.02
8	4	2	olivine		1.58	0.23	13.76	0.18				0.09		5.62	21.48						57.07
8	4	3	olivine outer		1.25	0.18	13.95					0.12		5.57	21.91						57.02
8	4	4	hercynite		0.38	25.19	0.16						0.28	1.73	15.72						56.52

Sample	Area	#		Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	Co	Ni	As	Zr	Ba	O
8	4	5	hole in olivine	1.50	0.45	4.60	13.13	0.74			1.91	0.56		3.93	15.76						57.42
8	4	6	hole in olivine	1.32		9.51	16.08	0.23	0.32		5.68		0.10	0.68	6.88						59.20
9	3	1	olivine		2.34		14.19	0.17				0.32		1.79	23.96						57.23
9	3	2	olivine		2.40		14.10	0.21			0.17	0.35		1.81	23.79						57.17
9	3	3	olivine		2.13	0.22	14.00	0.31			0.18	0.37		1.91	23.63						57.24
9	3	4	interstitial glass	3.41	0.19	6.28	16.12	1.32	0.34		5.85	0.53		0.36	6.97						58.64
9	3	5	interstitial glass	3.93		5.79	15.41	1.59	0.31		5.47	1.05		0.39	7.76						58.31
9	3	6	olivine		2.27	0.22	14.01	0.31			0.15	0.30		1.85	23.62						57.26
9	3	7	wustite		0.44								0.11	0.72	48.67						50.06
10	6	1	altered iron				0.69	0.82	0.21						46.27		0.34	0.40			51.27
10	6	2	altered iron				0.55	0.56	0.47	0.15					46.89		0.30				51.09
10	6	3	wustite?				0.83								48.45			0.24			50.48
10	6	4	dense zone in altered rion				0.24		0.40						48.84						50.52
10	6	5	wustite			0.33								0.50	49.09						50.08
10	6	6	altered iron				0.71	1.68	0.32						45.35						51.94
10	6	7	altered iron				0.45	0.65	0.32						47.55						51.03
10	6	8	bulk area - altered iron			0.63	0.72	0.63	0.39						46.24						51.38
10	6	9	bulk area - slag		0.87	2.86	13.59	0.57				0.46		0.88	22.84						57.94
10	7	1	olivine		1.74	0.21	14.03	0.21				0.42		1.31	24.86						57.23
10	7	2	olivine		1.76	0.47	14.51	0.28				0.43		1.23	23.74						57.58
10	7	3	olivine		2.22	0.24	14.26	0.31				0.32		1.27	23.93						57.43
10	7	4	altered iron				0.44	0.38	0.37						47.93						50.88
10	7	5	altered iron				0.65	0.40	0.25						47.83						50.87
10	7	6	wustite cavity rim			0.38							0.11	0.51	48.84						50.15
10	7	7	wustite										0.15	0.54	49.24						50.07
10	7	8	wustite			0.34							0.19	0.56	48.73						50.18
10	7	9	wustite cavity rim			0.28	0.39							0.44	48.62						50.27
10	7	10	interstitial black	0.28	0.24	5.80	18.01	1.00			0.10	0.80	0.15	0.44	11.99						61.18
10	7	11	interstitial black			9.81	10.47	0.71	0.10			0.64		0.41	19.54						58.32
10	7	12	interstitial black		0.34	4.04	16.39	0.53				0.79		0.76	17.53						59.61
10	7	13	olivine		1.89	0.30	14.23	0.29				0.33		1.19	24.36						57.41
10	7	14	altered iron										0.18	0.52	49.22						50.09

Sample	Area	#		Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	Co	Ni	As	Zr	Ba	O	
10	7	15	wustite cavity rim			0.41	0.80						0.18	0.54	47.48							50.59
10	7	16	altered iron				0.49	0.34	0.27						48.14							50.76
10	7	17	altered iron				0.49		0.33						48.60							50.58
10	7	18	altered iron				0.47	0.51	0.43						47.54							51.05
10	8	1	olivine		2.60		14.26				0.09	0.46		1.22	24.25							57.11
10	8	2	olivine		2.09	0.32	14.07	0.23			0.23	0.42		1.16	24.24							57.23
10	8	3	fine groundmass	2.09	0.17	7.09	15.58	1.40	0.33		5.85	1.50		0.25	6.77							58.96
10	8	4	fine groundmass	3.19		6.42	16.29	1.28	0.42		4.35	1.91		0.24	6.65							59.25
10	8	5	fine groundmass	3.22	0.21	6.97	16.21	1.19	0.26		4.54	1.54		0.26	6.54							59.06
10	8	6	olivine		2.12	0.27	14.17	0.20			0.20	0.41		1.21	24.17							57.25
10	8	7	olivine		2.44	0.30	14.36	0.16			0.09	0.46		1.21	23.64							57.35
10	8	8	wustite		0.48	0.26								0.61	48.58							50.06
10	8	9	wustite		0.51	0.32								0.56	48.53							50.08
10	9	1	wustite		0.63								0.17	1.28	47.83							50.08
10	9	2	olivine	0.60	3.51	1.46	13.94	0.47			0.92	0.66		2.09	19.05							57.31
10	9	3	olivine	0.41	4.12	0.67	13.91	0.35			0.58	0.57		2.22	20.03							57.14
10	9	4	olivine	0.35	3.37	0.64	14.02	0.30			0.42	0.53		2.33	20.83							57.20
10	9	5	fine groundmass	2.57	0.36	6.44	15.25	2.04	0.41		6.15	1.76		0.51	5.51							59.00
10	9	6	fine groundmass	3.34	0.49	5.91	15.35	1.72	0.36		4.53	1.43		0.68	7.35							58.83
10	9	7	fine groundmass	2.58	0.22	6.94	15.03	1.89	0.42		6.11	1.46	0.07	0.44	5.90							58.95
10	9	8	olivine		4.15	0.47	14.07	0.29			0.12	0.39		2.33	20.85							57.34
16	2	1	olivine margin	0.34	1.04	0.85	13.90	0.29			0.17	0.59		5.04	20.54							57.25
16	2	2	olivine inner		1.97		14.01					0.25		5.42	21.26							57.08
16	2	3	olivine inner		2.82		13.83					0.21		5.30	20.92							56.92
16	2	4	olivine margin		2.44		13.99					0.16		5.22	21.20							56.99
16	2	5	olivine margin		1.95	0.33	14.00					0.31		5.32	21.01							57.08
16	2	6	olivine inner		2.96	0.19	13.72	0.15				0.19		5.08	20.71							57.02
16	2	7	olivine inner		2.73		13.84					0.15		5.34	20.85				0.11			57.09
16	2	8	olivine margin		1.47	0.19	13.47	0.31				0.42		5.41	21.47							57.26
16	2	9	dark interstitial	1.62		9.56	15.14	2.29	0.12		6.41	2.20		0.51	2.23						0.13	59.92
16	2	10	intermediate interstitial			6.43	12.61	0.49	0.33	0.36	0.23	0.22		1.67	19.27							58.38
16	2	11	wustite			0.45							0.19	2.45	46.72							50.20

Sample	Area	#		Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	Co	Ni	As	Zr	Ba	O	
16	2	12	dark interstitial	3.22		11.12	14.83	0.98	0.36		5.86	0.99		0.55	3.08						59.01	
16	2	13	dark interstitial	0.48	0.24	11.05	17.00	2.56	0.28	0.34	0.40	2.01		0.83	1.74						63.07	
17	3	1	wustite			0.55								2.07	47.24						50.14	
17	3	2	olivine margin		0.93	0.96	13.73	0.41			0.64	0.27		3.67	22.13						57.26	
17	3	3	olivine		0.99	0.35	13.58	0.23				0.09		3.84	23.89						57.05	
17	3	4	olivine		1.18	0.22	13.61	0.25				0.10		3.77	23.83						57.04	
17	3	5	olivine		0.93	0.29	13.67	0.25				0.09		3.83	23.86						57.09	
17	3	6	olivine		0.91	0.38	13.43	0.23				0.14		3.83	24.10						56.98	
17	3	7	interstitial dark glass	2.14		8.01	13.94	1.55	0.61		5.06	0.89		1.00	7.86						58.95	
17	3	8	interstitial dark glass	2.14		7.86	14.68	1.39	0.34		5.09	0.85		1.03	7.72						58.89	
17	3	9	interstitial dark glass	2.22	0.19	8.58	14.35	1.59	0.41		5.34	0.83		0.95	6.50						59.04	
18	2	1	olivine inner		0.90		13.70	0.19						9.71	18.50						57.00	
18	2	2	olivine outer		0.67		13.65	0.18				0.09		9.63	18.82						56.96	
18	2	3	olivine margin		0.51	0.32	13.13	0.49				0.10		9.85	18.59						57.01	
18	2	4	olivine outer		0.92		13.30	0.40						9.79	18.65						56.95	
18	2	5	olivine		0.59	0.26	13.62	0.27						9.52	18.66						57.07	
18	2	6	olivine		0.87	0.35	13.46	0.25				0.11		9.63	18.34						57.00	
18	2	7	olivine outer		0.78	0.28	13.65	0.25						9.56	18.39						57.09	
18	2	8	interstitial bright (ol?)	0.95		8.07	12.17	1.52	0.66		4.90	0.47		3.91	8.90						58.44	
18	2	9	interstitial dark	0.61		12.64	14.78	1.73	0.19		5.32	0.41	0.11	0.77	2.83						60.62	
18	2	10	wustite			0.81								5.71	43.27						50.20	
18	3	1	olivine		0.78	0.32	13.34	0.28						9.17	19.15						56.96	
18	3	2	olivine		0.53	0.28	13.44	0.28				0.09		8.92	19.47						57.00	
18	3	3	interstitial dark glass	0.47		9.21	13.49	1.65	0.48		2.07	0.53	0.22	2.48	9.17						60.24	
18	3	4	wustite			0.73							0.14	5.11	43.77						50.25	
18	3	5	altered iron?						0.24					0.29	49.24						50.24	
18	3	6	altered iron?						0.24					0.56	48.96						50.24	
19	5	1	bulk area - Mn rich	0.93	1.16	0.25					2.66	0.25		43.35	1.36	0.24				0.29	49.52	
19	5	2	bulk area - Fe rich		3.01	3.23	0.52					0.13		0.52	39.85							52.75
19	5	3	Mn-rich	0.94	0.57						2.82			45.72	0.37	0.24				0.13	49.20	
19	5	4	Fe-rich		0.64	2.62	0.68								44.06						51.99	
19	5	5	hole?			33.22								0.16							66.61	

Sample	Area	#		Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	Co	Ni	As	Zr	Ba	O
19	5	6	Fe-rich		1.22	2.71	0.95					0.14		0.77	41.83						52.37
19	5	7	Fe-rich		0.67	2.95	0.65							0.28	43.32						52.13
19	5	8	Mn-rich	0.75	0.84						2.92			45.38	0.37	0.23				0.21	49.29
19	5	9	Mn-rich	0.87	0.69						3.07	0.22		45.53	0.33					0.11	49.19
19	6	Sum Spot	bulk - whole surface			7.56	5.58	0.62		0.91	0.78	0.21		8.75	21.10						54.49
19	7	1	euhedral dark			11.49	17.71				5.48	0.25		1.37	3.35						60.36
19	7	2	euhedral dark			32.13	4.07		0.35	1.40	1.07	0.18			1.33						59.45
19	7	3	euhedral dark			34.99	1.80		0.18	3.64	0.84	0.20			0.55						57.80
19	7	4	dense bright			1.83					2.48	0.23		43.26	1.62					0.74	49.84
19	7	5	dense bright	0.99		1.68	0.64				2.37	0.29		42.53	0.87		0.41			0.32	49.90
19	7	6	bright			1.59	2.48	0.95				0.17		2.20	40.25						52.35
19	7	7	bright			1.26	0.29				2.18	0.29		41.09	4.51					0.47	49.92
19	7	8	dull			4.68	3.34	0.78	0.37		0.21	0.35		3.17	33.06						53.74
19	7	9	dull			3.51	4.34	0.67	0.30	0.19	0.59	0.24		2.80	33.75						53.61
19	7	10	dense bright				1.81	0.56				0.18		0.25	45.88						51.32
19	7	11	euhedral dark			7.71	23.28				6.90				0.27						61.84

Table 4. Archive of EDS analyses. Elements presented as atom%. For locations of analyses see plates 1-14.

Figure 1

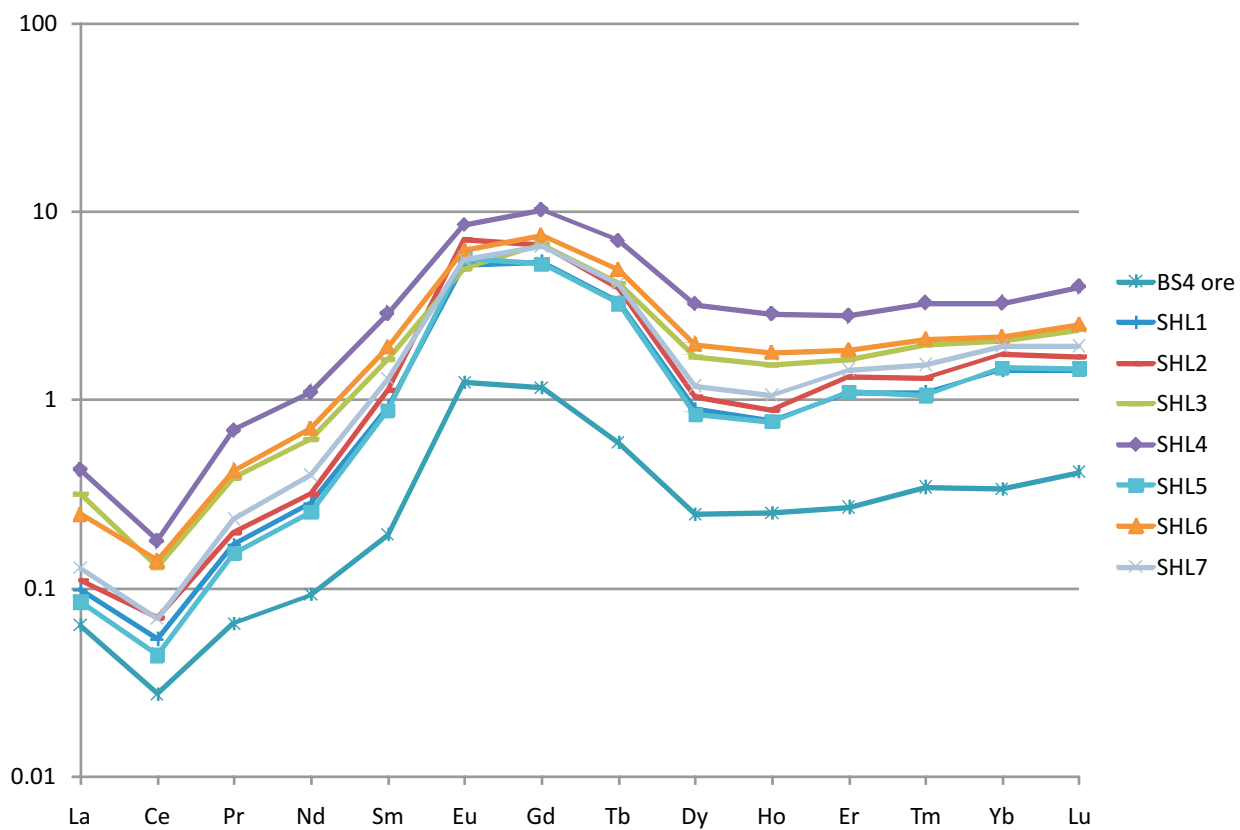


Figure 2

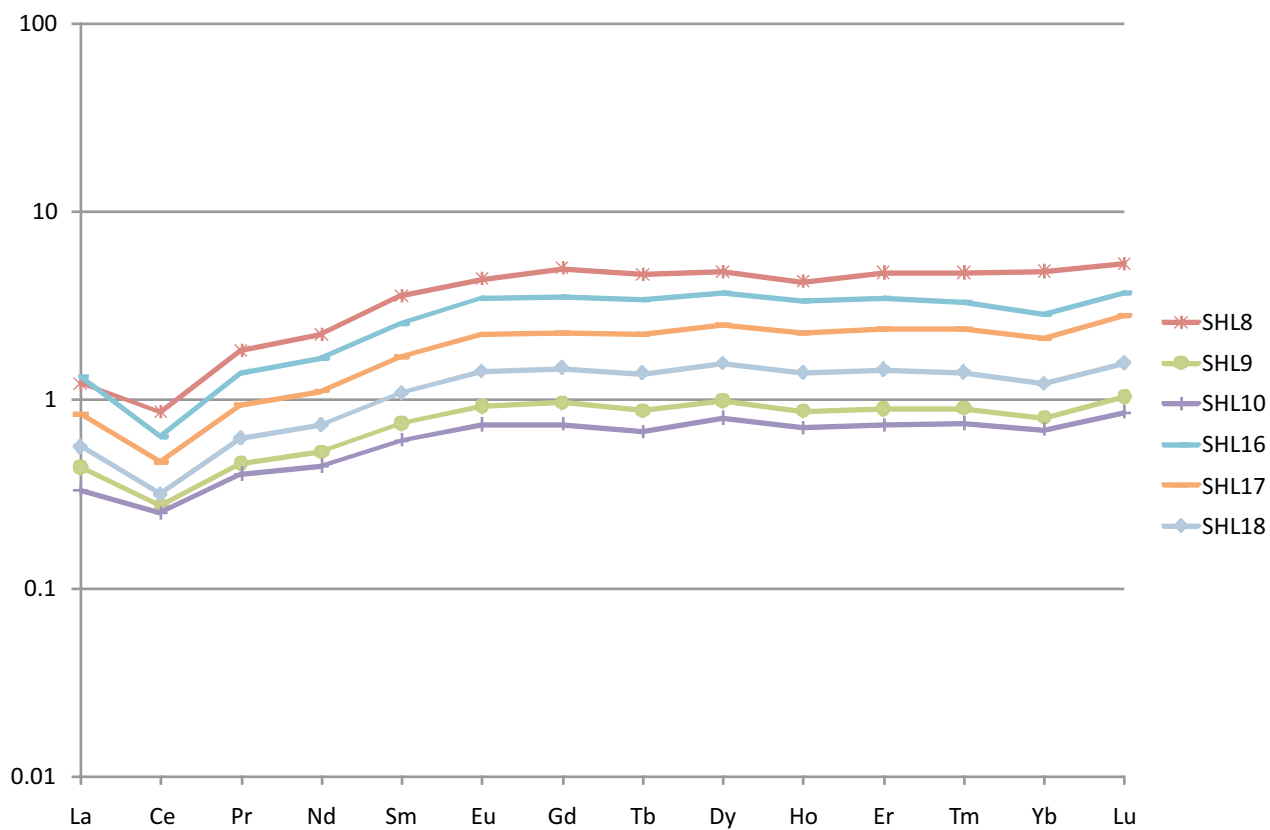


Figure 3

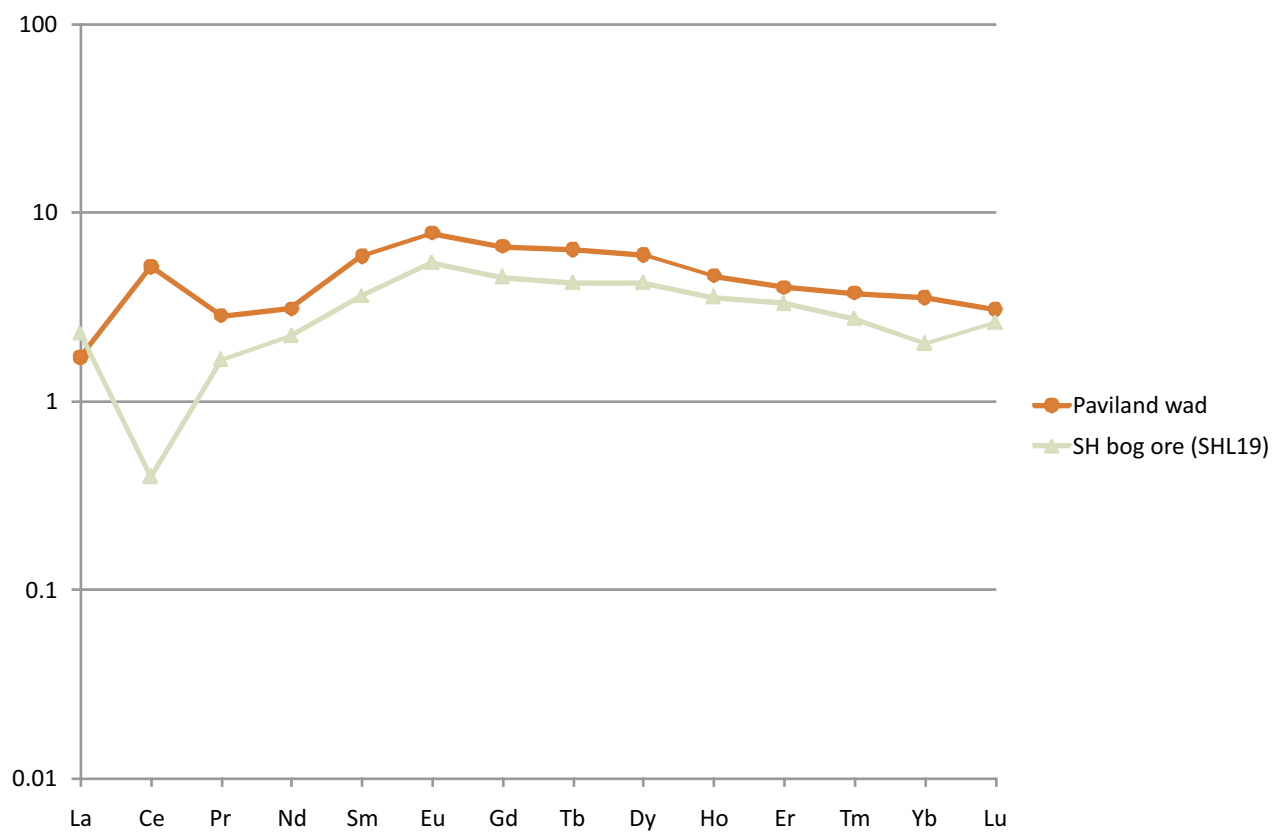


Figure 4

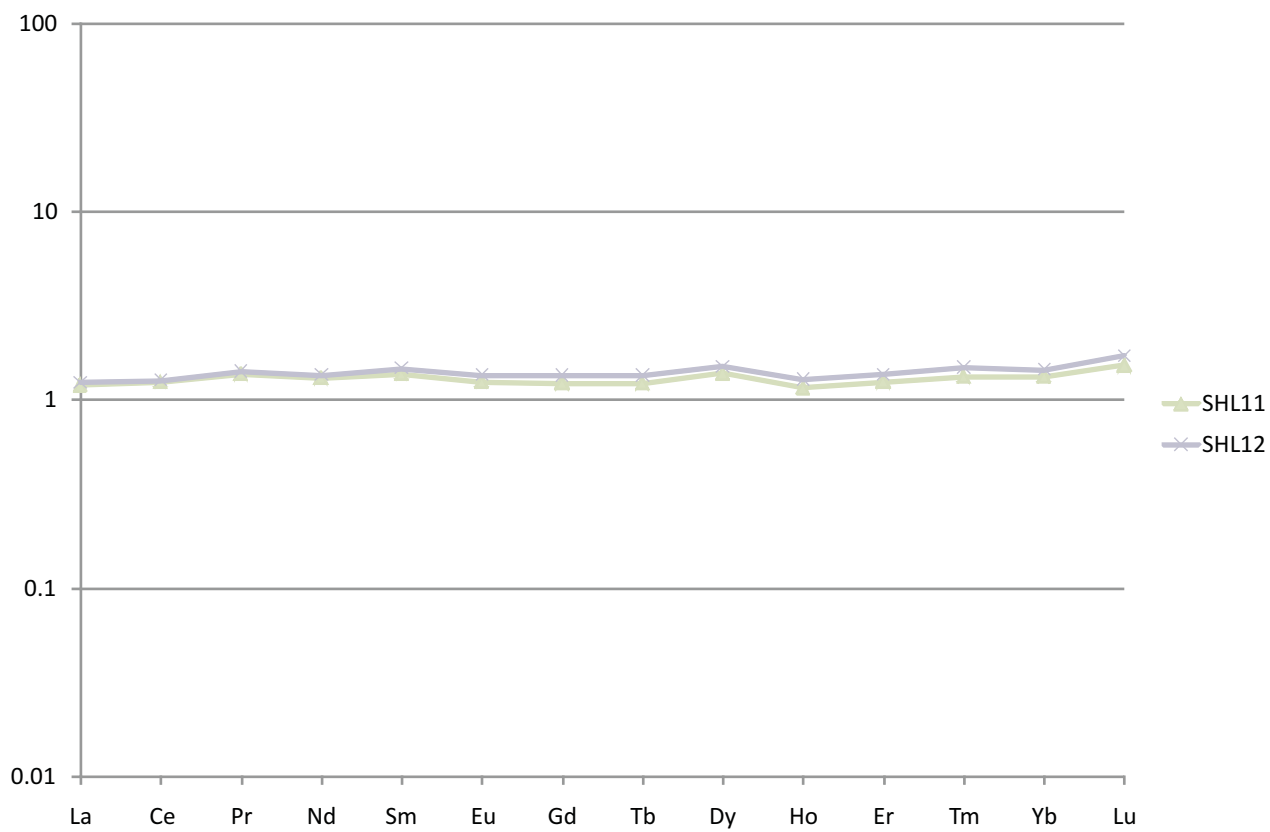


Figure 5

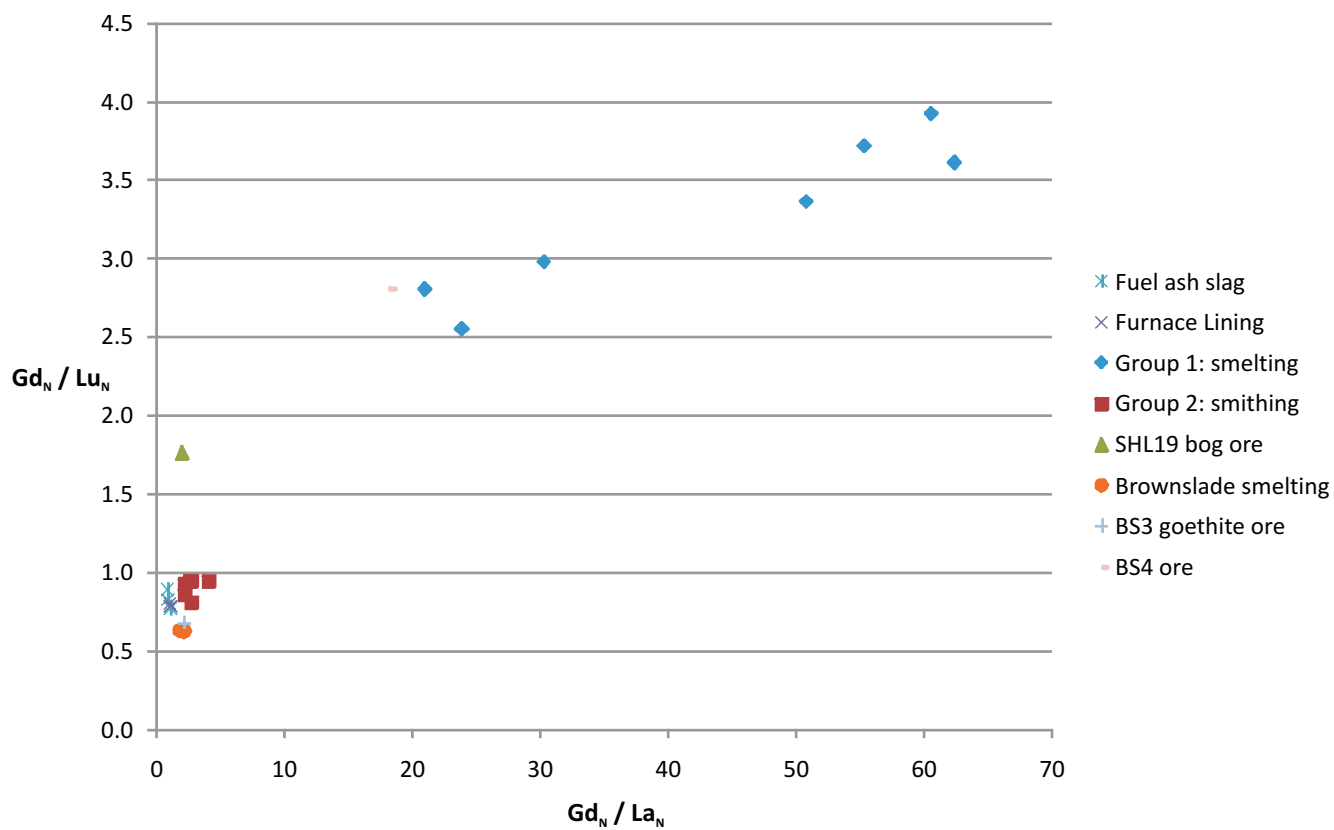


Figure 6

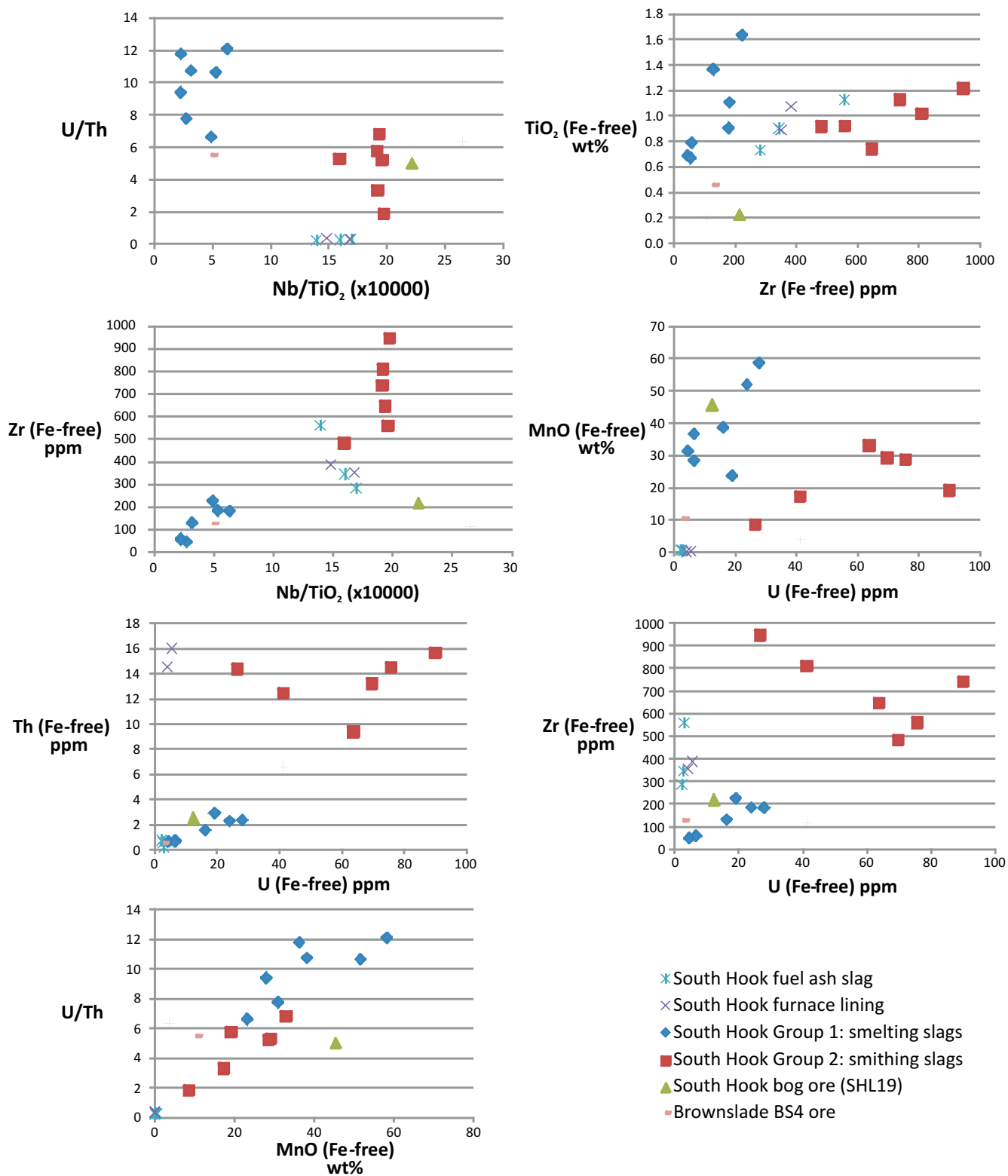
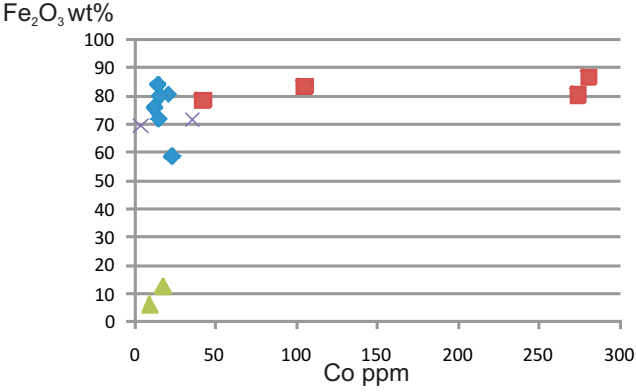
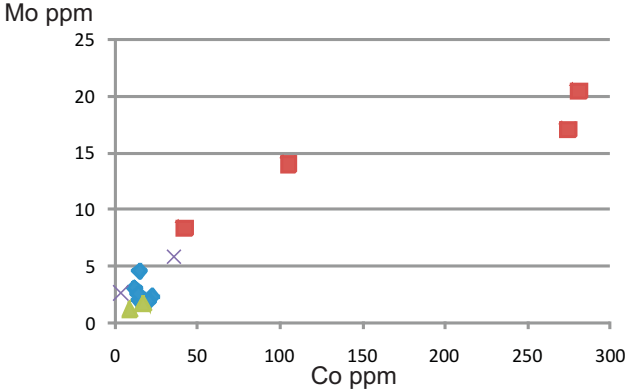
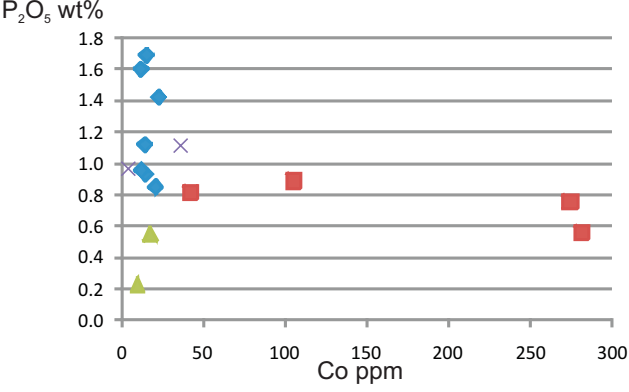
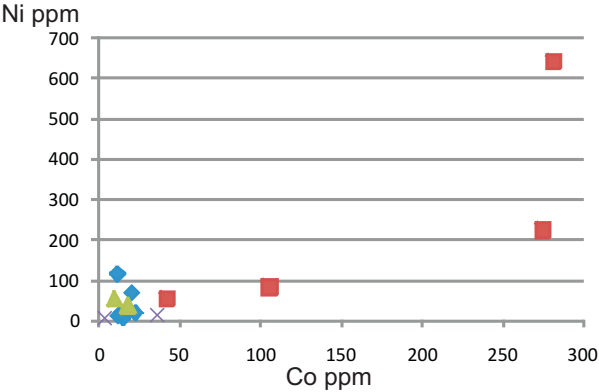
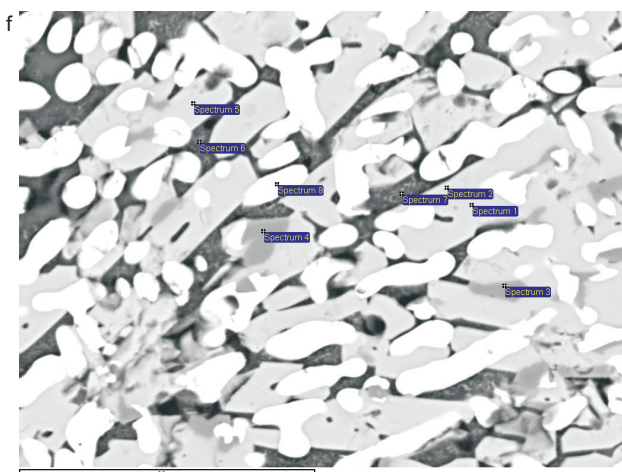
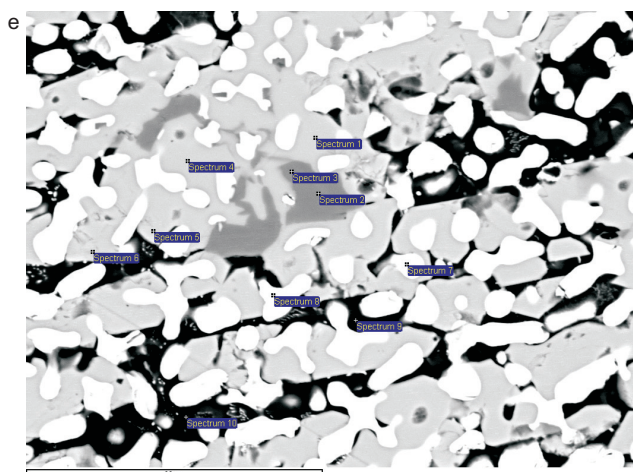
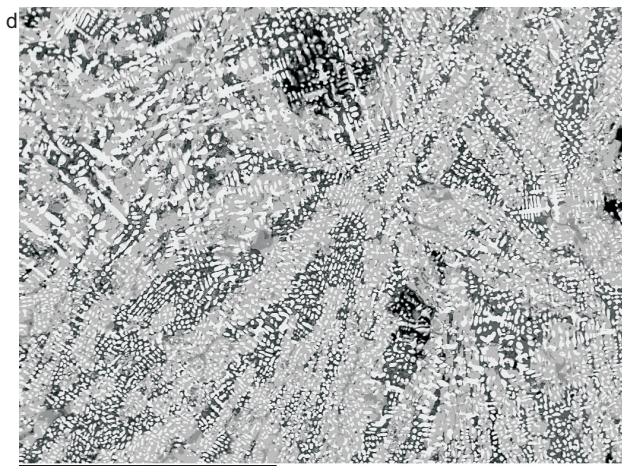
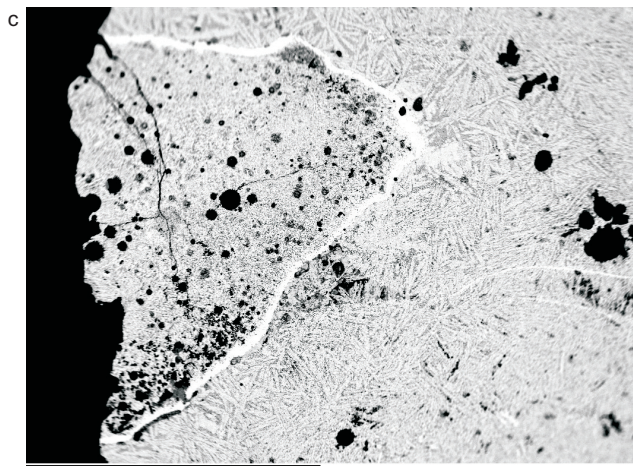
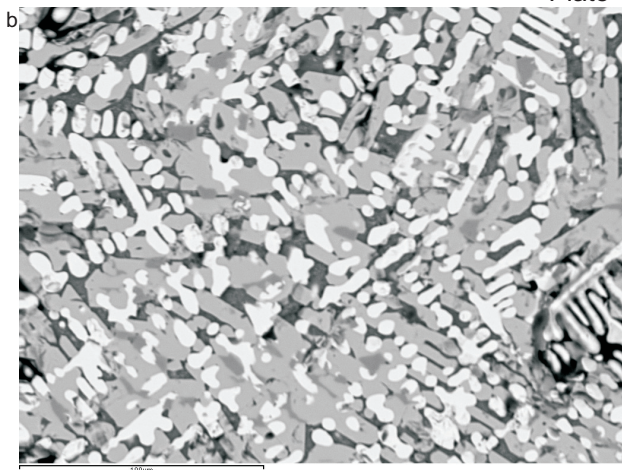
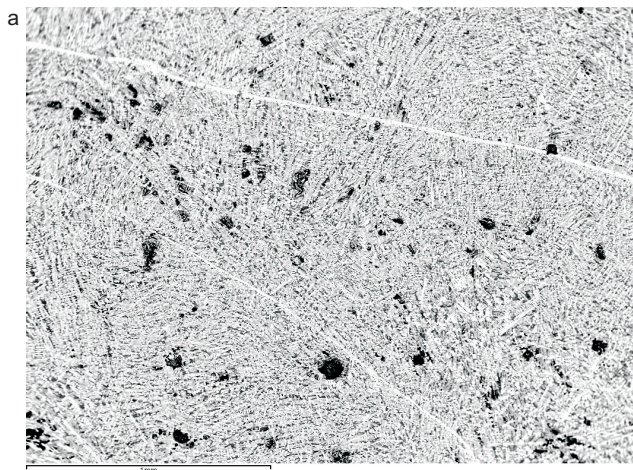


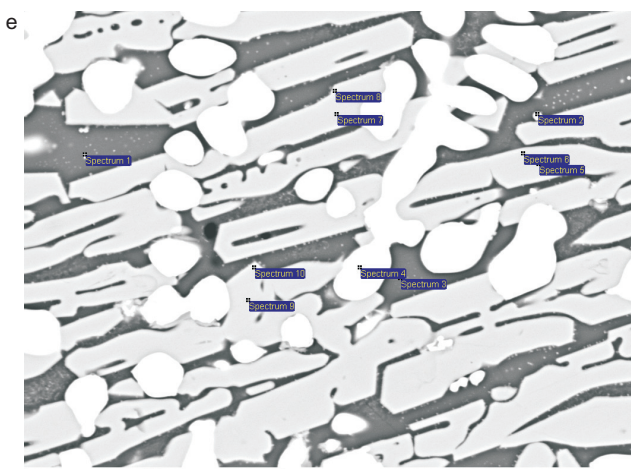
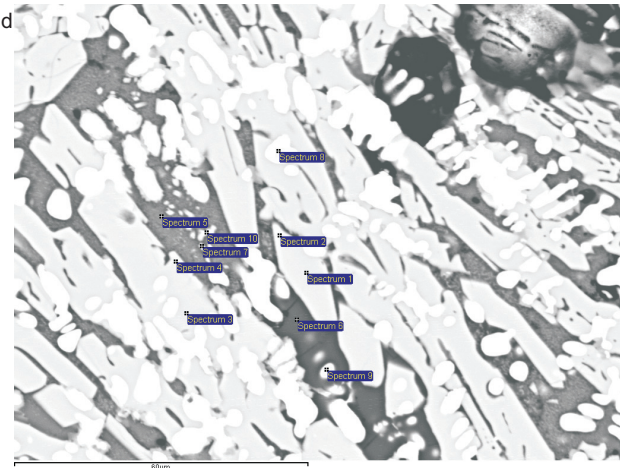
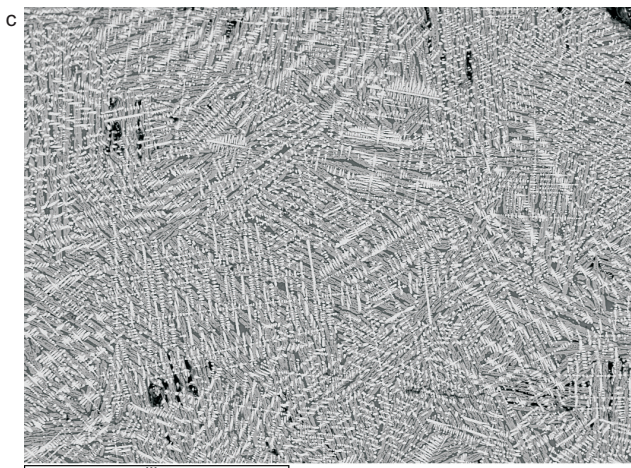
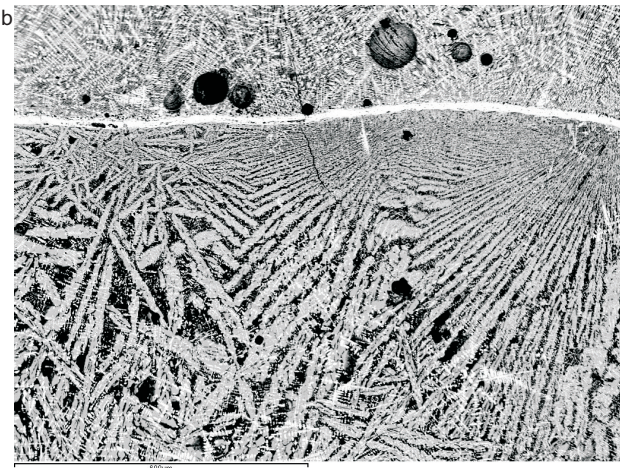
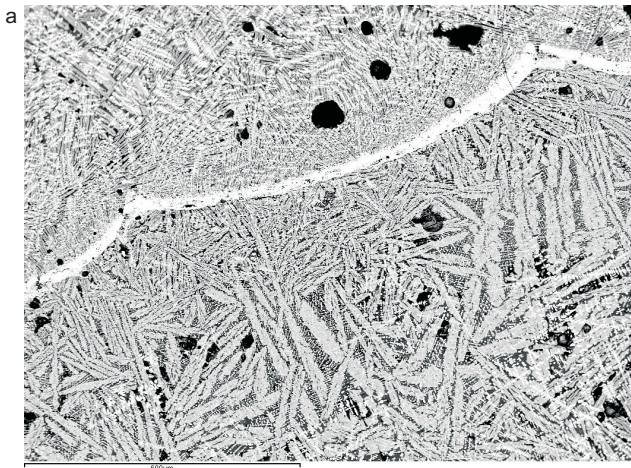
Figure 7

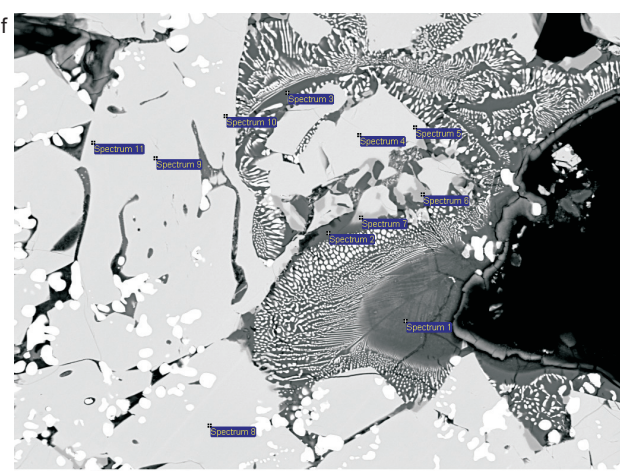
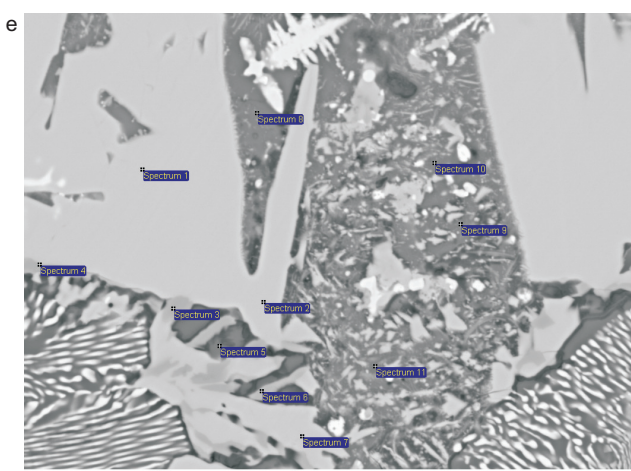
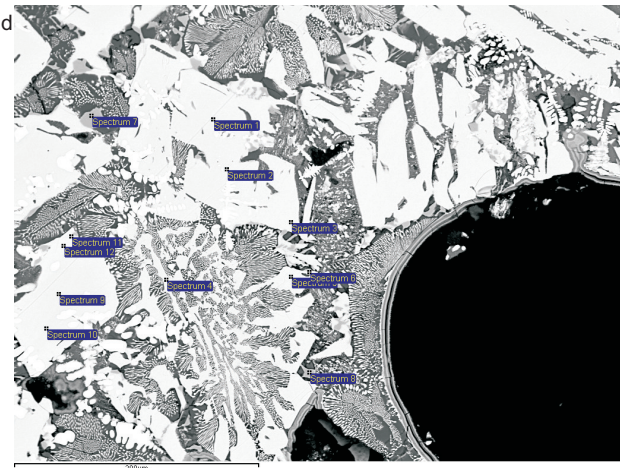
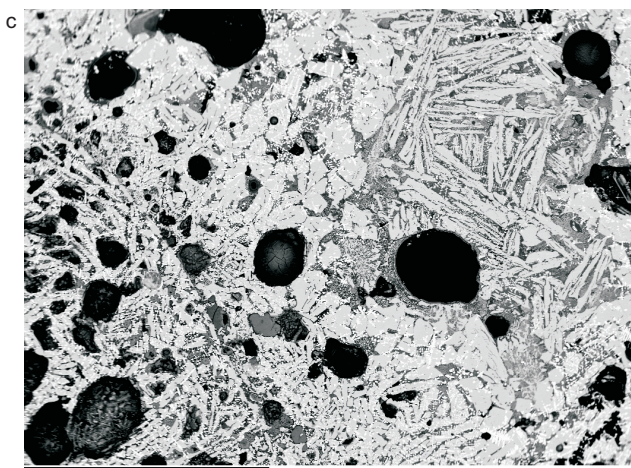
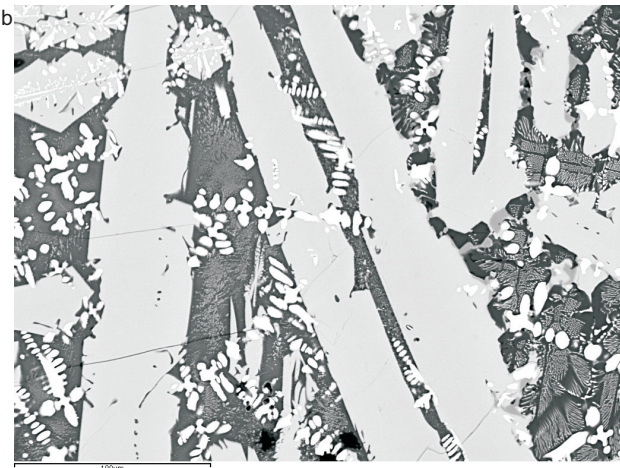
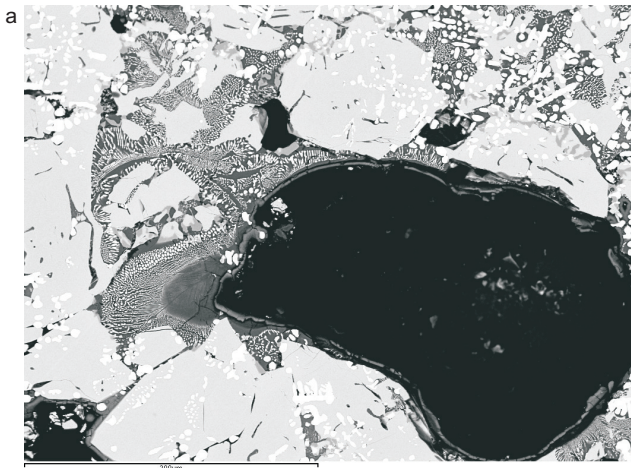


- ◆ Group 1: Tapslag
- Group 2b: Iron-bearing SHCs
- × Group 2a: SHCs
- ▲ lining

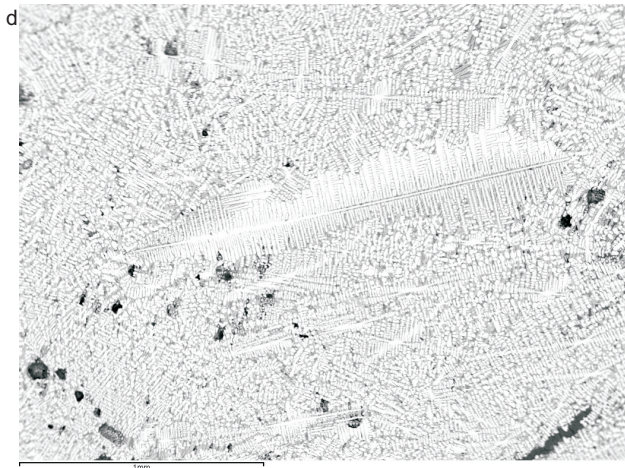
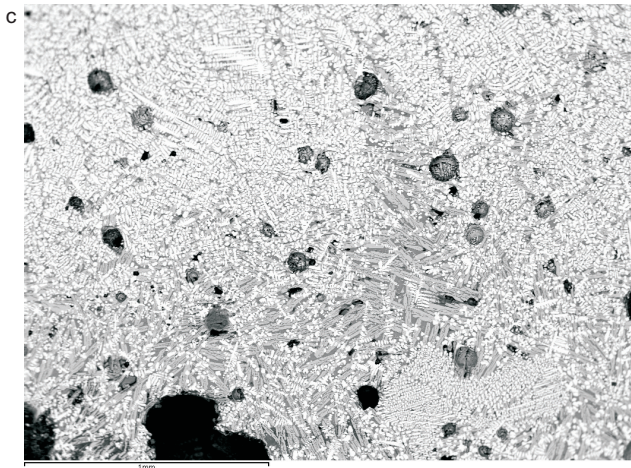
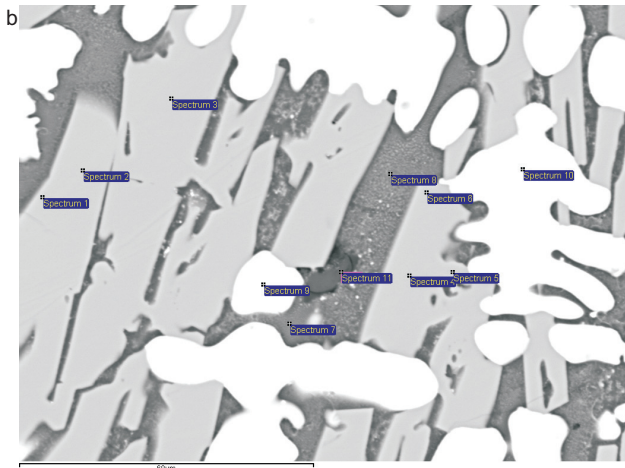
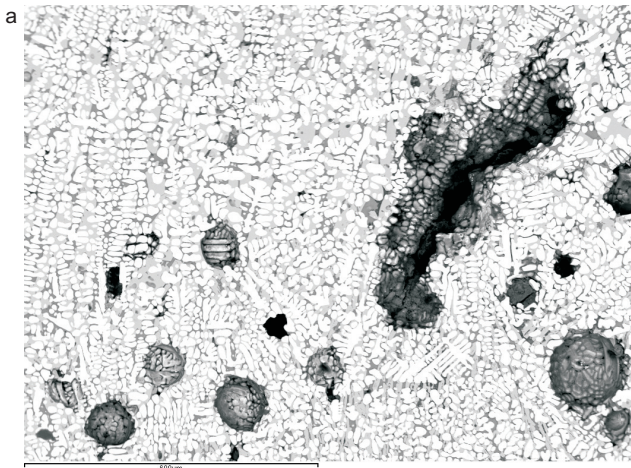


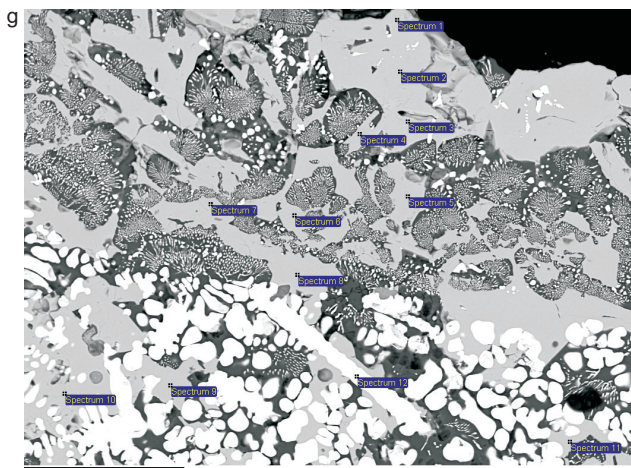
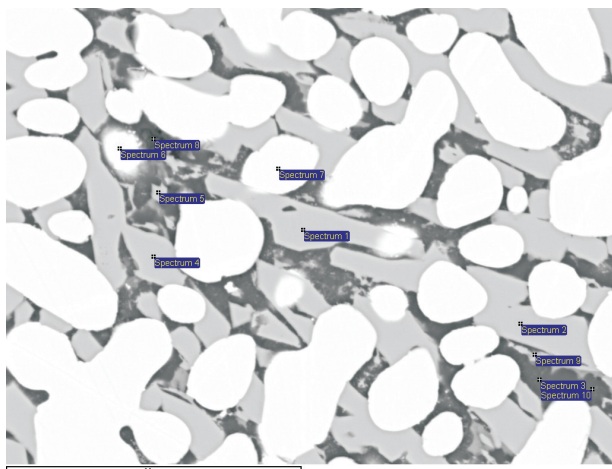
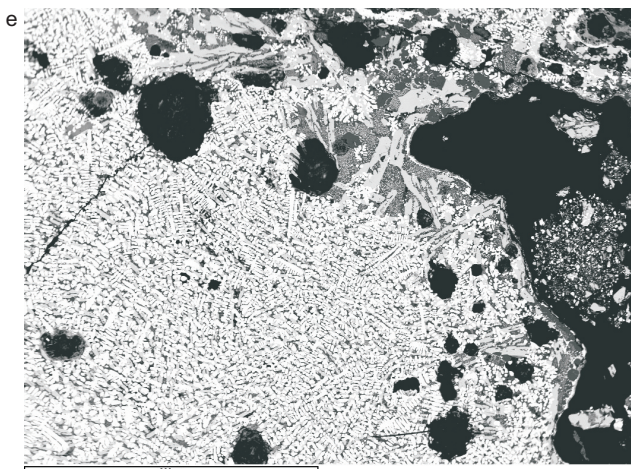
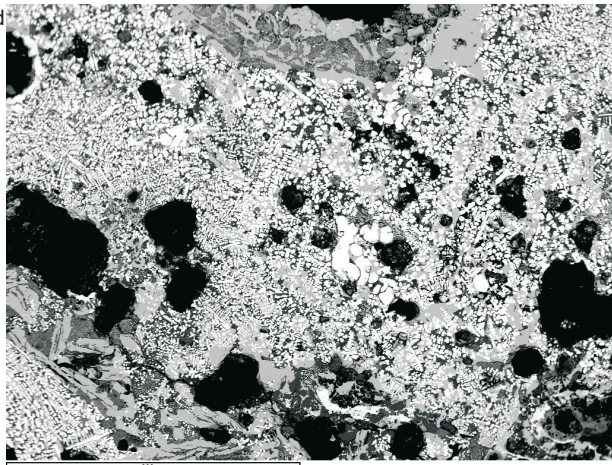
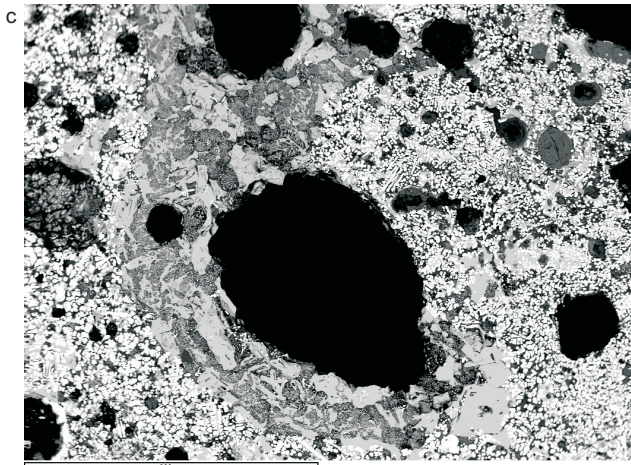
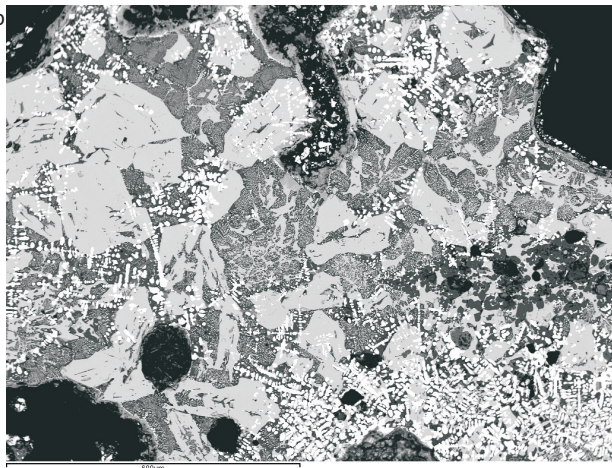
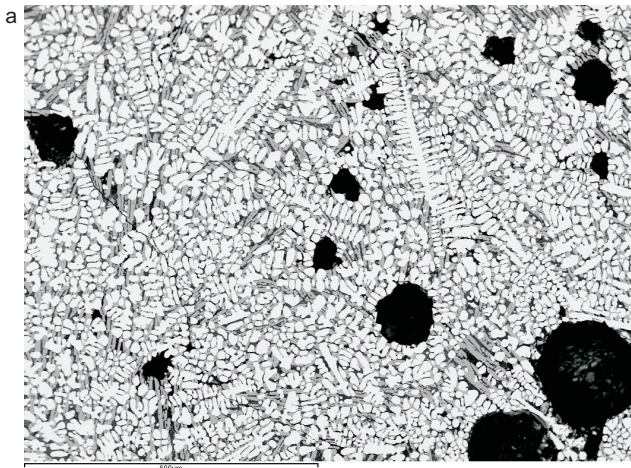


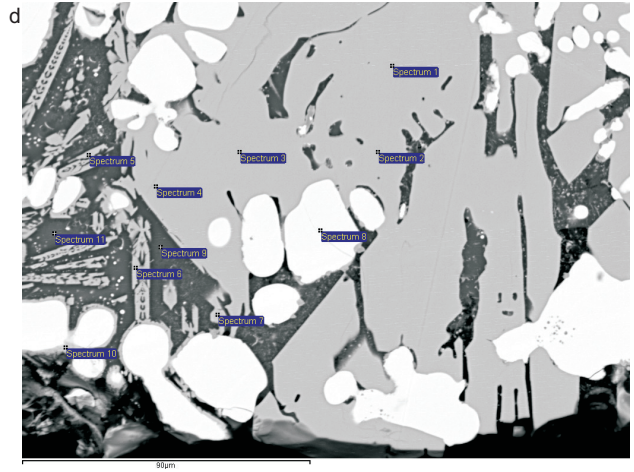
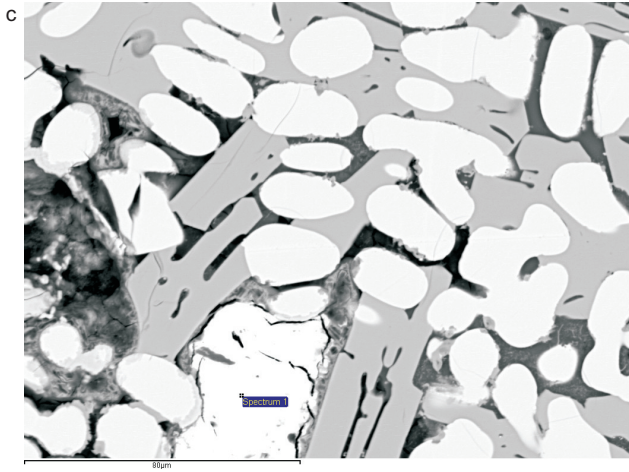
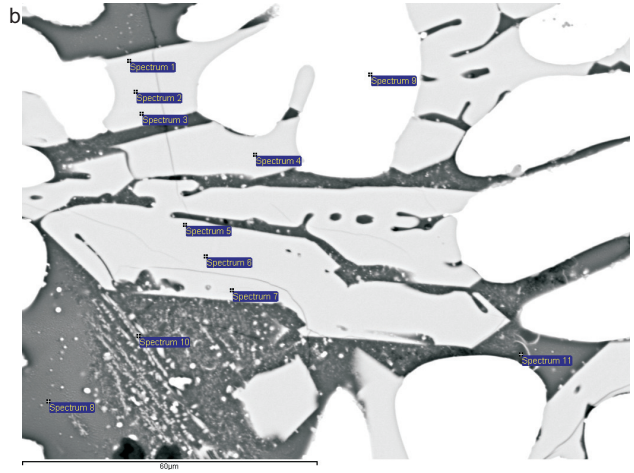
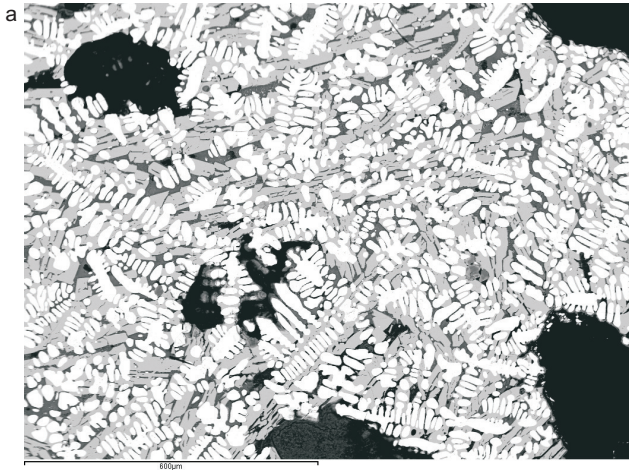


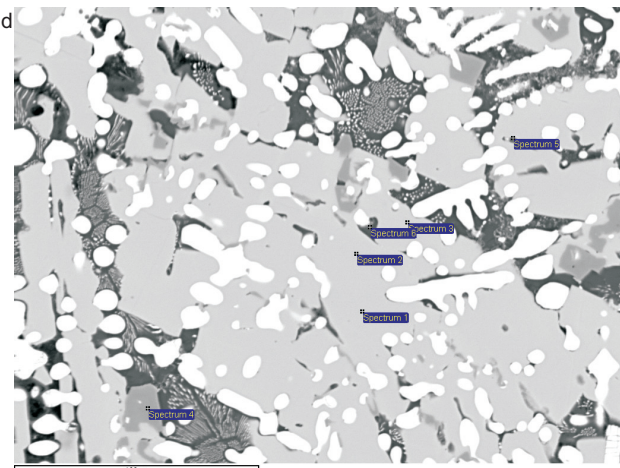
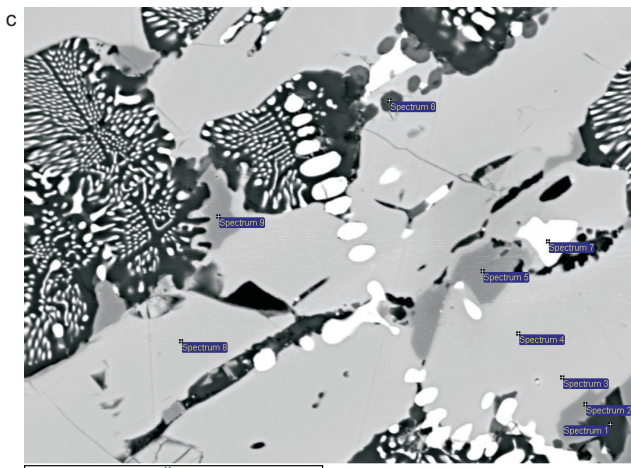
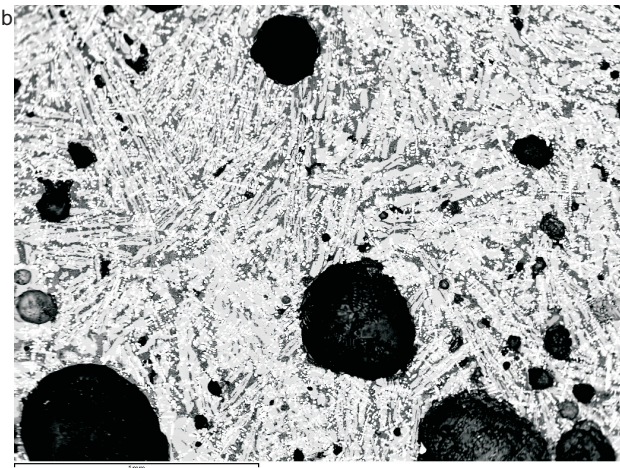
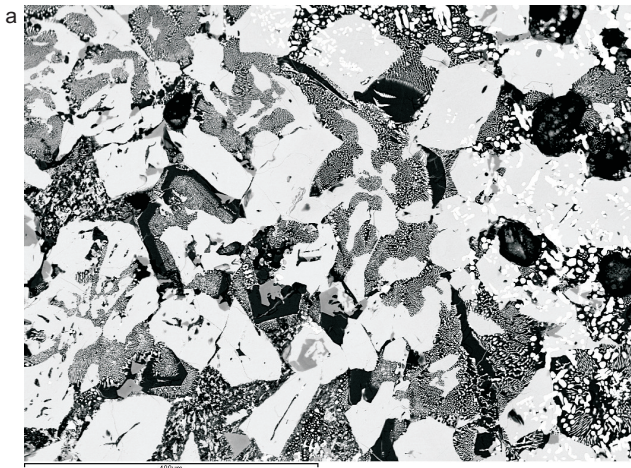


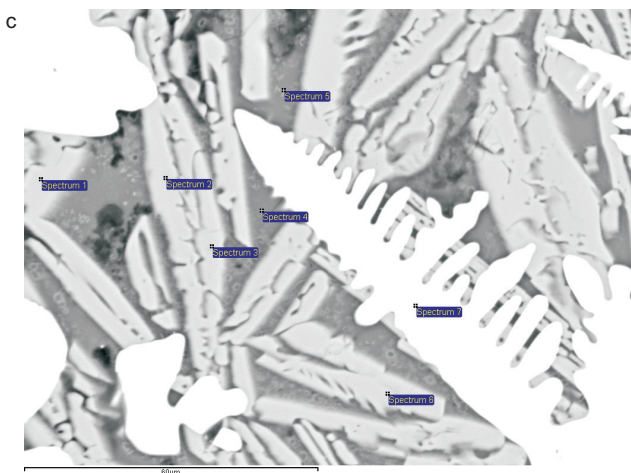
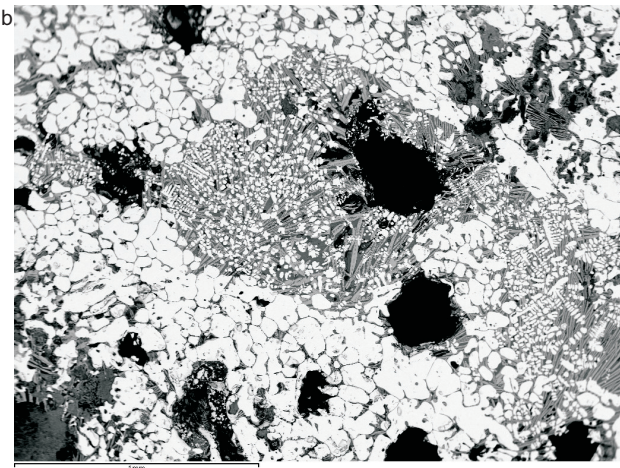
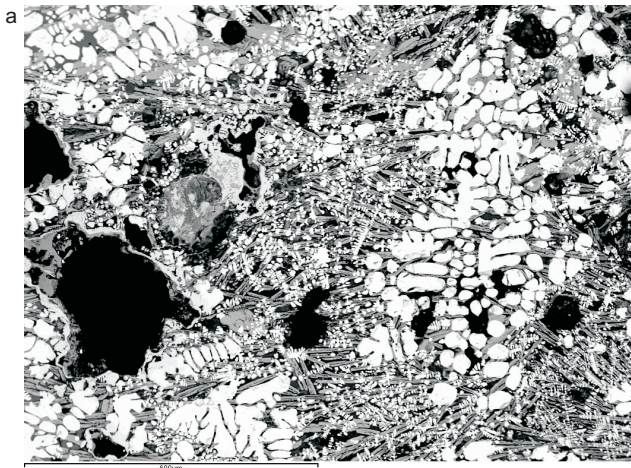


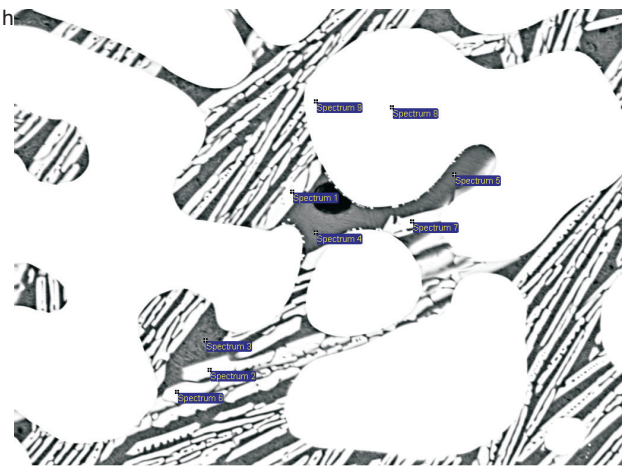
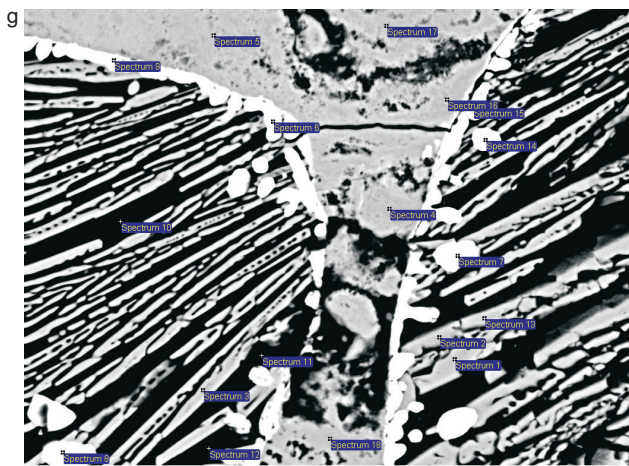
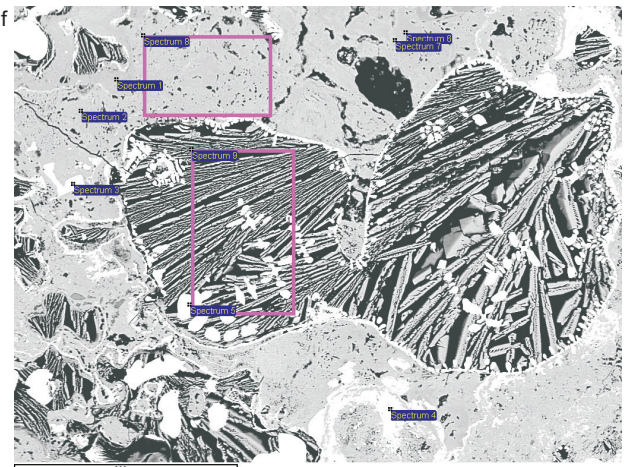
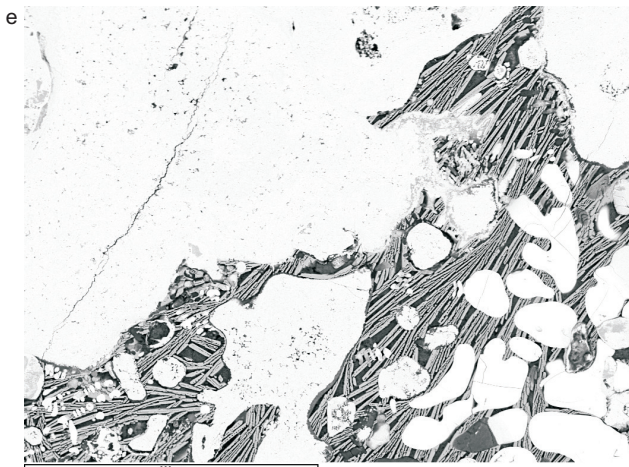
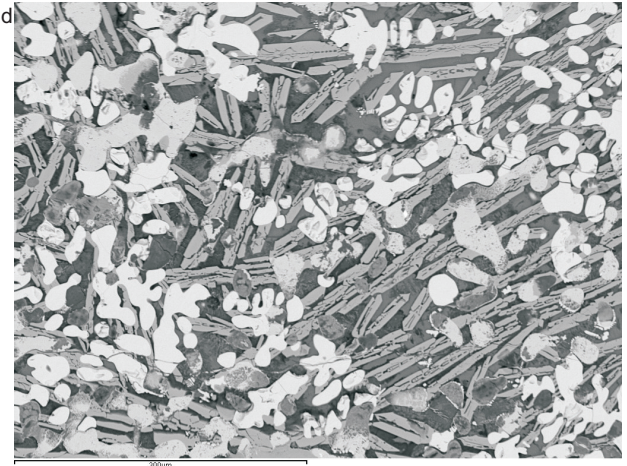
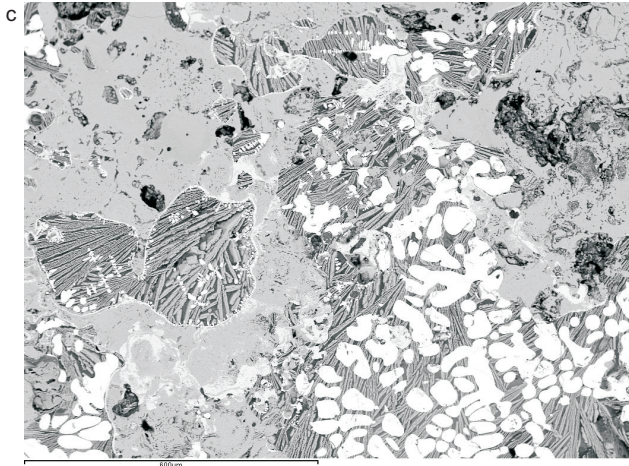
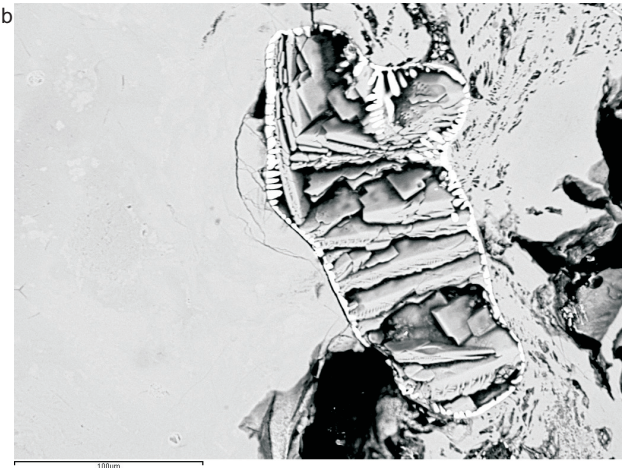
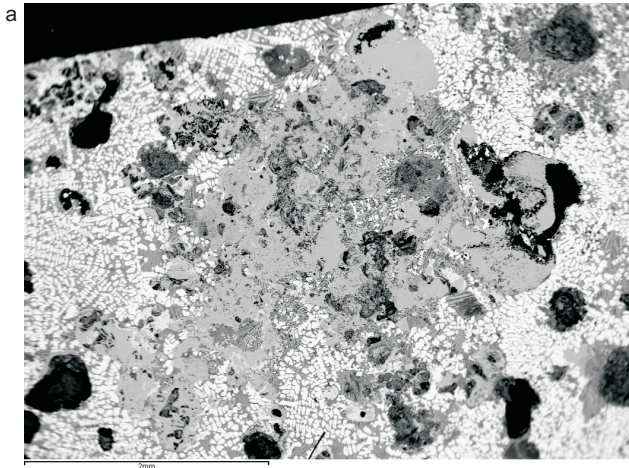


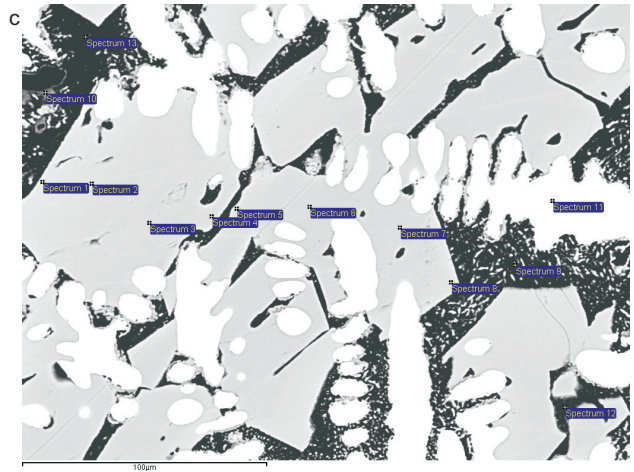
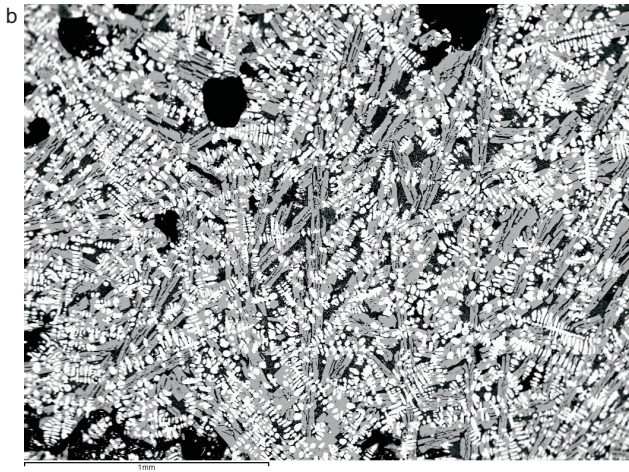
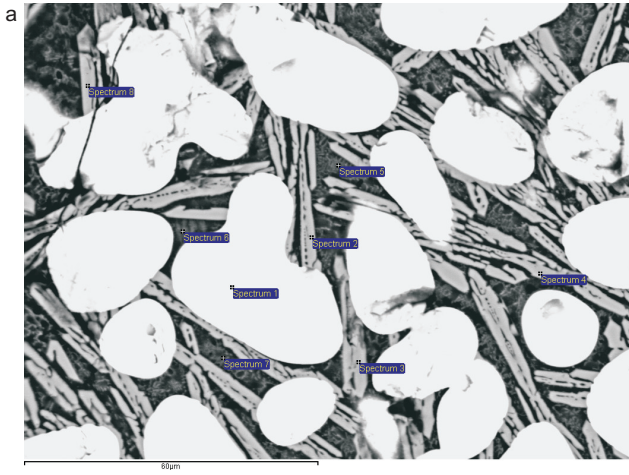


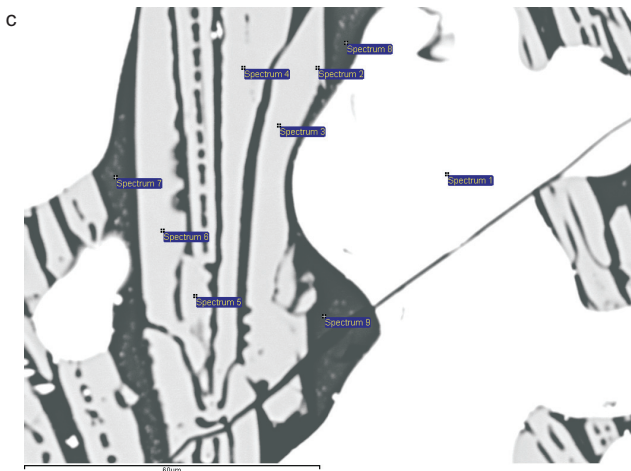
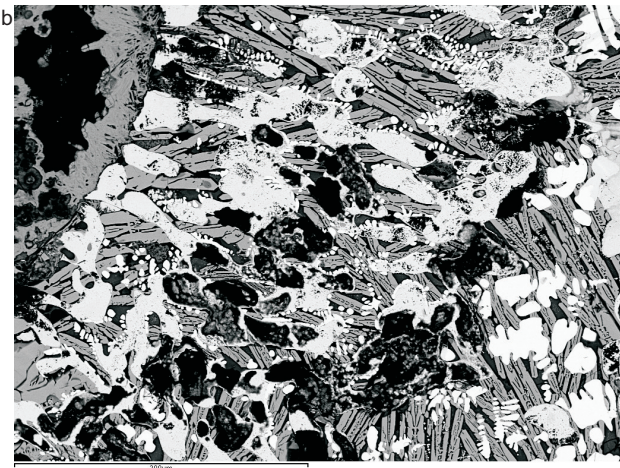
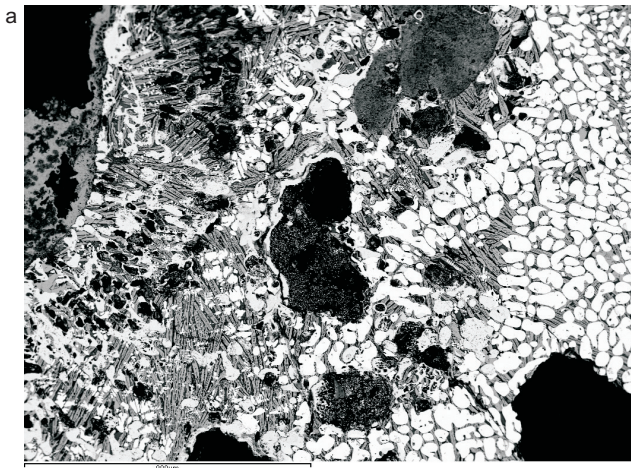


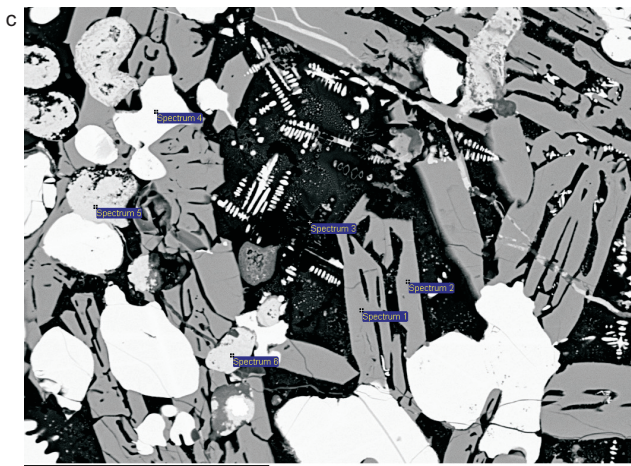
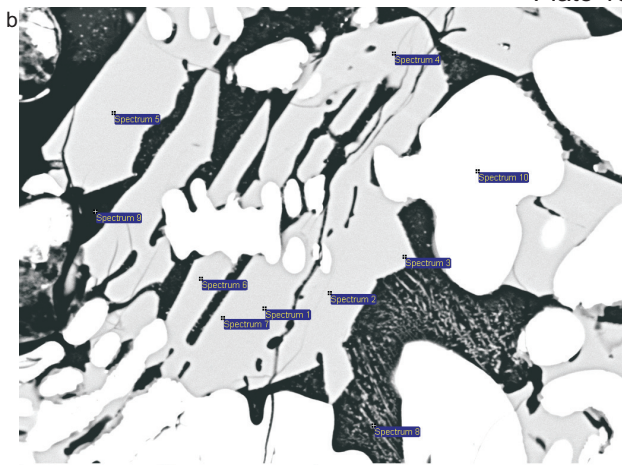
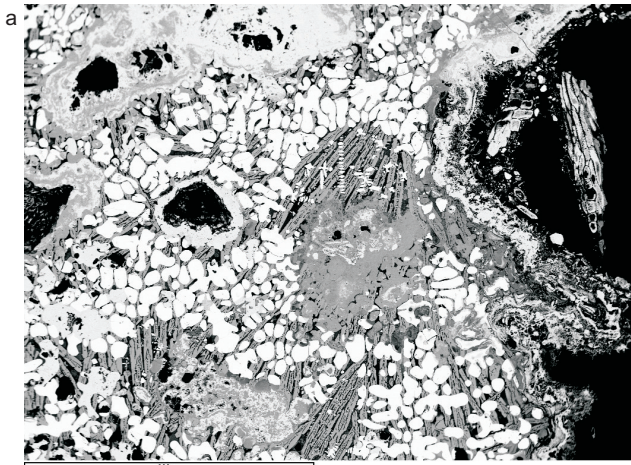


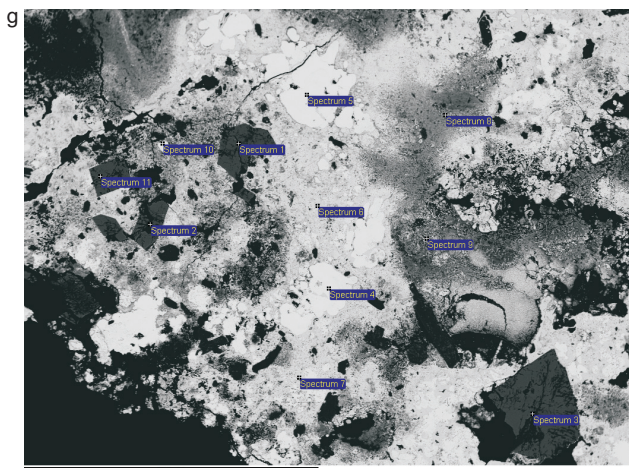
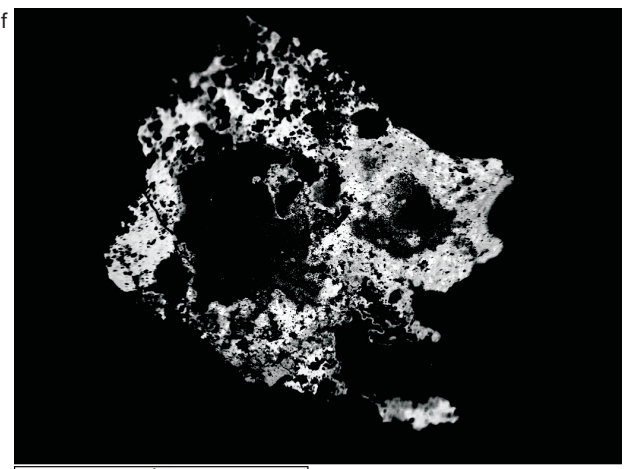
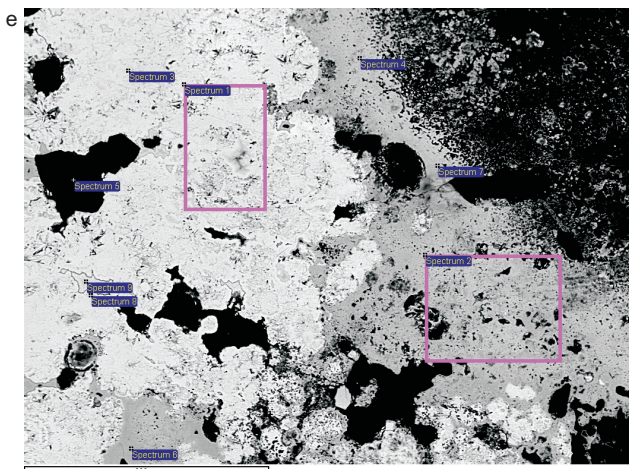
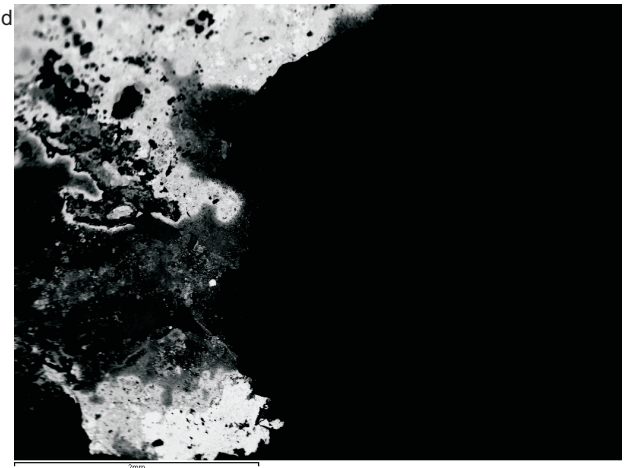
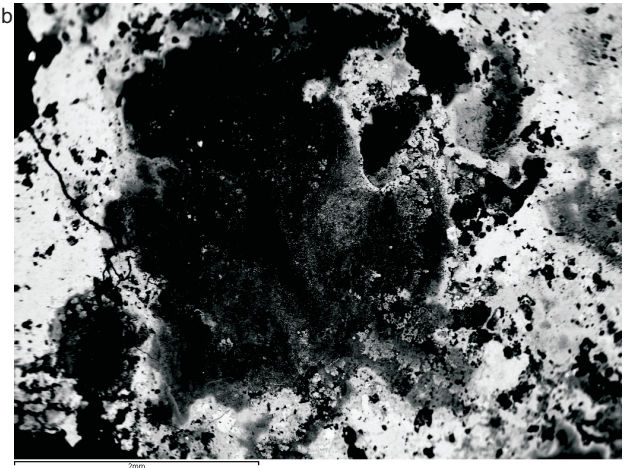
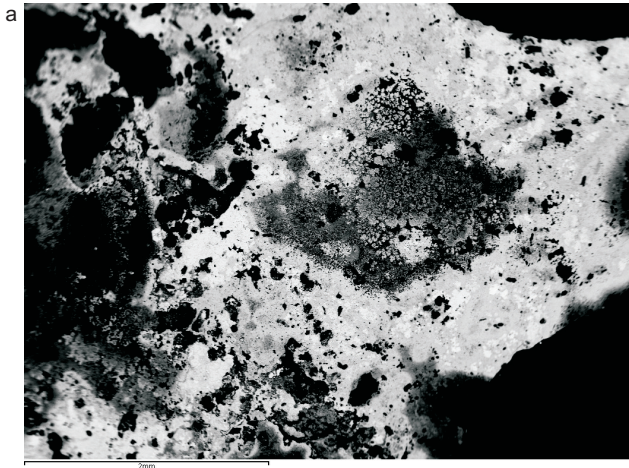












# GeoArch



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