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Archaeometallurgical residues from Coolamurry 7, 04E0323

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Archaeometallurgical residues from Coolamurry 7 (04E0325)

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Abstract

Coolamurry Site 7 produced a wide range of residues from blacksmithing, from three separate zones of the site. The northern area included a pit with rich blacksmithing microresidues, but very little slag. Adjacent to the pit was an area that may have been a dump from the forge, which yielded 10.3kg of slag. The south-western area contained a hearth, similar to that in the northern area, again with a very rich assemblage of smithing microresidues. The south-eastern area was larger and apparently comprised a dump yielding 14.6kg of picked macroscopic slag. Sieving of some of the dump's deposits at 5mm produced a further 10.6 kg of residues, sieving of some of the dump at 3mm and sieving of selected soil samples at 200µm indicated that there was also a very large quantity of blacksmithing microresidues in the dump. The collection of gridded samples was unfortunately not systematic enough reliably to detect systematic variations across the deposit, but the NE zone of the circular deposit seems to have the highest proportion of smithing fines, with the NE extension being gravelly and rich in macroscopic slags. Other features associated with the south-eastern area yielded a further 8.6kg of slag. Later and modern features produced a total of 5.9kg of slag, presumably derived from the earlier deposits.

The slags include over forty examples of smithing hearth cakes (SHCs) for which the original weight is preserved or can be estimated. 95% of the cakes for which an original weight can be measured or estimated weighed less than 1000g, with 83% being less than 500g. The dominance of small SHCs is unusual when compared with other well-studied Irish assemblages from early medieval and later contexts. This difference may indicate a difference in age between this assemblage and the others, or a limited range of task being undertaken on this site, or possibly a cultural difference, since small SHCs are the norm for blacksmithing sites of this age in Britain. The difference in the assemblage style is also marked by the absence of any certain tuyère fragments, which are almost ubiquitous on Irish post-early medieval iron working sites.

Detailed examination of smithing fines showed that microstructure and composition were very variable within the groups of residues classified by morphology. Plate-like particles conformed with the normal concept of oxide-dominated flake hammerscale only at a fine grain size (<3mm); larger particles tended to be dominated by silicate slag. Surprisingly small (<3mm) spheroidal particles were also dominated by iron oxide. Larger (>3mm) particles commonly contained isolated quartz and feldspar, and these are interpreted to be derived from the smithing flux.

Contents

1. Report Structure 1

2. Current draft of report for publication..... 2

3. Appendix 3:Materials for addition to next draft 28

4. Appendix 2: Catalogue..... 34
   Table A summary catalogue..... 35
   Table B gridded samples..... 43
   Table C processing of soil samples 45

5. Appendix 2: Microanalysis 46
   Table D. microanalytical results..... 47
   Plates showing microanalytical sites..... 50

1. Report Structure

Pressure to produce a report for publication has meant that this final report follows, rather than precedes, the publication text.

This report therefore bundles the May 2007 draft of the publication text together with appendices providing post first draft additions, details of the catalogue (after the evaluation report; Young 2006) and of the microanalytical results. Because of the enormous amount of analytical data generated by this project the data tables within this report are intended for viewing electronically, rather than as printed hardcopy.

It is anticipated that the final publication will supersede the version bundled herein.

Archaeometallurgical investigations at Coolamurray Site 7

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1. Introduction
2. Techniques of investigation
3. Previous studies of iron-working microresidues
4. Description of the Coolamurray residues
4.1 Macroscopic slags
4.1.1 General description
4.1.2 Details of microstructure
4.1.3 Details of chemical composition
4.2 Microresidues
4.2.1 General description
4.2.2 Details of microstructure
4.2.2a Spheroidal particles
4.2.2b Tabular particles
4.2.2c Other particles
4.2.3 Details of chemical composition
5. Description of the iron-working features
6. Interpretation of the smithing
7. Discussion of the residues
8. Conclusions
9. References

Plate and Figure captions

Table 1: Chemical analyses (Table 1a major elements by XRF, Tables 1b, 1c trace elements by ICP-MS).
Table 2: Major elements recast and normalised on iron-free basis.
Table 3: Comparison of Coolamurray SHC assemblage with other Irish early medieval assemblages.
Table 4: Comparison of Coolamurray SHC assemblage with some early British blacksmithing assemblages
Table 5: Variation in the proportions of iron oxide-dominated textures in hollow and vesicular spheroidal particles.

1. Introduction

The background and details of the archaeological investigations at Coolamurray Site 7 are described fully elsewhere in this volume (McCullough...); the purpose of this contribution is to describe and to discuss in more detail the archaeometallurgical residues and the light they shed on the nature of the metalworking being undertaken here in the 10th century. Despite widespread evidence for iron-production and iron- working in early medieval Ireland, studies providing detailed understanding of the nature of the techniques and technology employed are only in their infancy. The abundance of new data derived from sites excavated as part of the National Roads Programme is, however, driving the study of early Irish iron-working forward at a rapid pace. Coolamurray Site 7 is only a small site, which produced just a small amount of archaeometallurgical residues (less than 40kg of slag), but its value lies in the close association of the residues with structural evidence for metalworking, and in the relatively simple stratigraphic distribution of the residues. The site produced evidence for three separate areas of iron-working, each probably the remains of a relatively short-lived smithing hearth. This relatively simple stratigraphic context allows the assemblage to investigated in detail, in an attempt to tease-out aspects of the technology and techniques employed in a 10th century smithy, in a way which is rarely possible on larger sites. In particular, there was the exciting possibility of studying the large quantity of micro-residues associated with the hearths, with a reasonable degree of certainty that they can be associated with the processes indicate by the macroscopic slag assemblage. Micro-residues are currently a rather neglected aspect of ferrous archaeometallurgy, and they have not yet been studied in any detail from a site which employed ceramic tuyères.

2. Techniques of investigation

All materials were examined visually with a low powered binocular microscope as part of the evaluation (Young 2006a). The evaluation identified the assemblage as having been produced during iron working (smithing) and noted the potential significance of the abundant fine-grained residues on this site. A follow-up programme of analysis was designed to investigate the fines in more detail. Microresidue material was selected for detailed examination from the

slag dump overlying Hearth C (c56) and from a fill of Hearth A (c14). Representative macroscopic slags from the slag dump overlying Hearth C (c56) were also examined.

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.

(*insert Table 1*)

Sample details are given in Table 1. For the microresidues, chemical analysis was undertaken on bulk samples containing multiple particles, in order to achieve the weight of sample required. This procedure is not ideal, for it may hide the variability of the particles and also may lead to uncertainty as to whether the subsample imaged on the SEM and that employed for the chemical analysis were both similar to each and representative of the original sample. However, even with this approach, insufficient material was available to provide chemical analysis if the smaller classes of spheroidal particle.

3. Previous studies of iron-working microresidues

The general nature of microresidues from iron smithing has been established for a considerable time, with widespread recognition of two broad categories of hammerscale – flake and spheroidal. However, there has been little detailed analysis of hammerscale with which to compare the Coolamurray results.

In a seminal article Allen (1986) attempted detailed morphological classification of fines from Romano-British smithing at Awre (Gloucestershire, England). This work ascribed the microresidues to the process of bloomsmithing: his model appears to have been driven by the idea that the microresidues, particularly the spheroidal morphologies, were produced by slag expelled from the iron, which must therefore have been rich in slag inclusions and accordingly the expulsion process must belong in bloom refining, because a bloom contains abundant slag which is partially removed during refining. There appears, however, to be little intrinsic evidence to link the Awre residues to bloomsmithing rather than blacksmithing.

The Allen (1986) morphological classification identified the following categories: air-chilled spatter (subdivided into spheroidal air chilled spatter, smooth granules, rough granules, polyspheres and pear-shaped grains), surface-chilled spatter (subdivided into spheroidal grains, bun-like grains and biscuit-like grains), bloom scale (subdivided into flat bloom scale, angled bloom scale and striated bloom scale) and contact scale (subdivided into striated face + plane moulded surface, two striated faces and oval –semicircular striated scale). Although Allen's study was not mineralogical, he comments that the air-chilled and surface chilled spatter (equivalent to the broader spheroidal hammerscale of this paper) were "fayalitic, with silica contents similar to or somewhat less than the associated smelting slags" (which was 16-36 wt%, average 24%, according to the data presented by Allen 1988) and the bloom scale and contact scale (equivalent to the flake hammerscale of this paper) were "almost pure iron oxide (chiefly or wholly magnetite)".

19th century blacksmithing fines from Bixby blacksmith's shop (Barre Four Corners, Massachusetts, USA) were examined by Unglik (1991), who examined the microstructure and mineralogy of a variety of materials. He identified two main morphologies (globules and plates) with three recurrent microstructures, referred to granular, dendritic and fused microstructures respectively. His "smithing globules" (0.1 to 4.2mm diameter) and "smithing scales" are described as both being iron-rich (approximately 60 wt% iron, equivalent to 80 wt% calculated as FeO). Two thirds of the globules were hollow. Larger globules were less perfectly spheroidal than smaller ones. Unglik's study remains the only significant published account of hammerscale composition.

Previous work has therefore broadly drawn a picture of flake hammerscale being dominated by iron oxides and spheroidal hammerscale, typically with a slightly lower iron content, being the result of slag droplets freezing in flight after expulsion from the workpiece during hammering, particularly during hammer welding. The details of chemical composition, mineralogy and microstructure remain, however, poorly known.

4. Description of the Coolamurray residues

4.1 Macroscopic slags

4.1.1 General description

The macroscopic slag collection has a total weight of 38.2kg, of which the largest part comprises smithing hearth cakes (SHCs; sometimes referred to as *smithing hearth bottoms*, SHBs, or *plano-convex bottoms*, PCBs). SHCs are formed below the hot-zone of the smith's hearth from slag generated by the reaction of iron lost from the workpiece, melted ceramic from the area around and above the point of entry of the air blast into the hearth (the blowhole or

tuyère) and any flux used by the smith to aid fire-welding. The SHCs have a slightly concavo -convex shape in general, although a plano-convex shape is seen in some specimens. Many of the SHCs show some evidence for having been deformed on extraction, with twisting the most common effect. This deformation is the result of the smith cleaning the hearth between periods of work (perhaps daily, but possibly more frequently) and removing the slag when not completely solidified.

28 SHCs weighing 7.0kg are complete, with a further 14.7kg of certain SHC fragments. The original size of 41 SHCs can be measured or estimated with reasonable certainty. These SHCs have an original mean weight of 386g (range 62g – 2588g), with 83% of the SHCs weighing less than 500g (Figure 1). The SHCs are dominantly close to circular in plan. An SHC of average weight would have a diameter of approximately 90mm and thickness of 35-40mm. Examples of SHCs of these typical dimensions were selected for further detailed analysis.

(insert Figure 1)

In addition to certain SHC material, the macroscopic slag collection contains a further 13.1kg of slags which are indeterminate, but in practice much of this material is likely to comprise small fragments of SHCs. Lining-dominated slags make up a further 3kg of the assemblage, together with just 0.4kg of fired clay lining material.

4.1.2 Details of microstructure

Microstructural details of the SHCs were examined in two specimens (Mon16 and Mon17), both from the slag deposit overlying Hearth C (c56).

(insert Plate 1)

Mon 16 shows a fairly homogeneous microstructure (Plate 1, a-i). The texture includes variably sized, but moderately large (1 x 0.2mm), elongate fayalite crystals, with small (<100µm) intergranular crystals of dendritic form with fayalite (iron olivine; end member composition Fe_2SiO_4) overlying wustite (FeO). There is also an interstitial glass. The slag shows local variants of this texture associated with the infill of large (<5mm) early vesicles, with the infill distinguished from the body of the slag largely on the basis of fayalite crystal size.

The larger crystals of fayalite are typically close to the composition of the end member, but locally the cores show up to 6% forsterite (magnesium olivine; Mg_2SiO_4) and the margins are locally relatively Ca-rich, with up to 7% Ca-substitution. The smaller dendritic olivine is generally close to fayalite (forsterite < 2%), with 1-4% Ca-substitution. In areas of the slag with small open vesicles, the slag adjacent to the vesicles shows a more complex paragenesis involving leucite (a potassium aluminium silicate; $KAlSi_2O_6$), hercynite (an iron-aluminium spinel; $FeAl_2O_4$) and rhönite (an aenigmatite group mineral; typically $Ca_2[Mg,Fe^{2+},Fe^{3+},Ti]_6[Si,Al]_6O_{20}$), as well as wustite, fayalite and glass. The vesicles are typically rimmed with slag dominated by a leucite-wustite or leucite-wustite-fayalite syntectic. These complex syntectites are overlain by zones of larger leucite, hercynite and rhönite. These leucite-dominated zones are generally about 100µm wide. In other areas a wider (up to 1mm) zone of leucite-bearing material around the vesicles is marked by a variant of the standard texture in which the second generation of fayalite is not, or is not only, a fayalite-wustite syntectite, but is a fayalite-leucite syntectite. In both these variants of the textures associated with vesicles the latest crystalline phases (fayalite, hercynite and rhönite) are associated with a particularly calcic glass (13-16wt% CaO, but less than 2.5wt% K_2O). The rhönite is very close in composition to that described by Serneels (1993) from smelting slags from Montcherand, Switzerland, but slightly more Ti-rich, and also to examples from high (>5%) CaO tapped smelting slags from Laxton, Northamptonshire, UK (author's unpublished data). It is also broadly similar to unpublished analyses of smelting slags from the author's experiments (although slightly less iron-rich). This may be the first record of rhönite from a low-Ca slag, or indeed from a smithing slag.

Mon 17 has a microstructure comprising two distinct textures with an abrupt contact (Plate 1, l).

The lower part of the specimen is dominated by elongate (up to 1.2 x 0.2mm) fayalite laths (initially fayalite-wustite syntectite, overlain by a coarse fayalite-hercynite syntectite), mainly oriented normally to the base of the cake in the basal 6mm, but parallel to the base between 6 and 9mm above it (Plate 1, j-k). The early-formed fayalite is relatively magnesian (Fo_9Fa_{91}) with less than 1% Ca-substitution. The later olivine in association with hercynite is Fo_1Fa_{99} with 2% Ca-substitution. There is an interstitial glass, bearing a low volume of wustite blebs and dendrites, that may constitute the initial crystalline phases.

The upper part of the specimen (Plate 1, m-o) has a microstructure dominated by sheaves of very fine carious olivine (Fo_7Fa_{93}) laths (up to 600 x 30µm), associated with, and probably nucleated upon, dense concentrations of carious wustite, which probably represent partially reacted hammerscale. The glass also contains abundant grains of quartz and feldspar, of up to 800µm diameter, showing varying degrees of reaction and melting.

(insert Table 2)

(insert Table 3)

4.1.3 Details of chemical composition

The two sampled SHCs (Mon16 and Mon17) have rather similar chemical compositions (Table 1). They have a lower total iron content (58.9% and 60.4% expressed as FeO) than all the microresidues except for the largest spheroidal particles from c56, with which they share a similar major element composition.

They are moderately aluminous (5.2% and 6.0%) with silica:alumina ratios of 5.6 and 4.4. The elements expected to be associated strongly with fuel ash (Ca, K, P) are only moderately elevated in the SHCs compared with the microresidues, and of these calcium and phosphorus are not particularly elevated compared with the microresidues on an "iron-free" basis.

(insert Table 3)

4.2 Microresidues

4.2.1 General description
The microresidues and associated materials were classified on overall morphology:

Spheroidal particles

Spheroidal particles (Plate 2) range up to about 7mm in diameter. The smaller particles are frequently shiny, with a metallic lustre and often an almost perfectly spheroidal shape. Larger particles may be darker in colour and be less spheroidal. The smaller particles correspond to those commonly described as spheroidal hammerscale, with the larger ones probably being dominated by slag droplets rather than true hammerscale.

Tabular particles

Tabular particles (Plate 3) are subdivided on the basis of overall form, lustre and regularity:

- ***Flake hammerscale*** has a fine, even, thin, tabular morphology, with both surfaces essentially planar. The thickness of the flake hammerscale ranges up to 200µm in thickness. One surface of the flake hammerscale is usually very smooth and reflective. (e.g. Plate 3 A)
- ***Flats*** are tabular particles with one smooth surface, one surface which is irregular and vesicular), which have an irregular thickness (but typically thicker than flake hammerscale and ranging up to several mm) and which typically lack the high reflectivity of flake hammerscale. (e.g. Plate 3 C, D, I; Plate 4 I, L))
- ***Blisters*** are somewhat similar to flats, but have an irregularly concavo-convex form. (e.g. Plate 4 J, K)

Other particles

Other particles (Plate 4) found within the fine residues are not forms suggestive of an origin as hammerscale, but show a closer relationship to the macroscopic slags:

- ***Prills*** are flowed slags and may include both forms suggestive of vertical descent in the hearth and forms suggestive of horizontal flows. They are typically 2-5mm in diameter. (e.g. Plate 4 F)
- ***Irregular slags*** are small particles of slag which are vesicular, irregularly shaped, dense and dull in appearance. (e.g. Plate 4 D, E)
- ***Dull slag blebs*** are rounded blebs of dense slag with a dull surface. They are probably related to the prills and represent drips of slag that have cooled within the ashy hearth bed. (e.g. Plate 4 A-C)

4.2 .2 Details of microstructure

4.2.2a Spheroidal particles

The spheroidal particles were examined in four samples from c14 and one from c56. These were picked to be representative of material <1mm, 1-3mm, 3-5mm and >5mm in diameter. The spheroidal particles show a high degree of variability of internal structure (Plate 2).

(insert Plate 2)

(insert Table 4)

Spheroidal hammerscale is often described as being commonly hollow. In the present material the presence of a large central cavity (as opposed to a distributed vesicularity) was observed in 6 of 15 particles in the <1mm fraction, 8 of 18 in the 1-3mm fraction, 3 of 7 in the 3-5mm fraction and neither of the 2 particles in the >5mm fraction (Table 4).

The microstructures present in particles can be divided into several distinct classes. Single particles may contain zones of more than one microstructural class:

S1 (Plate 2 A, B, D, F): densely-packed angular crystals of wustite, locally oxidised to magnetite, and locally with thin films of glass on grain boundaries. This texture is related to the typical texture seen in flake hammerscale.

S2 (Plate 2 C, D, F, G, K, L, M, N): closely-packed rounded blebs and wustite "pseudo-dendrites" (structures with a few rounded arms and a rather sinuous form, lacking the geometric patterns of well-developed dendrites), locally altered to magnetite, in a groundmass of glass and/or olivine.

S3: quench textures, richer in silicate. Oxide phases are typically present as a thin peripheral crust and internally as dendrites, with olivine occurring as elongate carious quench-textured crystals. Although there is continuous variation across a broad compositional range, several distinct variations of this texture were observed, ranging from dendritic textures almost entirely of wustite (S3a: Plate 2 H, L, N) to those with appreciable to dominant silicates (S3b: Plate 2 M, N, P, Q, R, S). S3a grains almost entirely comprise wustite dendrites, which may be sufficiently dense to preclude interpenetration of the dendrites leading to a marked domain texture, in which the limits of individual dendritic structures are well-marked. The wustite dendrites may develop from small patches of rounded blebs or "pseudo-dendrites" of a type similar to those seen in texture S2. This texture is seen both on examples in which wustite is the dominant mineral and in examples where the early wustite dendrites are subordinate to the later olivine. Domain structures may also be developed in sheaves of fine fayalite dendrites in the S3b texture (Plate 2 R,S)

S4 (Plate 2 I,J): textures with granular to dendritic magnetite with a characteristic angular form, forming dendrites with angular expanded tips to the arms. This texture is commonly encountered in a thin zone just inside the oxide crust to the sphere, but in some examples may occupy part or all of the main body of the particle. The interstitial material may be crystalline olivine or glass. In several cases the magnetite is seen to form skeletal crystals made of plates, rather than dendrites. This texture is interpreted as being indicative of primary magnetite.

S5 (Plate 2 O,T): a low-iron glass bearing small spheroids of metallic iron (seen in only a single spheroid).

All particles contain a component of iron oxides. Only one single particle was observed in which the S1 texture was dominant, and this was a very thin-walled irregular hollow particle. Other particles contained a component of S1 material, typically as small angular fragments (probably flake hammerscale) on the periphery of the grain. Most iron-rich particles contained an S2 blebby pseudo-dendritic texture (9 examples) or a dendritic S3 texture (13 examples). The dendritic iron oxides have grown from larger rounded blebby wustite patches in many cases, suggesting quenching from liquids already containing some solid wustite. Particles with a lower iron content have a thin oxide crust, which serves to nucleate inward-growing oxide dendrites and a variable proportion of wustite in the silicate rich fill of the spheroid.

Alteration of wustite to more highly oxidised oxides, probably mainly magnetite, was observed in almost all particles, particularly as an outside-in alteration of the crust. The occurrence of the S4 texture with primary magnetite dendrites/skeletal crystals was limited to a narrow zone inside the crust in most cases, but a more general growth of magnetite dendrites was observed in 2 particles (both silicate-dominated).

The two largest "spheroidal" particles examined were, in fact, not particularly spheroidal. In the plane of the cut sections they have long axes of 6.6 and 6.8mm and short axes of 4.5 and 5.8mm. They show well-developed elongate fayalite crystals, superimposed on a network of fine wustite dendrites (Plate 2 P, Q). The particles are strongly vesicular, with variation in olivine distribution also revealing the outlines of former vesicles.

4.2.2b Tabular particles

Plate-like particles were examined in four samples from c14 (flake hammerscale >200□m sieved from a bulk sample, flake hammerscale from excavator's >3mm sample, flats from >3mm sample, flats from >5mm sample) together with two samples from c56 (flake hammerscale, blisters). Microscopic examination of the material did not entirely bear-out the classification based on optical inspection. Five distinct textures were evident (T1 to T5). Individual particles sometime display more than one texture and the distribution of the textures cross-cuts the classification of particles on external morphology:

(insert Plate 3)

T1 (Plate 3 A, B): what has been referred to a "scale" texture; angular crystals of wustite (with or without alteration to magnetite). Typically the grain boundaries become more prominent away from the basal surface, with the upper part of the plate showing larger quantities of glass in the intergranular spaces. This texture may grade into texture T2. Individual pieces of flake hammerscale may show multiple cycles of this textural progression (plate..).

T2 (Plate 3 B, C, D): dominated by densely-packed wustite (with or without secondary alteration to magnetite). The wustite grains appear as rounded blebs, which may be parts of more complex rounded pseudo-dendritic grains. The interstitial space is occupied by glass, or by glass with olivine.

T3 (Plate 3 E, F, G, H, I): early dendritic wustite followed by elongate olivine with interstitial glass. The proportion of the oxide material varies widely in this classic "slag" texture. Interesting variants occur in which the fayalite is cored by curved wustite crystals. Some examples show a fayalite-wustite syntectic. These slag textures frequently overlie a thin basal oxide crust with a texture related to T1. The slag immediately in contact with the oxide crust may be extremely fine grained indeed and the dendritic phases may radiate out from it.

T4 (Plate 3 I): angular fragments of material with a T1 or T2 texture embedded in a fine-grained groundmass, probably dominated by olivine. This texture normally occurs as distinct clasts near the base of the flats.

T5 (Plate 3 J): a granular texture of angular olivine and oxide grains. This does not appear to be a crystallisation texture, so may be the result of disruption of a partially solidified slag film by hammering.

In fine-grained (<3mm) material classified on visual appearance as flake hammerscale, the T1 texture was almost ubiquitous, with just a few pieces showing a tendency towards T2 in the upper part of their section. The >3mm fraction was divided visually into material classifiable as flake hammerscale and flats in c14, with blisters also present in c56. The >3mm "flake hammerscale" examined from c14 comprised grains with T1/T2 (1 example) and T3 textures (3 examples). The >3mm "flats" material from c14 comprised 1 particle with a T5 texture, three particles with T1 and T2 textures and one which includes T1 and T2 textures as well as localised areas with a T3 texture. The >3mm blistered slag plates from c56 (5 examples) all showed variants of the T3 texture.

The coarsest tabular material, comprising >5mm flats from c14 (7 examples) are all dominated by T3 texture. The texture in all cases is gradational from a basal layer with a thin oxide crust, with progressively coarsening olivine-dominated textures towards the outer part of plate. The materials are vesicular and often the vesicles are tubular, leading out to the outer margin which thus has an invaginated morphology. In three of the examples the lower part of the section bears large "clasts" of T4 texture. One example shows inclusions of sand-grade material (400-800μm diameter) mainly of quartz, but possibly formerly including mica and feldspar on the basis of relicts of grains.

4.2.2c Other Particles

Investigation of various small fragments of slag material from the microresidue assemblages showed a prill of slightly iron-enriched melted clay (Plate 4 F), an amorphous slag piece rich in charcoal debris and iron oxides (Plate 4 D-E) and a bleb of dull slag with a microstructure similar to that of the largest spheroidal particles and of the SHCs (Plate 4 A-C). These particles indicate the diversity of small slag bodies within the hearth, that are not incorporated within the SHC, but which, none-the-less, share textural and compositional similarities with the main slag accumulation.

4.2.3 Details of chemical composition

Chemical analysis of the residues shows a range of composition dominated by variation in the iron content of the materials (59-89% when expressed at wt% FeO). The materials with iron contents low in this range (59-71 wt% FeO) are the samples of SHCs, the flats, the samples of other minor hearth slag types and the largest spheroidal particles. Smaller spheroidal particles have much higher iron contents (80-82 wt% FeO), but the highest iron contents are to be found in the flake hammerscale (88-90 wt%). Most of the remainder of the analyses is provided by silica and alumina. The silica:alumina wt% ratio lies in the range of 4.0-5.6 for most of the residues, but smaller spheroidal particles have a much higher ratio (that for the bulk sample of 3-5mm spheroids from c14 was 9.2).

Trace elements are typically present in rather low concentrations. The rare earth elements (REEs) show an upper-crust normalised profile with slight light REE depletion. The only exception to this was the small reduce-fired clay fragment (from c56) which has slight relative LREE enrichment. The significance of this observation is to suggest that the fired clay debris in c56 is representative of the source of silicate material for the slag-forming process (i.e. this material did not contribute to the slag through melting, and it is therefore unlikely to have been derived from hearth ceramics near the hearth hot-zone).

In order to investigate the chemical trends of the silicate component of the residues further, the analyses have been recast on a normalised, iron-free basis. Inspection of these figures suggests that the silicate component does not have a single origin. This is demonstrated by the graph of the silica:alumina ratio plotted against the sum of wt% CaO and P_2O_5. This graph demonstrates that the unusually high silica:alumina ratio of the smaller spheroids is accompanied by a low content of calcium and phosphorus. In contrast, the residues within the more normal silica:alumina ratio show a progressive enrichment of calcium and phosphorus from the straightforward hearth slags (SHCs, prills and large spheroids), through flake hammerscale with the highest degrees of calcium and phosphorous enrichment in the minor hearth slags and the flats/blisters.

These observations suggest that either there were at least two sources of silicate material, with different silica:alumina ratios, or that the smaller spheroids have evolved through a fractionation process. It appears much more likely that there were at least two sources of the silicate fraction. The smaller spheroids show a higher silica:alumina ratio than the other residues, and this would be compatible with derivation of the silicate from a sand smithing flux. In the other residues, although the sand may also be a component, the silicate input was dominated by other sources, richer in alumina. The likely main input would be the hearth ceramics (wall, tuyère), although the charcoal fuel would have had a small silicate component (2–6 wt% SiO2 for 7 charcoal ash samples from the author's unpublished data) and there would also have been a minor input from the slag inclusions within the workpiece. The variable calcium content of this group of residues is suggestive of a variable uptake of the fuel ash; a material normally high in calcium (48-65 wt% CaO for the samples from the author's unpublished data).

5. Description of the iron-working features

As described by McCullough elsewhere in this volume, the site produced three features which were probably hearths: Hearth A, 1.0 x 0.9 x 0.2m, in the northern metalworking area (c27), Hearth B, 0.92 x 0.82 x 0.30m, in the southwestern metalworking area (c59) and Hearth C, 1.20 x 0.80m, in the southeastern metalworking area (c100). The three features were not associated with features which indicated with any certainty that they lay within structures, but some evidence from the area of Hearth C suggested that this may have been the case (see McCullough...). Hearths A and B both had a "stake" hole 0.5m to their northwest, described as being filled with "brown gritty sand" and being 0.14m in diameter and 0.03m deep. The similarity of these two features suggests that they are an integral part of the metalworking facilities. A "stake" hole close to the hearth is suggestive of a feature associated with the bellows, a feature associated with the anvil or a feature related to the cooling of tools. Of these possibilities, a relationship with the anvil seems most likely. Anvils are typically of iron mounted on a wooden block; 0.14m is small for an anvil block, but not impossibly so.

Hearth B had a series of at least 8 stake holes arranged around its sides. These are likely to be supports for a hearth wall, but the nature of the wall construction remains uncertain. This hearth also has other nearby stake- or post-holes, but it is unclear whether these are directly associated with the hearth.

6. Interpretation of the smithing

The Coolamurray slag assemblage bears close comparison with those from other minor sites of the same period, but is strongly contrasting with assemblages from larger metalworking sites.

(*Insert Table 5*)

Assemblages from Carrigoran, Co. Clare and a site on the Navan Inner Relief Road, Co. Meath (both from the author's unpublished data) are, in particular, similar to the present assemblage in overall composition and character (Table 5). These assemblages share a profile of small, conventional smithing hearth cakes, almost all less than 1000g each, and mainly less than 500g, with just a few larger cakes ranging up to several kg.

This group of assemblages is distinct from those of some sites producing particularly large slag assemblages (the Clonmacnoise water-treatment plant, Young 2005b, Clonfad 3, Young 2006b, and Woodstown 6, Young 2006e) of broadly similar age. These large assemblages show much larger modal, mean and maximum SHC size. The SHCs from these sites are still under investigation, but it is hypothesised that they indicate residues at least partially derived from bloomsmithing, the refining and compaction of the raw bloom down to finished iron. In contrast (Table 6) the distribution of SHC size in the Coolamurray assemblage compares more favourably with assemblages from other areas that are attributed to blacksmithing.

(*Insert Table 6*)

As well as a similarity in archaeometallurgical residues, Coolamurray shares with the Carrigoran and Navan sites a strong similarity in the morphology of the features interpreted as possible smithing hearths. The Carrigoran slag assemblage includes material indicative of iron smelting, and at least one feature (C767) 0.5m in diameter may the base of a slag-pit shaft smelting furnace, however, an adjacent cut feature (C768) is an elongate pit, approximately 1.15m x 0.77m, which may have been a smithing hearth, whereas a third cut feature (C887), 0.77m in diameter and 0.20m deep, contained an assemblage of mixed smelting and smithing residues. At Navan, C62 was a cut feature, probably a hearth, 0.78m diameter by 0.13m deep and closely associated, both stratigraphically and spatially, with the majority of the slag assemblage.

These hearth sizes can be compared with those of modern side blast hearths, which traditionally started at around 0.75m square for small farriers' shoeing forges, and although some modern hearths, particularly for school use, may be as small as 0.6 x 0.8m, rectangular hearths of approximately 0.9 x 1.1m are more typical in general purpose smithies.

As with modern side-blast hearths, it is very likely that tuyères were employed at Coolamurray, in contrast to the widespread use of a simple blowhole in a clay wall on early sites in Britain. There was, however, little direct evidence for tuyère use at Coolamurray, with all the fragments of fired or vitrified ceramic being too small for certain identification. On other sites of this period in Ireland the use of tuyères is widely indicated by abundant finds, but the mode of use of the tuyères is very poorly understood. In the literature they are often presented as being almost disc-like. Examination of such material however strongly suggests that the pieces described as discs are the strongly fired and vitrified faces of elongate tuyères. The sides of tuyères typically show a rapid disappearance of vitrification away from the front face, with the localised development of a green wood-ash glaze near to the face, but behind that a reduced-fired surface (in contrast to the oxidised-fired fabric close to the bore) preserving the delicate striations from the manufacturing process. Although some examples, particularly some of the larger ones, show a longitudinal curvature of the side faces suggesting a slightly bulbous form, it much for common for the sides to suggest a more cylindrical overall shape. In no cases examined by the author have the tuyères shown preservation of a rear face, or even of the sides more than 50mm behind the face. It would appear that the typical early medieval tuyère was cylindrical and poorly-fired, of unknown length, with specimens from this period being typically of 120-180mm diameter with a bore of 16-22mm.

It would appear likely that the early medieval hearth must have had some form of wall. The hearth functions by allowing combustion in a zone in front of the tip of the tuyère, within which conditions will be oxidising, and above

which the rising gases will generate a reducing atmosphere. It is within this reduced zone, in front of and above the tuyère, that the smith will heat the workpiece while minimising its oxidation. Thus the fuel in the hearth must be raised to a considerable height above the tuyère tip. To help support the fuel most modern forge hearths have a wall extending 50-75mm above the air input. These walls are distanced from the heat of the fire by the protrusion of the tuyère into the hearth. The height of the air input above the floor of the hearth is variable in different hearth types, from almost nothing to about 75mm. In early hearths with a ceramic tuyère the production of slag would have been larger than that of the clinker in a modern coal-fired hearth with an iron tuyère. The space below the tuyère level would provide room for the accumulation of the slag (the smithing hearth cake, SHC). The smith would manipulate the ash in the hearth base to ensure suitable space for the slag was available before commencing work.

Considerations of these requirements allow the construction of a model for the use of the Coolamurray hearths. The Coolamurray features interpreted as hearths are moderately deep: 0.2 and 0.3m in the two better preserved examples. Such a depth easily allows for large slag accumulations below the tuyère, if the tuyère enters the hearth at ground level, as would seem likely. Indeed, these depths might seem excessive. Some form of wall would still, however, be likely to be required in order to contain the fuel, which in this model would have to be largely above ground level. This would particularly apply on the side of the hearth containing the tuyère – where the fuel would be highest. Whatever this wall was, it is represented only by the 8 supporting stake holes in the sides of Hearth B; presumably it was sufficiently removed from the heat of the hearth to be perhaps unfired clay/turf, or perhaps wooden or maybe wattle and daub.

The overall hearth technology as discussed above is thus very similar to that of a modern side-blast hearth. There are, however, two significant differences: firstly that the hearths are cut features rather than raised, so called "waist-level", hearths, and secondly the tuyère is ceramic, rather than iron as has become standard since the 18th century. The hearth height is not likely to affect the residues produced, but if the smith worked on the floor then it might have implications for the layout of the smithy, in particular the proximity of the anvil to the hearth. The "stake holes" observed to the northwest of hearths A and B might possibly be associated with small anvil blocks (the wooden block or post supporting a small iron anvil). They are closer (0.5m) to the hearth than would be expected in a modern forge, but if the smith worked on the ground, then this closeness might be expected (compare the illustration of medieval floor level hearth, of rather more elaborate design than those at Coolamurray, with two working smiths in Plate 5).

(insert Plate 5)

The tuyère material is of great significance for the nature of the residues, for melting of the tuyère tip will supply silicate material into the hearth to contribute to the slag-forming process. The restricted volume of tuyère impinging on the hot zone of the hearth, compared with a hearth employing a simple blowhole in a clay wall, will lead to a restricted silicate supply. The tuyère is not the only source of silicate material into the hearth however, there may be a limited supply of silicate from the fuel (although charcoal ash is likely to be only in the range of 2-5% silica, Thomas 2000), and potentially also from any silicate flux used to aid in welding. Smiths commonly use a flux to assist in fire-welding in order to reduce the melting point of the oxide crust on the metal, which is then expelled as a liquid by hammering the weld.

The microstructure of some slag flats and blisters (Plate 4 I-L), together with those of the SHCs (Plate 1 M), suggests that a sand flux was employed at Coolamurray. Certain distinction of sand flux from partially melted sandy hearth ceramic is difficult however, and much stronger evidence is provided by the chemical composition of the smaller spheroids, which show a higher silica:alumina ratio than the other residues, hinting at a dominance of sand flux in the silicate fraction.

7. Discussion of residues

The SHCs that were examined in detail provide detail illuminating the origin of these slags. Sample Mon17 shows a two-layer structure suggesting the development of a homogeneous slag through reaction of silicate material with oxidised iron (flake hammerscale). The silicate material is interpreted as being derived mainly from hearth ceramic, but unfortunately the assemblage contained no suitable ceramic with which to compare the material within the SHC. It remains uncertain, therefore, whether the sand grade (up to 800μm) quartz and feldspar observed in this layer represents a coarse temper from the hearth ceramic or a separate input of sand flux. The preservation of the partially-reacted material indicates rapid cooling of the slag after the last period of working in the hearth.
Sample Mon16 shows a strongly inhomogeneous composition, with the slag mineralogy and chemical composition strongly influenced by the proximity of vesicles. The slags adjacent to the vesicles show textures in which leucite is prominent. The evolution of the melt in slags with local leucite development is not fully understood (e.g. discussion in Thomas 2000, p. Nn), but it is likely that it includes the development of systems exhibiting liquid immiscibility. In general, slags with such zones of leucite (plus calcic olivine, hercynite and rhönite) do not show significant bulk enrichment of calcium or potassium when compared to homogeneous slags in the same assemblages. What they are demonstrating appears to be simply an inhomogeneity of incorporation of fuel ash.

Some of the larger particles from the sieved samples, including those identified as "slag" fragments and prills (Mon 10, 12, 13), but also including some of the larger, denser spheroidal particles (Mon 8), share a common chemical composition, microstructure and, therefore, origin with the SHCs. These particles can be interpreted as slag which either derives from the fragile, charcoal-rich margins of the larger slag bodies, or which represent drips of slag which did not become incorporated within the main slag mass.

The tabular particles had been divided initially into flake hammerscale, slag flats and blisters. The chemical evidence suggests that the coarser flat and blister material has an origin in slag-forming processes similar to those of

the macroscopic material, but it shows an increased influence of fuel ash, perhaps because of the thin morphology having a large surface area. Most of these particles showed an olivine-dominated microstructure, related to those of the macroresidues, but with a basal iron oxide film. Some particles showed an irregular granular microstructure, rather than a typical slag texture, and these particles are interpreted as showing the effects of disruption of the microstructure through hammering.

The thinner tabular particles were those normally classed as flake hammerscale, and they showed oxide-dominated microstructures. In the smallest material the wustite was angular and closely-packed towards the base of the scale, with the grain boundaries opening up towards the upper surface where they are filled with a glassy phase. Such material probably represents in-situ oxidation of the workpiece. In slightly coarser material, the wustite shows a tendency to become more rounded and even to become pseudo-dendritic locally. This is interpreted as demonstrating a larger proportion of melted material being involved in scale formation.

Rather similar flake hammerscale textures are commonly observed in the spheroidal particles, particularly as discrete clasts within the external surface of the particles. Many of the smaller spheroidal particles contain textures wholly- or partially-dominated by pseudo-dendritic wustite. Some of these particles also contain silicate-dominated areas. Such textures are indicative of derivation of these spheroidal particles from the surface of the workpiece, from which they derive unmelted surficial oxidised crust fragments or more or less well-fluxed iron-rich melts. These particles are true spheroidal hammerscale.

Chemical analysis of the spheroidal hammerscale suggests these particles may be derived from reaction of the oxidised surface of the workpiece with a silica-rich material, which is very likely to have been a sand smithing flux. Thus small (<3mm) particles are largely derived from the surficial oxidation of the workpiece, and are expelled in both flake and spheroidal morphologies, with a dominantly wustite mineralogy. Material of slightly coarser grain size tends to be much more silicate dominated (whether spheroidal or tabular).

A few of the oxide-dominated spheroidal particles (e.g. Plate nn, mm) have a morphology with a very thin, slightly irregular crust around a large central vesicle similar to that suggested by Dungworth (in prep.) to be indicative of the particles produced by burning of the iron. This occurs when the workpiece becomes very hot and rapid oxidation occurs. It is indicated by the production of “sparklers”: burning fragments of metal which are spontaneously ejected from the workpiece and often fragment during flight.

Location and extraction of hammerscale usually relies on the strong magnetic properties of the material. It was interesting to observe therefore that in only very rare examples did the microresidues contain primary magnetite (which would indicate less strongly reducing conditions within the melt). Almost all the microresidues showed some partial secondary oxidation of wustite to magnetite. This oxidation was most commonly associated with the surfaces of the particles, suggesting oxidation of the hot particles through contact with air, but that the conditions within the hearth were more reducing.

8. Conclusions

The slags from the site were dominated by the plano-convex slag cakes known as smithing hearth cakes (SHCs), which is usually the main accumulation of slag of a smithing hearth in which the hot-zone impinges on either clay hearth-lining, or a ceramic tuyère. The size distribution of SHCs at Coolamurray is based on measurements of over forty examples of SHCs for which the original weight is preserved or can be estimated. 95% of these cakes weighed less than 1000g, with 83% being less than 500g. This dominance of small SHCs is unusual when compared with other well-studied Irish assemblages from early medieval contexts. Assemblages from sites such as the Clonmacnoise water-treatment plant, Clonfad and Woodstown have 30% or more of the SHCs with weights over 1kg, with maximum SHC size of between 5 and 11kg. It is proposed that these sites with large SHCs were involved with the refining of primary raw blooms. Sites yielding assemblages of small SHCs with only a few outlying large examples, such as Coolamurray site 7, are less well known, but somewhat similar assemblages are known from Carrigoran (Co. Clare) and a site on the Navan relief road. Similar assemblages, but without the outlying large cakes, are however widely recognised in Britain and elsewhere as the residues from blacksmithing, the end-use of iron produced elsewhere. These Irish assemblages are therefore also interpreted as being primarily from blacksmithing, although at present the significance of the outlying large SHCs is not understood (they may indicate the undertaking of a small proportion of bloomsmithing, or they may indicate that hearths were cleaned less frequently during intense periods of work).

Analysis of SHCs from Coolamurray has demonstrated the nature of the reaction forming the slag with pieces of flake hammerscale, lost by oxidation of the workpiece, dissolving in a silicate melt derived from the melting of the hearth ceramic and possibly from welding flux. The slag thus generated can be then seen to evolve through reaction with fuel ash to produce some complex and inhomogeneous microstructures.

Although direct evidence is lacking from Coolamurray, all other contemporary Irish iron-working sites investigated by the author have produced evidence that smithing hearths were blown through ceramic tuyères. Fired or vitrified hearth lining is unknown on these sites. This indicates a technology apparently distinct from that of other areas of western Europe, and particularly southern Britain, where tuyères are largely unknown, except in areas with a strong Scandinavian influence. The use of a tuyère brings the early medieval Irish smithy at Coolamurray close to a modern style of forge morphology and use. This provides an important counterpoint to some of the large iron-producing sites (e.g. Clonfad, Clonmacnoise and Woodstown), where markedly different types of residue hint at different techniques and technologies, yet to be fully described.

Micro-residues have not yet been studied in any detail from a site which employed ceramic tuyères. Such sites might be expected to show a different evolution of both macroscopic and microscopic slags within the hearth, because there is less ceramic material within the hot-zone when a tuyère is employed compared with a blowhole in clay wall. This would allow less silicate material to enter the slag generating process with the iron oxides lost from the workpiece.

The microresidues from Coolamurray included spheroidal particles, ranging from high sphericity grains of <1mm up to lower sphericity grains of several mm, together with materials of a platy form, ranging from small shiny pieces of flake hammerscale up to larger pieces of rougher appearance with a single smooth surface.

The small particles of both platy and spheroidal form (commonly referred to as flake and spheroidal hammerscale) were both very iron-rich, with a primary mineralogy dominated by wustite (FeO). Silicates were present locally. Except in one example, magnetite (Fe_3O_4) was not a primary phase, but present as an oxidation product of wustite. In the case of the flake hammerscale, some fragments show clear evidence for granular wustite textures derived from oxidation of the iron workpiece. In other examples, and in the spheroidal hammerscale, the wustite shows a blebby or dendritic texture indicating formation from a melt. Interestingly, a large proportion of the spheroidal hammerscale contained a short length of flake hammerscale within the surficial layer of the spheroid.

Larger particles show a much lower proportion of iron and a greater influence of silicate material. They show chemical compositions related to those of the smithing hearth cakes, and therefore presumably share an origin in similar slag-forming reactions. Like one of the analysed smithing hearth cakes, they show occasional incorporation of sand-grade grains of quartz and feldspar. Although sand might be derived from the temper of the supposed tuyères, an alternative source might be the use of a sand welding flux. Such a flux is commonly employed by smiths to assist with fire-welding, for the addition of silica lowers the melting point of the oxides contaminating the weld site and allows the oxides to be expelled more easily as liquid slag as the two surfaces are hammered together. Demonstrating the use of such a flux in an ancient example has proved very difficult in the past, but here at Coolamurray is apparently just such evidence.

The full significance of the analytical data from this site will probably only become clear when equivalent analyses have been undertaken on other sites, employing other styles of iron-working. The Coolamurray assemblage helps to document the generation of silicate slags within a relatively silicate-poor system. Promotion of slag generation may have been achieved through deliberate addition of a welding flux. Despite this possible use of flux, the hammerscale particles are extremely iron-rich. Indeed, the spheroidal hammerscale is more iron-rich than perhaps would be expected from the current literature. Whether this is a failing in the current literature, or whether spheroidal hammerscale produced during the working of iron heated in a hearth with a ceramic tuyère is more iron-rich than that produced in a clay-lined hearth with a blowhole, remains to be determined.

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Illustration Captions

Plate 1: Backscattered electron photomicrographs of textures of smithing hearth cakes
A-I Mon16

A . Typical microstructure from central part of specimen. Dark areas are voids (vesicles). Mid-grey large crystals are fayalite, dark grey areas are interstitial glass bearing intergranular fayalite-wustite. Scale bar 1mm.
B. Detail from centre of field of view of A. Scale bar 300µm.
C. Detail from right of centre of B. Shows detail of late-stage intergranular fayalite-wustite with interstitial glass. Scale bar 80µm.
D. Partially infilled vesicle, showing vesicle filled by slag with essentially the same mineralogy as the body of the slag, but with a finer crystal size. Scale bar 1mm.
E. Detail from lower left of vesicle fill seen in D. Texture closely comparable with that seen in B & C, but finer. Scale bar 100µm.
F . Microstructure in an area with modified mineralogy around vesicles. The smaller vesicle, upper right of centre, shows a complex halo, with textures as shown in G & H. The larger vesicle on the lower edge of the field of view shows a narrower halo of the type illustrated in I which is modified form of the normal texture. Scale bar 300µm.
G. Detail from centre of field of view of F. The vesicle to the right, has a halo with two distinct mineralogical zones. The inner has a fine syntectite of fayalite and leucite, whereas the outer has a coarser intergrowth of fayalite (pale grey), leucite (dark grey) and hercynite (intermediate grey). The adjacent dark grey interstitial glass bears elongate crystals of rhönite. Scale bar 80µm.
H. Detail from the upper centre of F. The microstructure is similar to the shown in G (which lies immediately below this field of view), but the interstitial glass bearing rhönite is particularly clearly seen. Scale bar 100µm.
I . Detail from a vesicle margin where the intergranular fayalite-wustite of the dominant microstructure (cf. C above) is intergrown with leucite. Scale bar 80µm.

J-O Mon17

J. Microstructures in the lower part of the cake. The margin of the specimen in the lower right is close to the base of the cake, with the large fayalite crystals dominantly perpendicular to the base. Scale bar 800µm.
K. Detail from upper left of centre of J. Large fayalite crystals (pale grey) can be seen to have a central zone involving a syntectite with wustite (white), marginally to be a coarse syntectite with hercynite (mid grey). The interstitial glass (dark) contains white blebs which may be parts of coarse early wustite dendrites. The large white bleb lower right of centre is a metallic iron inclusion. Scale bar 100µm.
L. Detail of the sharp interface separating the coarsely crystalline lower part of the cake (right) from the finer, more glassy upper section (left). The top of the lower part of the cake is dominated by large fayalites (cf. those in J) aligned parallel (rather than perpendicular to the base of the cake). The upper part of the cake is characterised by sheaves and radial structures of finer fayalite crystals. Scale bar 1mm.
M. Zone near the top of the cake in which grains of feldspar and quartz (dark grey) had been undergoing melting into the slag. In this area the elongate fayalite crystals are very fine-grained and form sheaves. Scale bar 600µm.
N . Detail of margin of partially melted quartz grain (dark grey, top) surrounded by delicate quench-textured fayalite crystals with interstitial glass. Scale bar 300µm.
O. Detail of partially-melted grain of angular wustite, probably a piece of flake hammerscale, surrounded by similar slag to that seen in N above. Scale bar 300µm.

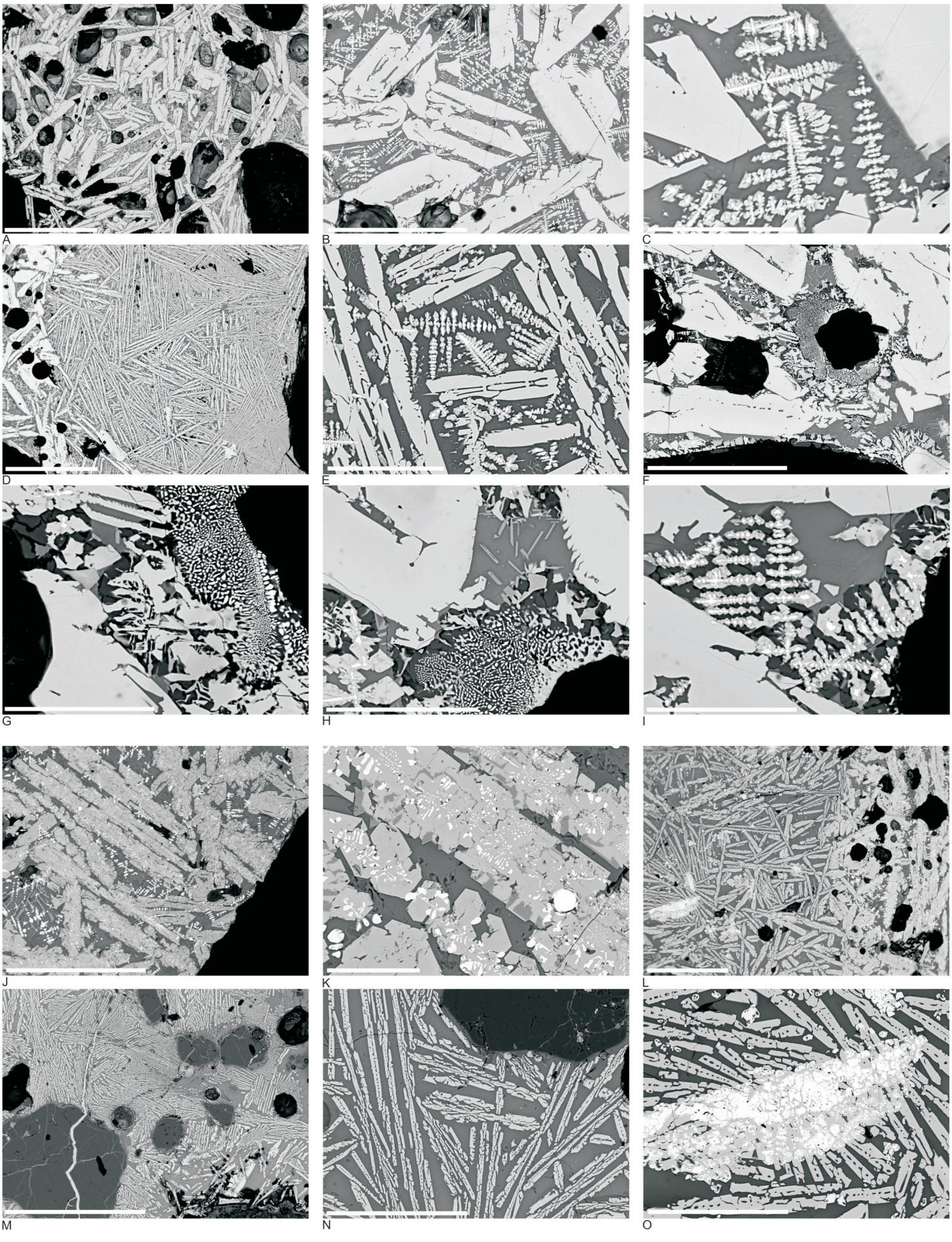

A
B
C
D
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F
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K
L
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Plate 2: Backscattered electron photomicrographs of textures of spheroidal smithing microresidues

In these images wustite is typically bright, with areas of oxidation to magnetite showing slightly darker. Olivine appears mid to dark grey, with very dark grey being glass. Voids appear black.

A. Mon5. Spheroidal hammerscale with dominant S3 texture, containing zones of coarse S1 texture with rounded wustite blebs (detail in B). These zones are probably relict wustite scale. Scale bar 1mm.
B. Mon5. Detail of S1 zone within particle shown in A. Scale bar 80 μm.

C. Mon6. Spheroidal hammerscale with dominantly S2 texture. Detail shown in D. Scale bar 2mm.
D. Mon6.Detail of particle shown in C, showing dominance of S1 texture near margin, but internally S2 dominates, including partially infilling vesicles. Scale bar 200 μm.

E. Mon9. Extremely irregular spheroidal hammerscale grain, with mineralogy dominated by iron oxides. This particle shows a strong resemblance to the particles produced by burning iron as illustrated by Dungworth, in prep. Scale bar 600 μm.

F. Mon5. Thin-shelled spheroidal hammerscale with S1 texture on external margin, grading inwards to S2. Detail shown in G. Scale bar 1mm.
G. Mon5. Detail of particle shown in F. Scale bar 60μm.

H. Mon5. Spheroidal hammerscale with dominant dendritic wustite, Texture S3a. Scale bar 100μm.

I. Mon4. Spheroidal hammerscale with small fragment of oxide scale (S1 texture) embedded in the shell (upper left). Adjacent to the oxide scale fragment the primary phase in the slag is magnetite (S4; detail shown in J). Scale bar 800μm.
J. Mon4. Detail of oxide scale fragment (S1 texture), showing characteristic angular and platy morphologies of primary magnetite (S4 texture) in the adjacent slag (same particle as I). Scale bar 100μm.

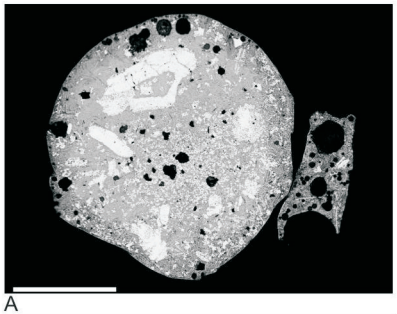
K. Mon6. Slag texture in spheroidal hammerscale dominated by blebby and pseudo-dendritic wustite, Texture S2.Scale bar 200μm.
L. Mon6. Slag texture in spheroidal hammerscale showing a marked differentiation between coarse pseudo-dendritic areas (Texture S2) and areas with a higher proportion of olivine and truly dendritic wustite (Texture S3a). Scale bar 200μm.
M. Mon6. Slag texture in spheroidal hammerscale showing a marked differentiation between small areas of coarse pseudo-dendritic wustite (Texture S2) and areas with dominant olivine and extremely fine dendritic wustite (Texture S3b). Scale bar 200μm.
N. Mon9. Spheroidal hammerscale with thin external iron oxide crust, with coarse wustite pseudo-dendrites immediately adjacent (Texture S2). This is overlain by a zone bearing fine wustite dendrites about 100μm thick, beyond which the spheroid is almost entirely olivine plus glass (Texture S3). Scale bar 100μm.

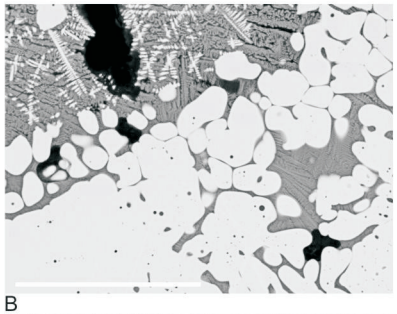
O. Mon4. Spheroidal hammerscale with S5 texture of spheroids of iron in glass. Scale bar 600μm. Detail shown in T.

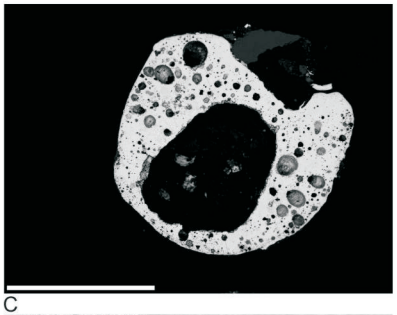
P. Mon7. Large sub-spheroidal particle. Has S3b microstructure of wustite plus olivine and glass. Scale bar 4mm. Detail shown in Q.
Q. Mon7. Large sub-spheroidal particle. Detail of particle shown in P. Variations in the S3b textures reveal infilled vesicles. Scale bar 200μm.

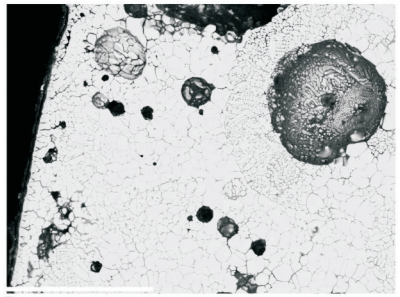
R. Mon5. Spheroidal hammerscale with S3b texture dominated by finely dendritic fayalite crystals defining discrete domains. Detail shown in S. Scale bar 1mm.
S. Mon5. Spheroidal hammerscale. Discrete domains are occupied by sets of fine fayalite dendrites. Some areas to left of field of view and centre bottom have fine early dendrites of wustite, apparently either cored on S2 blebby zones or centred on small vesicles. Detail of particle shown in R. Scale bar 200μm.

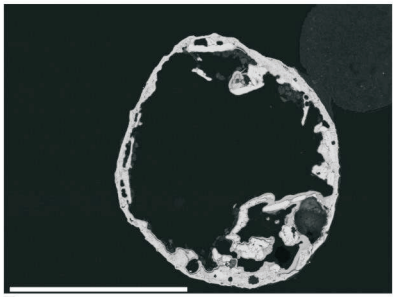
T. Mon 4. Detail of upper margin of particle with S5 texture of iron blebs in glass shown in O. Scale bar 80μm.

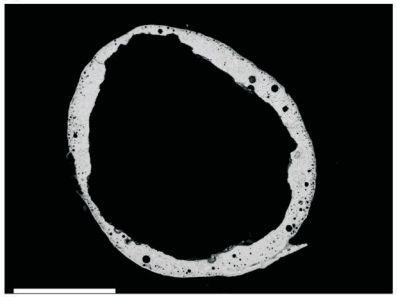

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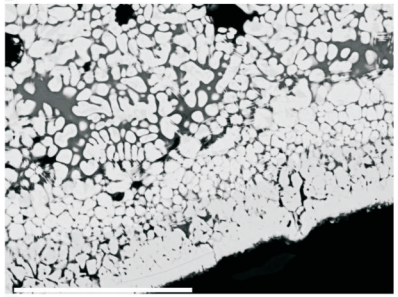

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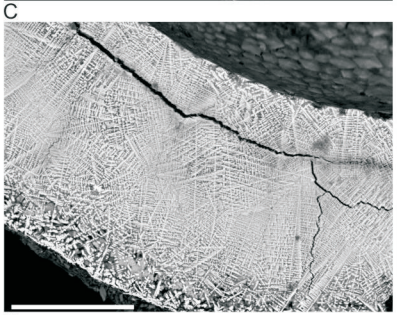

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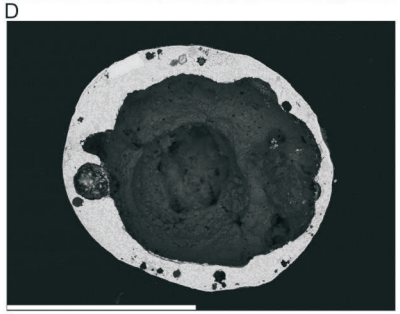

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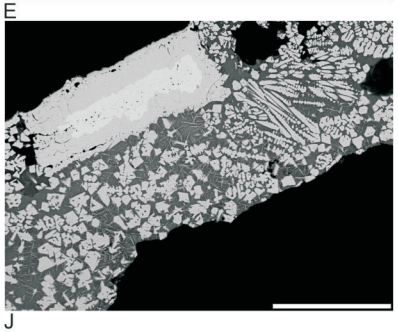

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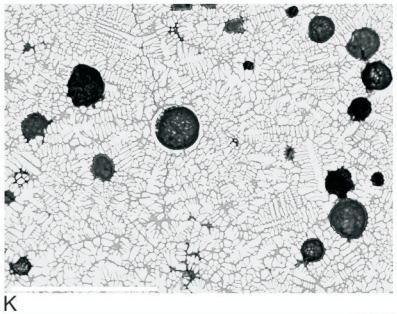

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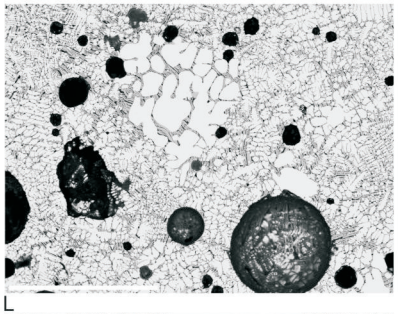

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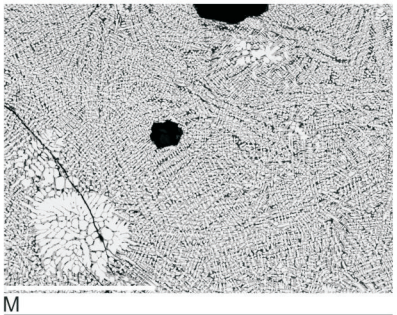

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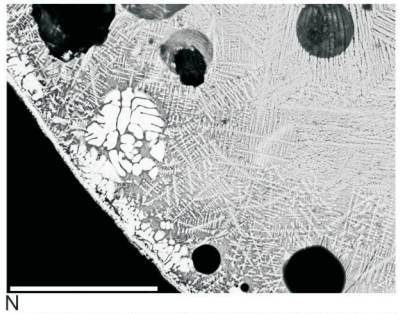

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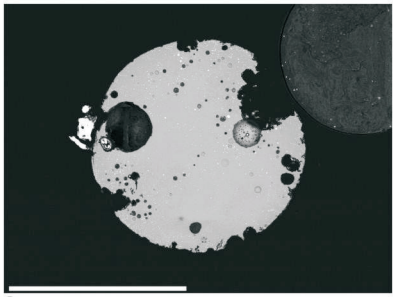

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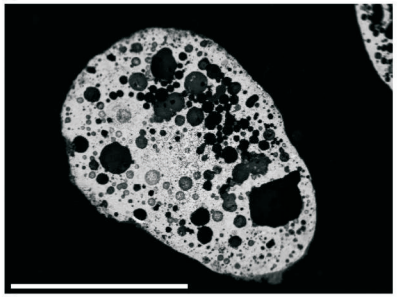

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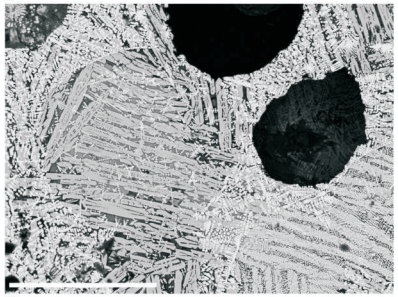

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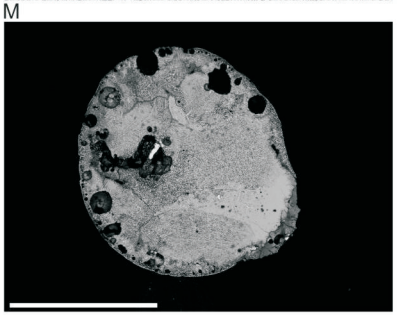

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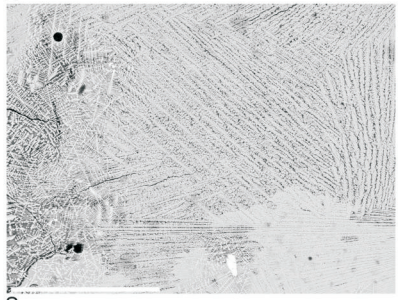

N


O


P


Q


R


S

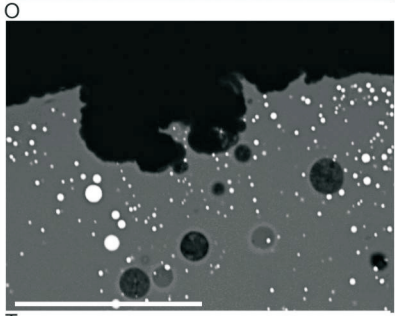
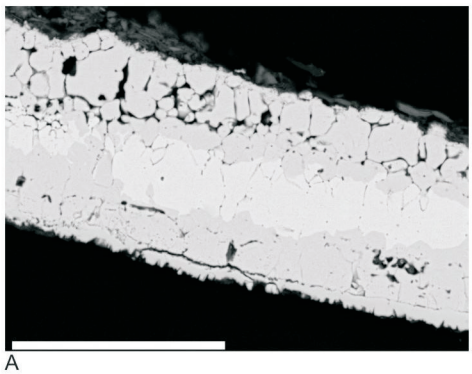
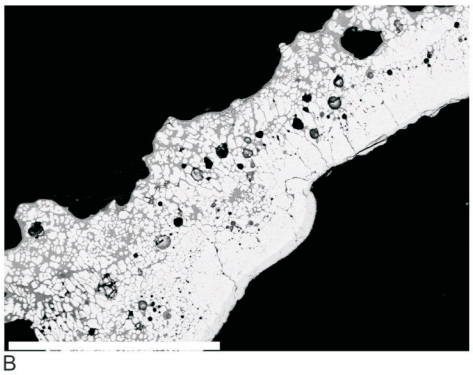

T

Plate 3: Backscattered electron photomicrographs of textures of tabular smithing microresidues
In these images wustite is typically bright, with areas of oxidation to magnetite showing slightly darker. Olivine appears mid to dark grey, with very dark grey being glass. Voids appear black.

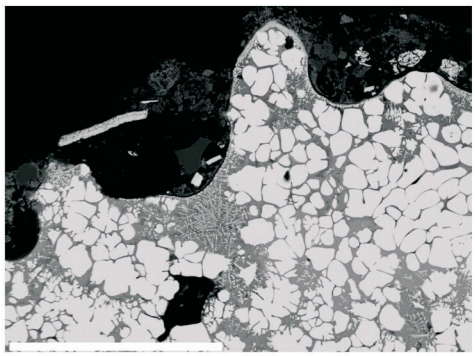
A. Mon2, T1 texture. Scale bar 1mm.
B. Mon14, T1 texture grading up into T2. Scale bar 80 μm.
C. Mon14, upper part of flat (same particle as D), dominantly T2 texture grading into more finely dendritic wustite. Undulating upper surface is typical of the slag flats. Scale bar 2mm.
D. Mon14, lower part of flat (same particle as C), dominantly T2 texture grading into more finely dendritic wustite. Lower part of particle shows P4 texture, with rounded oxide scale fragments. Scale bar 200 μm.
E. Mon1, (same particle as F), fine T3 texture in lower part of particle. Scale bar 600 μm.
F. Mon1, (same particle as E), coarser T3 texture at top of particle. Upper surface of particle (right) shows surficial oxide crust. Scale bar 1mm.
G. Mon1, (same particle as H), very fine T3 texture of olivine. Scale bar 60μm
H. Mon1, (same particle as G), detail of basal oxide crust to particle with delicate oxide dendrites extending into main body of the piece. Scale bar 100μm.
I. Mon3, complex T4 texture with scale fragments embedded within lower (upper left) part of slag flat. Upper part of particle, shows an olivine-dominated T3 texture (lower right). Scale bar 800μm.
J. Mon14. Granular T5 texture. Scale bar 100μm.



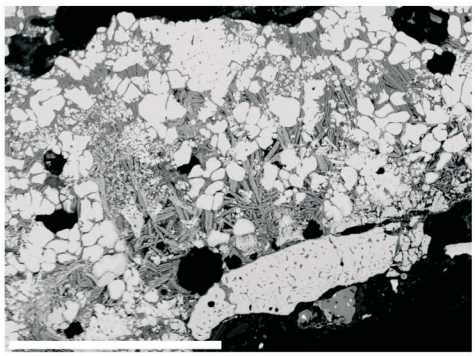
A



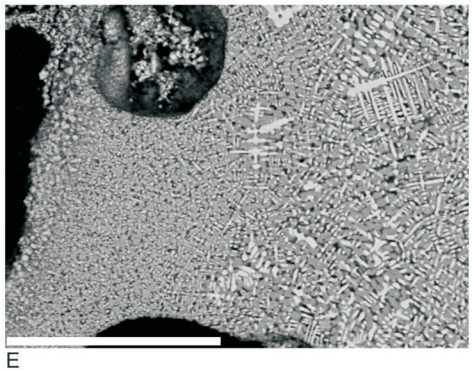
B



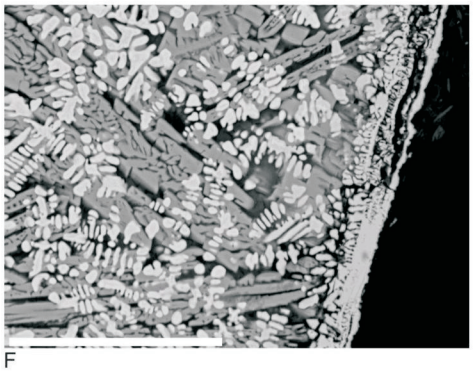
C



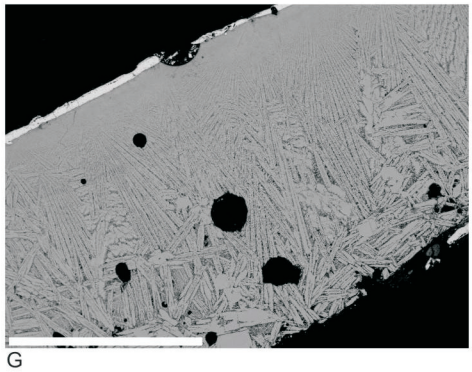
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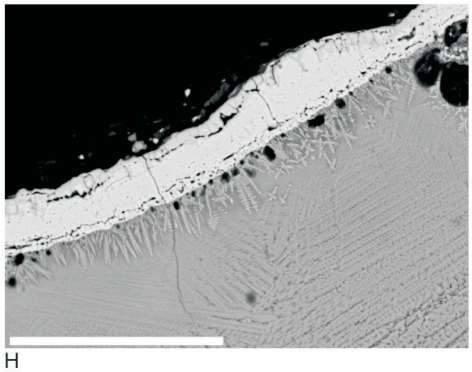
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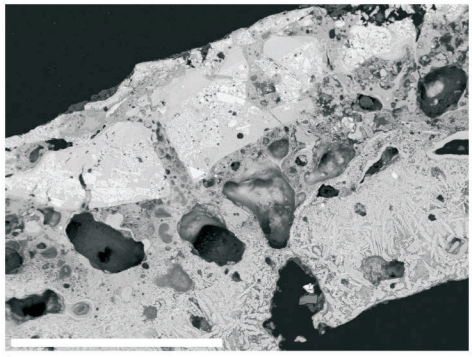
F



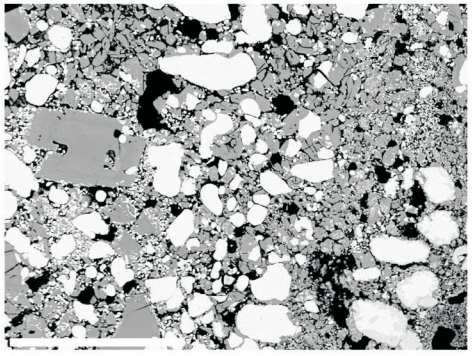
G



H



I



J

Plate 4: Backscattered electron photomicrographs of minor slag categories and of microresidues containing quartz. In these images wustite is typically bright, with areas of oxidation to magnetite showing slightly darker. Olivine appears mid to dark grey, with very dark grey being glass. Voids appear black.
Minor slag categories
A-C Mon16, dull dense slag bleb.
Texture shows early large, but delicate, wustite dendrites with later carious elongate olivine crystals. In some areas (e.g. upper left in C) there is a wustite-olivine syntectite. Interstitial areas contain glass and very fine olivine dendrites.
A. Scale bar 200µm.
B. Scale bar 80µm.
C. Scale bar 80µm.

D-E Mon13, amorphous slag fragment

D. A wustite-dominated texture with pseudo-dendrites. Darker matrix includes olivine and glass. Scale bar 200µm.
E. Shows complex textures with iron oxide in various textures (bright), charcoal fragment (upper left) and slag (upper right), with abundant fine-grained material (pale grey), much of which may be secondary alteration. Scale bar 200µm.

F. Mon12, slag prill.

F. Poorly mixed iron-rich (bright) and iron-poor (mid grey) glasses, bearing partially melted material including grains of feldspar and quartz (dark grey). Scale bar 800µm.

Microresidues containing quartz grains

Mon6. Irregular rounded particle bearing multiple silicate grains

G. Scale bar 3mm
H. Scale bar 400µm.

Mon3. Slag flat with several quartz grains

I. Scale bar 800µm.
L. Scale bar 1mm

Mon9. Blister bearing rounded quartz grains

J. Scale bar 2mm
K. Scale bar 100µm.

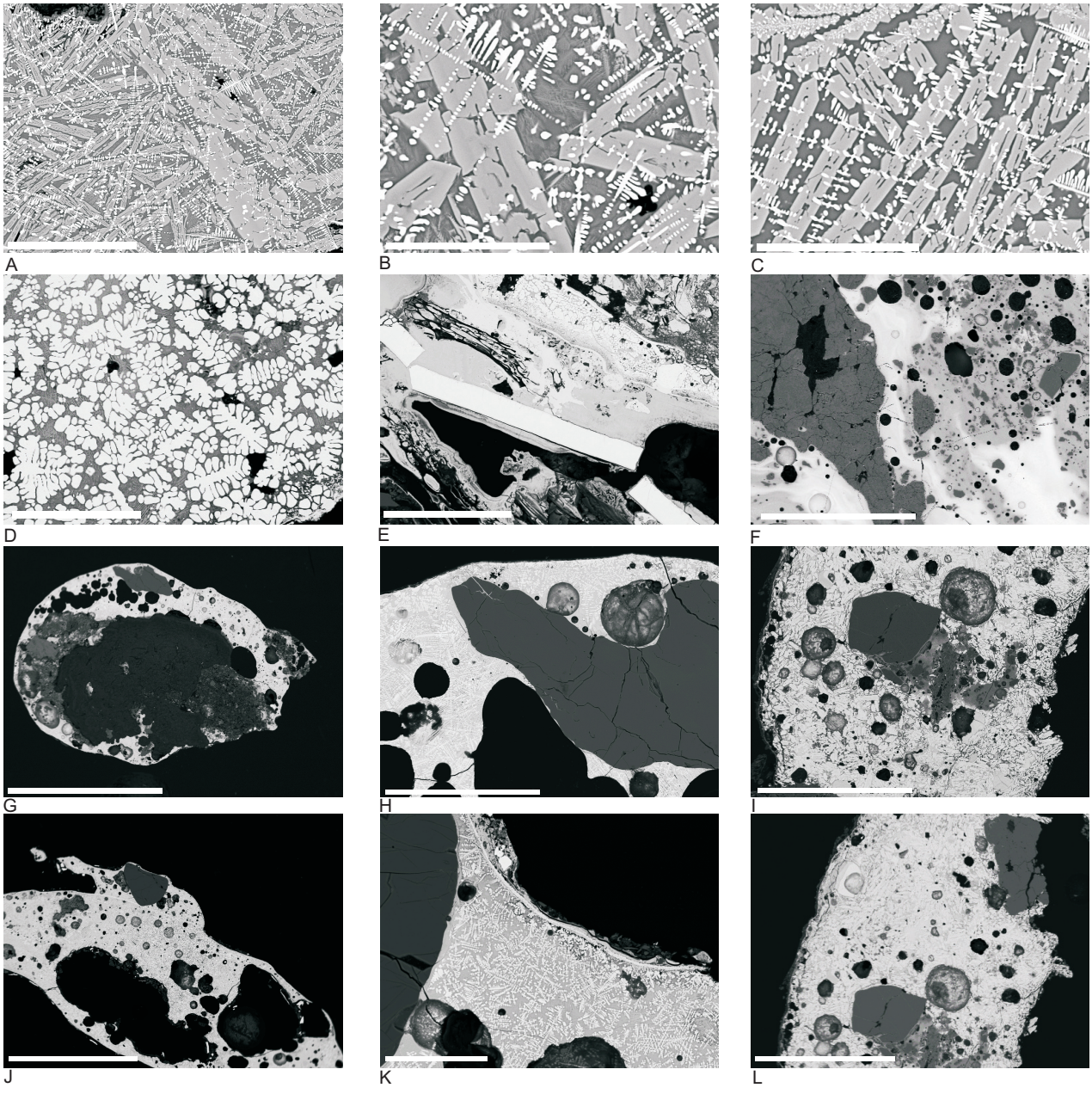

A
B
C
D
E
F
G
H
I
J
K
L

Plate 5. A floor-level smithing hearth, with smiths working at small anvils. From “The Romance of Alexander” in French verse, with miniatures illustrating legends of Alexander the Great and with marginal scenes of everyday life, by the Flemish illuminator Jehan de Grise and his workshop, 1338-44, Bodleian Library, MS. Bodl. 264, folio 84 recto. This hooded hearth is a more elaborate structure than the Coolamurray hearths, but the style of use would be similar. Notice the small anvils supported on wooden blocks, located close to the hearth to facilitate use by the kneeling smiths.

Plate 5



Figure 1. Frequency distribution of SHCs by weight, 50g class interval

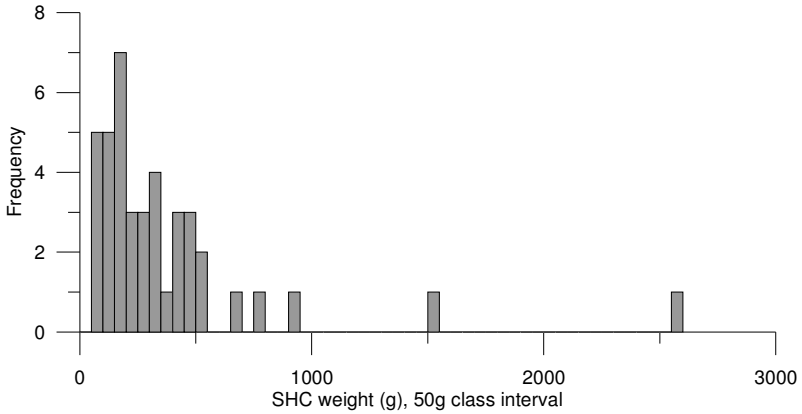


Figure 1. Frequency distribution of SHCs by weight, 50g class interval

			ICP-MS	XRF	SEM
Mon1	c14	flake hammerscale >3mm	✔	✔	✔
Mon2	c14	flake hammerscale from soil sample	✔	✔	✔
Mon3	c14	macro flats (>5mm)	✔	✔	✔
Mon4	c14	spheroids <1mm from soil	✔		✔
Mon5	c14	spheroids 1-3mm from soil	✔		✔
Mon6	c14	spheroids 3-5mm from soil and >3mm	✔	✔	✔
Mon7	c14	spheroids >5mm from >5mm	✔	✔	✔
Mon8	c56 aii + c	spheroids >5mm	✔	✔	
Mon9	c56 aii	blisters	✔	✔	✔
Mon10	c56 aii	dense dull slag	✔	✔	✔
Mon11	c56 aii	flake hammerscale	✔	✔	
Mon12	c56 aii	dense prills	✔	✔	✔
Mon13	c14	amorphous slag >3mm	✔	✔	✔
Mon14	c14	flats >3mm	✔	✔	✔
Mon15	c56	fired clay	✔	✔	
Mon16	c56	SHC1	✔	✔	✔
Mon17	c56	SHC2	✔	✔	✔

Table 1: Sample provenance, description and analysis.

			SiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI*	total	LOI meas.	SiO_2 Al_2O_3
Mon1	c14	flake hammerscale >3	6.05	1.39	87.25	0.06	0.45	0.31	0.10	0.20	0.11	0.11	3.94	99.97	-5.77	4.4
Mon2	c14	flake hammerscale from soil sample	3.57	1.04	88.87	0.05	0.30	0.19	0.08	0.14	0.09	0.08	5.66	100.06	-4.24	3.4
Mon3	c14	macro flats (>5mm)	15.84	3.01	69.08	0.14	1.83	2.23	0.17	0.53	0.21	0.22	6.56	99.82	-1.13	5.3
Mon4	c14	spheroids <1mm from soil														
Mon5	c14	spheroids 1-3mm from soil														
Mon6	c14	spheroids 3-5mm from soil and >3mm	13.29	1.45	80.62	0.08	0.60	0.42	0.05	0.14	0.13	0.12	3.05	99.96	-5.93	9.2
Mon7	c14	spheroids >5mm from >5mm	12.20	1.55	81.81	0.07	0.37	0.26	0.00	0.18	0.13	0.12	2.91	99.60	-6.20	7.9
Mon8	c56 aii + c	spheroids >5mm	27.73	5.30	60.24	0.17	1.16	1.50	0.38	1.25	0.33	0.17	1.67	99.88	-5.04	5.2
Mon9	c56 aii	blisters	19.77	4.17	68.23	0.15	1.20	1.55	0.22	0.90	0.26	0.20	3.74	100.37	-3.86	4.7
Mon10	c56 aii	dense dull slag	19.61	4.60	66.11	0.18	1.46	2.50	0.26	1.28	0.31	0.24	2.17	98.73	-5.19	4.3
Mon11	c56 aii	flake hammerscale	25.33	5.26	62.17	0.17	1.36	1.65	0.28	1.09	0.30	0.23	2.60	100.44	-4.32	4.8
Mon12	c56 aii	dense prills	24.55	6.09	62.78	0.20	0.77	1.38	0.39	1.25	0.40	0.18	1.65	99.64	-5.34	4.0
Mon13	c14	amorphous slag >3mm	15.97	2.97	70.99	0.15	1.33	1.49	0.16	0.53	0.22	0.18	5.69	99.68	-2.21	5.4
Mon14	c14	flats >3mm	10.08	1.77	81.15	0.10	0.88	0.74	0.12	0.24	0.14	0.16	4.41	99.78	-4.63	5.7
Mon15	c56	fired clay	59.26	18.37	10.04	0.23	0.98	0.33	0.86	2.63	0.97	0.11	6.87	100.64	5.75	3.2
Mon16	c56	SHC1	29.52	5.24	58.94	0.20	0.95	1.69	0.49	1.35	0.34	0.17	0.89	99.80	-5.67	5.6
Mon17	c56	SHC2	26.41	5.99	60.38	0.20	1.18	1.43	0.43	1.23	0.34	0.24	2.24	100.07	-4.48	4.4

Table 2a: Chemical analyses. Major elements expressed as wt% oxide, determined by XRF on fused beads. LOI meas. is the raw measurement of loss on ignition. LOI* is the loss on ignition corrected for the weight gain due to the oxidation of iron II to iron III oxides.

	Be	V	Cr	Co	Ni	Zn	Ga	Rb	Sr	Y	Zr	Nb	Mo	Sn	Cs	Ba
Mon1	0.41	10.8	38.0	11.0	159.2	146.7	4.8	3.3	25.0	2.1	91.5	1.18	1.61	1.84	9.60	148.3
Mon2	0.48	11.5	4.7	14.5	57.7	95.3	5.1	2.4	19.2	1.9	94.2	1.20	0.78	1.08	4.32	83.1
Mon3	3.42	26.9	15.3	6.0	12.4	88.3	5.9	4.6	66.8	8.1	126.0	2.72	0.91	0.61	2.05	88.0
Mon4	1.20	26.9	19.0	7.3	46.4	51.2	5.6	3.6	26.3	3.8	124.6	2.54	0.84	1.95	3.12	164.1
Mon5	1.69	31.1	23.7	4.0	61.6	40.1	5.3	3.4	32.4	5.6	124.7	2.51	0.82	0.79	0.58	159.4
Mon6	0.37	17.2	15.2	6.0	117.9	53.2	6.0	7.1	27.5	4.5	104.3	2.19	0.92	6.94	1.84	78.8
Mon7	0.96	28.6	21.6	5.9	31.0	43.6	6.8	8.2	44.7	6.5	126.0	3.46	0.68	2.31	1.56	166.8
Mon8	0.24	0.9	1.0	10.5	38.4	55.5	4.2	2.0	25.1	2.1	82.1	0.76	0.80	0.75	3.98	123.4
Mon9	1.55	24.6	14.1	4.7	93.6	48.1	5.8	18.6	56.0	8.2	129.6	3.29	0.66	1.53	3.79	527.6
Mon10	1.45	34.8	23.4	5.0	18.0	51.9	7.6	37.1	108.3	10.9	137.5	4.76	0.57	0.50	6.74	381.2
Mon11	3.26	39.0	22.3	3.4	9.7	50.3	6.9	15.5	80.4	16.4	139.1	4.06	0.63	0.69	2.46	362.5
Mon12	1.99	32.8	23.1	8.5	40.6	53.6	7.4	23.2	98.1	12.3	133.5	4.12	0.85	1.34	3.24	192.3
Mon13	2.66	27.5	7.4	5.4	17.8	77.6	6.1	23.2	59.0	10.3	133.1	3.34	0.78	0.69	4.95	255.5
Mon14	0.75	15.1	8.2	11.2	34.6	102.4	5.8	4.4	27.4	4.8	119.0	2.40	0.92	0.59	2.24	170.5
Mon15	1.79	120.7	104.0	14.3	46.5	278.4	28.1	118.5	116.3	26.8	185.8	11.65	0.68	1.52	13.36	237.3
Mon16	1.56	30.3	19.2	3.8	20.4	29.7	7.7	25.4	149.6	11.9	142.0	5.01	0.55	0.65	2.71	88.2
Mon17	2.31	49.7	45.2	6.5	13.6	55.3	8.6	30.1	77.2	18.1	142.1	4.55	0.70	0.74	3.27	83.3

Table 2b: Chemical analyses continued. Selected trace elements in ppm, determined by ICP-MS.

	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Th	U
Mon1	3.32	2.26	0.30	1.13	0.23	0.08	0.23	0.04	0.21	0.04	0.12	0.02	0.14	0.02	0.61	0.04	0.43	0.35
Mon2	1.52	2.95	0.36	1.35	0.29	0.06	0.24	0.04	0.23	0.05	0.14	0.02	0.15	0.03	0.67	0.06	0.50	0.36
Mon3	5.77	11.52	1.51	5.84	1.26	0.31	1.21	0.20	1.15	0.22	0.66	0.10	0.69	0.11	1.55	0.17	1.83	4.58
Mon4	2.51	5.24	0.68	2.66	0.59	0.14	0.54	0.09	0.54	0.10	0.29	0.04	0.34	0.05	1.44	0.15	1.54	1.52
Mon5	3.37	7.02	0.94	3.45	0.81	0.15	0.72	0.13	0.77	0.15	0.46	0.07	0.51	0.08	1.48	0.17	1.84	2.50
Mon6	3.43	6.80	0.89	3.37	0.74	0.22	0.68	0.11	0.69	0.13	0.40	0.06	0.41	0.07	1.14	0.18	1.54	0.85
Mon7	5.08	10.80	1.35	5.21	1.12	0.22	1.01	0.17	1.04	0.20	0.60	0.10	0.66	0.10	1.69	0.25	2.46	1.73
Mon8	2.32	3.16	0.41	1.56	0.31	0.05	0.24	0.05	0.27	0.05	0.16	0.02	0.17	0.02	0.54	0.06	0.49	0.38
Mon9	7.18	14.64	1.79	6.67	1.39	0.26	1.26	0.20	1.17	0.22	0.65	0.10	0.70	0.11	1.55	0.22	2.11	2.91
Mon10	12.30	25.24	3.05	11.40	2.36	0.44	1.93	0.29	1.69	0.32	0.90	0.14	0.97	0.15	1.98	0.36	3.46	2.35
Mon11	12.53	24.23	3.13	11.98	2.53	0.56	2.50	0.37	2.24	0.42	1.18	0.19	1.26	0.19	1.89	0.30	3.24	7.30
Mon12	11.06	21.71	2.69	10.12	2.13	0.45	1.95	0.31	1.76	0.33	0.95	0.15	0.98	0.15	1.73	0.30	2.76	3.87
Mon13	8.50	16.72	2.18	8.18	1.72	0.32	1.57	0.25	1.45	0.28	0.79	0.13	0.84	0.13	1.64	0.25	2.51	6.71
Mon14	2.75	6.16	0.84	3.12	0.67	0.13	0.63	0.13	0.67	0.13	0.39	0.06	0.47	0.07	1.33	0.15	1.49	2.24
Mon15	48.45	103.87	12.43	43.28	8.65	1.61	6.38	0.86	4.65	0.84	2.38	0.38	2.54	0.37	3.46	1.15	11.89	2.18
Mon16	12.57	25.91	3.21	11.41	2.35	0.47	2.04	0.32	1.86	0.35	1.00	0.16	1.02	0.16	2.10	0.37	3.43	3.11
Mon17	13.66	27.62	3.61	13.35	3.07	0.62	2.74	0.43	2.61	0.49	1.45	0.23	1.49	0.24	2.12	0.38	3.60	4.20

Table 2c: Chemical analyses continued. Rare Earth Elements and other trace elements in ppm, determined by ICP-MS.

			SiO_2	Al_2O_3	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5
Mon1	c14	flake hammerscale >3	68.96	15.82	0.70	5.08	3.48	1.17	2.30	1.25	1.25
Mon2	c14	flake hammerscale from soil sample	64.40	18.71	0.95	5.35	3.47	1.49	2.51	1.67	1.46
Mon3	c14	macro flats (>5mm)	65.51	12.44	0.57	7.56	9.23	0.72	2.21	0.86	0.90
Mon4	c14	spheroids <1mm from soil									
Mon5	c14	spheroids 1-3mm from soil									
Mon6	c14	spheroids 3-5mm from soil and >3mm	81.60	8.89	0.49	3.69	2.59	0.33	0.85	0.83	0.72
Mon7	c14	spheroids >5mm from >5mm	82.00	10.39	0.45	2.49	1.76	0.00	1.22	0.88	0.79
Mon8	c56 aii + c	spheroids >5mm	73.02	13.95	0.45	3.04	3.96	1.00	3.29	0.87	0.44
Mon9	c56 aii	blisters	69.58	14.67	0.54	4.22	5.45	0.77	3.16	0.92	0.69
Mon10	c56 aii	dense dull slag	64.39	15.11	0.60	4.79	8.21	0.86	4.21	1.02	0.80
Mon11	c56 aii	flake hammerscale	71.02	14.73	0.47	3.82	4.62	0.79	3.04	0.85	0.65
Mon12	c56 aii	dense prills	69.73	17.30	0.58	2.19	3.92	1.10	3.56	1.13	0.50
Mon13	c14	amorphous slag >3mm	69.45	12.91	0.63	5.77	6.48	0.70	2.31	0.95	0.80
Mon14	c14	flats >3mm	70.84	12.44	0.70	6.16	5.21	0.87	1.66	0.98	1.13
Mon15	c56	fired clay	70.77	21.94	0.28	1.17	0.39	1.03	3.14	1.16	0.13
Mon16	c56	SHC1	73.87	13.11	0.51	2.38	4.23	1.24	3.38	0.86	0.43
Mon17	c56	SHC2	70.53	16.01	0.55	3.15	3.81	1.14	3.28	0.90	0.64

Table 3: Chemical analyses. Major elements expressed as wt% oxide, determined by XRF on fused beads. Analyses recast and normalised on iron-free basis.

Fraction	n	% hollow	Of those % Fe-oxide	% vesicular	Of those % Fe-oxide
<1mm	15	40%	100%	60%	67%
1-3mm	18	44%	63%	56%	30%
3-5mm	7	43%	100%	57%	75%
>5mm	2	0%	-	100%	0%

Table 4. Variation of the proportion of Fe oxide-dominated spheroidal particles (dominance of textures S1, S2, S3a, S4) versus silicate-dominated spheroids (textures S3b, S5 dominant) in hollow and vesicular particles

	Coolamurray	Navan Site 1	Carrigoran	Clonfad	Clonmacnoise (Waste water scheme)	Woodstown 6	Clonmacnoise (New Graveyard site)
count	41	17	18	513	38	140	117
min		60				68	100
max	2588	2990	3866	11000	5540	6310	7815
average	386	507	553	1153	1087	1060	843
<500	83%	82%	72%	29%	39%	40%	50%
<1000	95%	88%	89%	64%	68%	71%	78%
>1000	5%	12%	11%	36%	32%	29%	22%
>3000	0%	0%	6%	7%	8%	7%	3%
modal class	100-200	100-200	100-200	300-400	300-400	200-300	400-500

Table 5: Comparison of the Coolamurray SHC assemblage with other Irish early medieval assemblages. Navan Site 1 from Young 2007; Carrigoran from Young , 2006e; Clonfad from Young, 2006e; Clonmacnoise Waste Water Scheme from Young 2005b; Woodstown from Young, 2006f; Clonmacnoise New Graveyard site from the author's work in progress.

The early medieval assemblages from Coolamurray, Carrigoran and Navan are interpreted as being dominantly blacksmithing residues. The early medieval assemblages from Clonfad, Clonmacnoise and Woodstown are interpreted as including bloomsmithing residues.

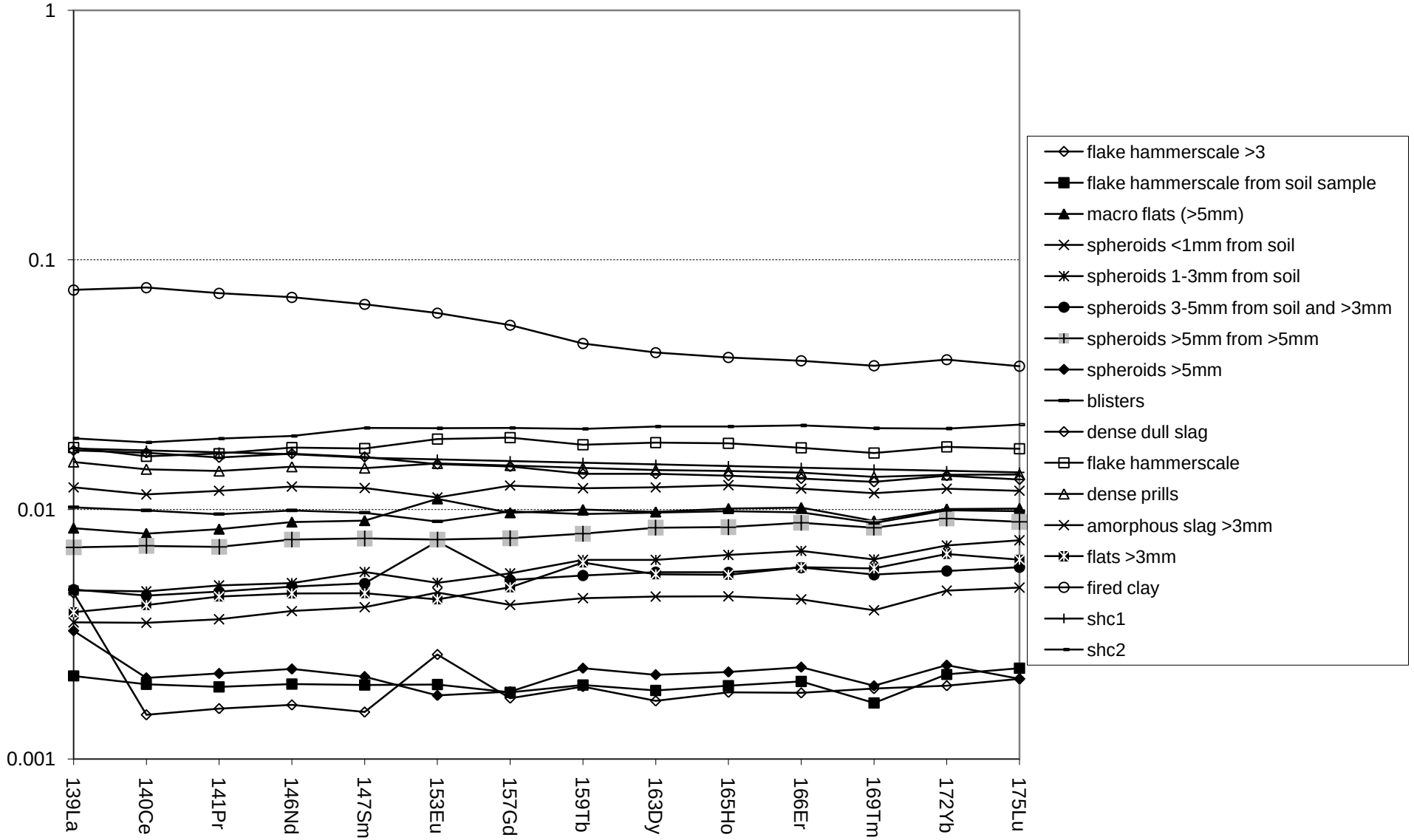
	Coolamurray	Marsh Leys Farm	Carmarthen	Worcester Deansway (period 8)	Worcester Deansway (period 9)	Burton Dassett
		Roman	Roman	11th – 13th	13th-15th	14th- 15th
count	41	30	136	61	32	60
min			100	168	144	130
max	2588	824	820	1490	1800	1670
average	386	333	227	492	499	550
<500	83%	77%	94%			
<1000	95%	100%	100%			
>1000	5%	0%	0%			
>3000	0%	0%	0%			
modal class	100-200	100-200	100-200			

Table 6: Comparison of the Coolamurray SHC assemblage with British blacksmithing assemblages. Burton Dassett from McDonnell 1992; Marsh Leys Farm from Young 2005a; Carmarthen from Crew 2003; Worcester Deansway from McDonnell & Swiss 2004.

Appendix 1: Additional materials for published report

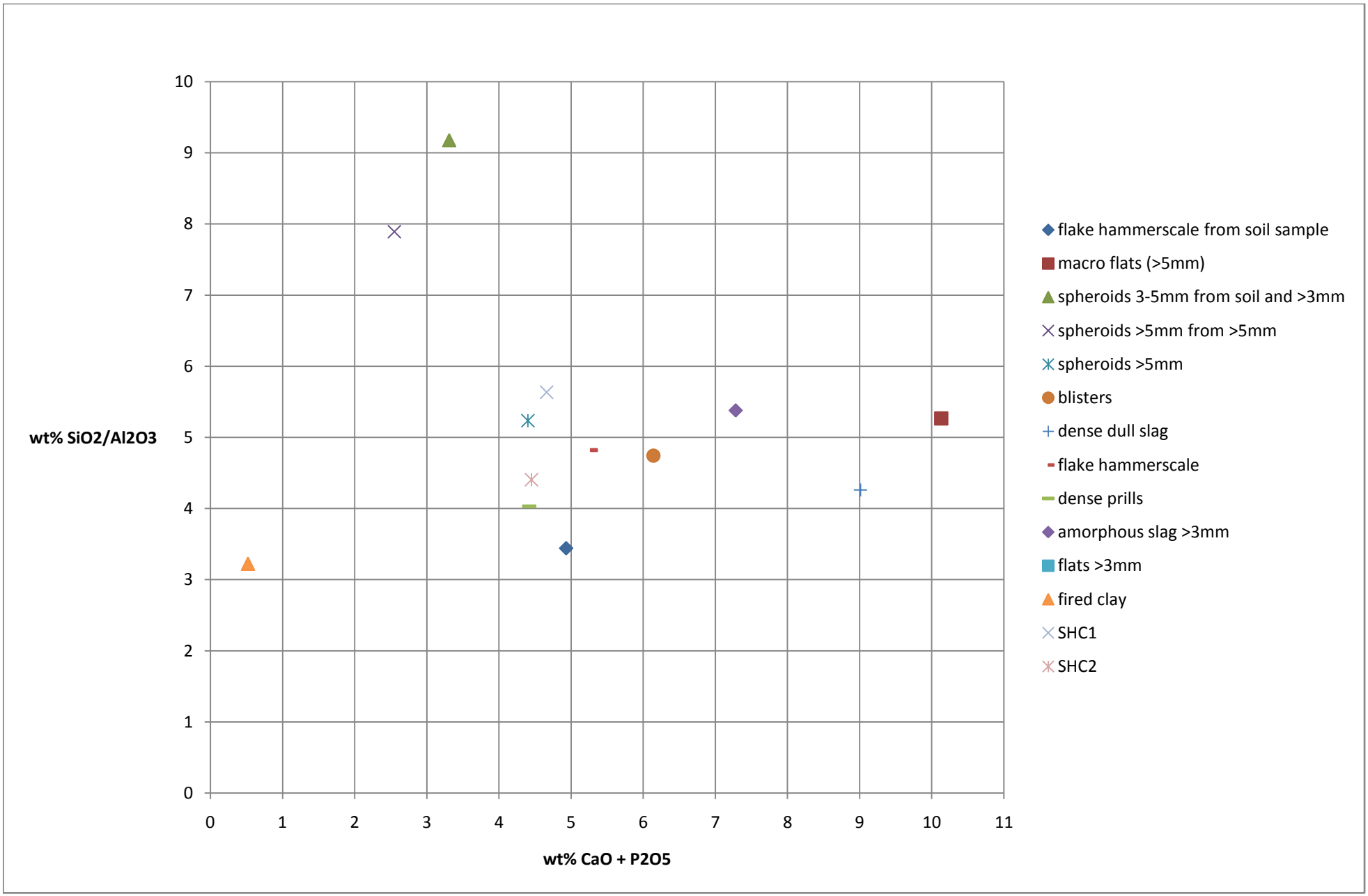
Additional Figure nn

Upper Crust –normalised REE profiles (normalisation after Taylor and McLennan 1981)


1
0.1
0.01
0.001
139La
140Ce
141Pr
146Nd
147Sm
153Eu
157Gd
159Tb
163Dy
165Ho
166Er
169Tm
172Yb
175Lu
flake hammerscale >3
flake hammerscale from soil sample
macro flats (>5mm)
spheroids <1mm from soil
spheroids 1-3mm from soil
spheroids 3-5mm from soil and >3mm
spheroids >5mm from >5mm
spheroids >5mm
blisters
dense dull slag
flake hammerscale
dense prills
amorphous slag >3mm
flats >3mm
fired clay
shc1
shc2

Additional Figure nn

Ratio of wt% SiO_2 to Al_2O_3 plotted against the total wt% of CaO and P_2O_5


wt% SiO2/Al2O3
wt% CaO + P2O5
0
1
2
3
4
5
6
7
8
9
10
11
flake hammerscale from soil sample
macro flats (>5mm)
spheroids 3-5mm from soil and >3mm
spheroids >5mm from >5mm
spheroids >5mm
blisters
dense dull slag
flake hammerscale
dense prills
amorphous slag >3mm
flats >3mm
fired clay
SHC1
SHC2

Additions to text

Section 4.2.3

(provide reference and insertion points for the two additional figures)

Section 5

An additional possibility for a stake hole close to the hearth would be as a support for a pivot for the a possible foot board to work the bellows. It appears that, certainly by later medieval times, the blast to forge hearths was typically provided by a pair of bellows working alternately. This system was superseded by the “double-action” smiths’ bellows of post-medieval times. Both systems were intended to provide a more constant draft than could be provided by a single bellows. The twin arrangement is often depicted with an overhead frame providing the pivot (e.g. Plate 5). For systems bowing a floor-level hearth (as opposed to a waist-level hearth), the overhead frame might be unnecessary, and a simple pivoting board, with the operator transferring their weight from one bellows to the other might suffice.

References

DUNGWORTH, D.

TAYLOR, S.R. & McLENNAN, S.M. 1981. The composition and evolution of the continental crust: rare earth element evidence from sedimentary rocks. Philosophical Transactions of the Royal Society, A301, 381-399.

Appendix 2: Summary Catalogue

Table A Metallurgical residues from Site 7, listed by bag

context	sample	find	find note	number	total wt (g)	description
Modern/late features				***total***	***5852***	
10				1	315	SHC fragment, base incorporates lots of shale gravel. Top shows a little black surface but otherwise this material is pale grey
				1	352	another similar very dense SHC weathered entirely pale grey, base of this one smoothish and vesicular, top smooth blown
				1	160	SHC fragment with preservation as two above, it has fallen lining on top surface with red fired clay and a small pebble, base vesicular as example above
				2	50	fragments of material as above
					877	very odd preservation to this material!
10				4	28	vitrified lining
				2	44	lining slag balls
				8	176	assorted dense slag fragments, mainly smoothed and concreted
					248	
10				1	126	small part of large SHC, base rather prilly, appears smooth but has ridge of lining slag stuck on, crust 25mm thick, probably rather deformed on extraction
				6	18	vitrified lining
				1	54	lobe of well flowed material penetrating into all, probably from burr region.
				2	78	small SHC fragments - probably from very small cakes
				1	50	worn very weathered SHC fragment with thick crust
				1	68	crudely flow lobed dense slag with dimpled lower surface
				15	178	various assorted indeterminate iron slags
					572	curious white weathering/coating
29				1	754	wide dense SHC, slightly dished smooth top, base slightly microprilly 120x110x45mm
				1	42	vitrified lining
				2	26	small weathered rounded slag nubs
				1	522	slightly incomplete double layer SHC, 110x70x80mm. Lower cake 90mm diameter, 25mm thick ,upper incomplete
					1344	
30				1	550	perfect SHC. 115x100x30mm, blown hollow top, base finely dimpled with some slight tool marks
				1	300	probably 60% of small SHC highly concreted top, base finely dimpled - cake probably very similar to above
				3	330	SHC fragments
				1	14	lining slag ball
				4	130	irregular dense slag fragments
					1324	
58				8	248	concretion; one piece probably a nail?
				1	1035	probably about 40% of thick crust SHC, approximately 180x140x70mm is best guess for original size, crust 35mm thick in centre, smooth top flown edge, no filling, heavily concreted
					1283	

Table A (contd.)

context	sample	find	find note	number	total wt (g)	description
Northern metalworking area						
c27 - circular feature 1 x 0.9m x 0.2 deep, filled by c14. Has burnt stake hole 0.14 diameter, 0.5 to NE (c21) and posthole c17 filled with c16 to north						
				total	***2012***	
	14	ex27		29	288	smithing floor with flake and some spheroidal hammerscale, slag and charcoal in abundance
				5	68	dense SHC fragments
				6	22	lining slags
				6	16	fired and vitrified lining
				2	8	light blebby, almost flown, lining dominated slag
					402	
	14			7	100	vitrified lining
	14				***1510***	(total of sieved residues - see table 4)
area to NE may be dump (C15=26)				***total***	***10280***	
	15			80	722	various assorted indeterminate iron slags
				24	186	lining and lining slags
				3	6	flown prill and 2 subspherical blebs
				3	12	rusty concretionary slags
				1	142	70x50x25mm very dense small SHC with smooth dished maroon top, lower face finely dimpled
				1	64	tongue of slag probably small SHC, smooth maroon flat top, finely but deeply dimpled base
					1132	
	15			103	2186	various assorted indeterminate iron slags
				20	216	lining slag
				4	24	dense prilly horizontal flows
				1	78	Slag tongue 95x50x15mm lining slag on top, dimpled underneath, look as if formed in inclined position
				2	52	concretionary material
				15	816	pieces of thinnish crust, folded, presumably deformed on extraction, none a complete piece
				1	218	c45% of dense open bowl shaped SHC with linear bit protruding at top on one side, crust c 10mm thick uniformly, probably originally c100mm diameter and 35mm deep
				1	132	probably a complete small, deformed SHC 70x50x40mm smoothish top, well dimpled base
				1	206	thick crust SHC fragment, crust to 28mm, tubular vesicles, top with free crystals. Estimated to be from cake c 140mm across, 40mm deep
				1	200	probably c 60-70% of dense SHC, specimen rather worn, base appears v slightly dimpled, top probably smooth
				5	326	pieces from fairly small SHCs
				1	92	c40% of SHC with dimpled base, c80mm diameter, top with additional 15mm of localised rather rough material
				6	360	small pieces of SHCs with thick crusts (I.e.>20mm thick), one of these is 66g piece from almost identical cake to the 92g piece above.
					4906	

Table A (contd.)

context	sample	find	find note	number	total wt (g)	description
15				2	122	SHC fragments, 1 from v small one from larger cakes
				3	12	vitrified lining
				15	84	lining slag blebs and balls
				99	896	irregular dense slags in various nubs and fragments
					1114	
15				1	290	complete SHC, slightly dished smooth top, edges slightly flowed, then dimpled zone, but most of base is charcoal rich, top slightly irregular 80x80x35mm
				1	276	90x80x25mm SHC, smooth top (mostly masked by concreted material) base rather irregular with some charcoal; some dimpled concreted material may be collapsed wall, layer of charcoal sealed between two, top smooth but irregular
				1	324	2 pieces probably from same thick crust SHC, base micro dimpled smooth and hard, crust has maximum thickness of 40mm, relatively few vesicles, top has free crystals, very small part of big cake
				6	714	SHC fragments, range from pieces similar to first two, to a piece with a 22mm crust
				5	82	lining slag lumps
				8	172	miscellaneous dense slag nubs, lobes and fragments
					1858	
15				8	136	lining slags
				1	8	lining
				6	348	SHC fragments, better bits show dimpled bases
				43	778	assorted indeterminate dense slags
					1270	
26 (total of sieved residues - see table B)					***126***	

Table A (contd.)

context	sample	find	find note	number	total wt (g)	description
Metalworking area 2						
c59 - circular bowl 0.92 x 0.82m x 0.3m in depth, filled with c60, 61, 62, 63, 44. Has burnt stake hole 0.35m from edge, c43.						
no macroscopic slag samples						
	63				***148***	(total of sieved residues - see table 4)
SE Metalworking area						
burnt deposit c56 overlies bowl 100 (1.2 x 0.8m), bowl 101 (0.85 x 0.3) and a line of stake holes						
				total	***28521***	
	56	area B		6	66	vitrified lining fragments
				22	288	vitrified deformed, lobate material from lining slags
				6	42	dense slag prills, probably mainly horizontal flows
				2	46	fragments from crust of dense slag cake, base microlobate, not very vesicular
				10	188	charcoal rich rusty irregular slags with some concretion. Both flake and spheroidal hammerscale seen
				35	884	denser lobate slags, all very irregular hearth slags, some show development of prills
				1	140	possible deformed small concavo-convex SHC - looks broken and twisted on extraction, originally 70x70x20, top smooth, bottom charcoal rich
				1	62	irregular disk of lining slag - possibly an Fe-poor SHC
				1	68	approx half of small bowl-shaped SHC, 65mm diameter x 30mm deep
				1	52	possible very irregular SHC fragment
				1	48	small piece from small SHC, rough base, smoothish maroon top, c65mm diameter and 20mm deep
					1884	
	56	area B		30	498	irregular to lobate dense slags
				32	306	irregular but generally lobate to slightly prilly lining slags
				1	12	oxidised lining fragment
				5	104	extremely dense lobate slag flow - looks like tap slag but generally only one lobe thick
				13	214	irregular fragments of charcoal bearing rusty grey slag - charcoal generally fine and one case straw-like
					1134	also 5 stones weighing 36g
	56	area B			50	fine debris
				9	8	lining fragments
				14	116	dense flowed material, mainly heavily fragmented poor flows
				12	108	rusty material, mainly rich in fine organics
				36	420	irregular, mainly slightly lobate material, formed of moderately dense slag,
				33	140	irregular, mainly slightly lobate material, formed of low density lining slag
					842	also 6=214g stones

Table A (contd.)

context	sample	find	find note	number	total wt (g)	description
56		SW		1	148	probably 80% of small SHC, rather folded, excellent mineralised organics on base including bracken, 60x80x25mm (proximal end gone), top smooth, base smooth but covered by accreted impregnated organics
				1	404	85x88x40mm, very neat SHC, slightly dished smooth top, base very regular microdimpled, cake very nearly circular
				1	194	small SHC with lots of accreted debris, nearly circular dished cake approx. 80mm diameter
				3	292	irregular dense slag pieces probably from SHCs
				10	1210	fragments of SHCs, all probably fairly small as those above
				1	42	tiny cake, possibly a SHC
				1	170	approximately half of an SHC with an organic coated base, top with very marked charcoal dimples and points, approx 90mm diameter, 30mm deep of which crust is 17mm in the centre and thinning to edges
				1	202	small piece from presumably big SHC, 50mm thick of which 30mm crust, approx 50x50mm
				1	200	double layer SHC with abundant charcoal and vesicles, upper part c 70mm diameter, lower on one side only, total 50mm thick
				10	216	irregular pieces of rounded lining slag
				1	138	lining dominated probable shc, v irregular
				1	82	lining dominated irregular lump possible shc
				3	214	SHC-related slags with deeply charcoal dimpled bases (almost prilly)
				4	256	irregular probably slightly flowed flattened pats of dense slag
				10	226	irregular fragments of dense slag
				1	8	oxidised lining
					4002	
56		SW		1	90	possibly corroded tiny SHC, 60x50x25mm, smooth top dimpled base
				44	596	indeterminate iron slag fragments
				2	36	lining
				14	94	fragments and nubs of lining slag
				1	10	slagged pebble fragment
				8	590	SHC fragments
					1416	
56				1	***18***	well lobed horizontal flow of dense slag
56		area d	3 of 3	8	436	irregular but generally rather lobed slab like masses with mainly Fe-rich dense below and lining dominant above
				7	416	irregular slags, dominantly dense
				10	532	dense, fragments including a crust
				3	122	lining slags
				3	54	concretionary
				2	60	dense slags with very strong dimples/microprills
				1	196	extremely irregular SHC, blown upper sheet 80x60x20mm with prilly base, on lower cake with microprilly/dimpled base 80x40x30mm - not clear but probably a double-layer cake. The 436g category above contains several flaps rather like the upper cake.
				1	344	very irregular cake with prilly base, upper part and margins broken
					2160	

Table A (contd.)

context	sample	find	find note	number	total wt (g)	description
56		area d	2 of 3	26	484	irregular dense smithing hearth slags
				3	38	vitrified lining
				6	90	lining slag lumps
				2	84	heavily concreted material
				1	22	flown slag lobe
				6	206	dense fragments including a crust
				1	210	dished SHC with smooth top and finely deeply dimpled base 80x105x30
				1	168	small SHC greatly deformed on extraction, cut in half with lots of flowage
				1	142	small SHC with deeply dimpled base and extreme charcoal lobes/dimples on top 75x60x25mm with further 25mm of lobes on top
				1	100	60x65x25mm smooth topped SHC with fines dimpled base with up to 15mm of amorphous material stuck to top - very neat cake
				1	280	approx 60%? of SHC cut in half on extraction .smooth blown top, bowl shaped probably approx 120mm diameter 30mm deep, cake only 7mm thick in centre- thicken at edges
				1	120	irregular prilly mass, probably a poorly formed SHC, but may be missing its top
					1944	
56		area D		95	872	irregular dense slags
				3	110	SHC fragment
				2	26	concretion around artefacts?
				19	108	concretionary material
				17	84	lining slag blebs
				2	4	dense slag flowed material
					1204	
56					***13917***	(total of sieved residues - see table B)

Features associated with SE metalworking area

				total	***8834***	
48				6	204	dense slags of various types with 1 SHC fragment, concreted surface with organics and in one case hammerscale
66				1	110	thin dense slab - probably a broken part of small SHC, concreted material is very rich in hammerscale, both flake and scale, as well as small pieces of broken slag.
				1	94	very irregularly lobate small sub b/h slag. Some lobes dense some more lining dominated 60x65x30mm
					204	

Table A (contd.)

context	sample	find	find note	number	total wt (g)	description
77				2	40	lining
				18	630	lining slags, some of the largest have denser iron rich parts - so these are mixed hearth slags
				1	128	small dish-shaped SHC, probably c80% c60x90x28mm
				1	98	contorted lining rich slag - probably a low density SHC
				1	460	small piece of large thick crust SHC, crust 30mm in centre, base with irregular tool marks, top smooth, has small puddle of black sediment rich glass in centre of smooth dished top. Probably less than 30% of whole.
				28	794	amorphous pieces and nubs of dense slag, all slightly to moderately concreted
				1	156	small piece of basal angle of "thin crust" granular to microprilly SHC. Side at 80 deg to base. What crust there is has maximum thickness of 5mm. Internally lots of fine charcoal
				6	662	various SHC fragments, most standard type, one is more prilly internal like example above
					2968	
77				1	456	very curious triangular SHC, probably pinched up on extraction, main part 50x130x55mm with tongue extending distally at top
				1	320	incomplete, probably deformed SHC, base slightly prilly as example above
				1	268	small SHC with heavy concretion of material rich in organics, 80x114x40mm, smooth top
				1	126	broken piece of complex and probably deformed SHC
				1	110	lobate slab of lining slag with concretion attached
				7	60	vitrified lining
				1	20	lining slag nub
				39	608	irregular pieces of dense slag - many heavily concreted
					1968	
77				1	344	pyramidal granular to finely prilly slag SHC. Highly rusted and exploding protrusion on the top - suggestive of an adhering iron piece. Ignoring protrusion cake is 60x75x55mm, protrusion adds another 20mm
				1	162	small SHC - or part SHC, very charcoal-rich 80x60x45mm, base smooth to microdimpled with tool (or fold?) mark
				4	96	lining and lining slag
				4	106	indeterminate dense slags
					708	
77				1	18	piece of iron bar,38 wide, 5 thick, 1 edge perpendicular, 1 cut oblique - so 13 long one side and 18 the other, bar margins appear to thin slightly
				1	938	double SHC, lower one 65x85x35mm, upper 100x110x50mm, both appear to have smooth blown tops and be dense. Lower surfaces partly microprilly, partly adhering charcoal-rich, minimal contact of cakes, all rather corroded
				1	554	probably c80% of dense wide SHC, 100x100x45mm, smooth blown top, lower probably microprilly but corroded
				1	362	100x75x45mm, most of small dense SHC, but edges knocked off, top very smooth, dished, base, microprilly/microdimpled
				1	270	large part of dense SHC, probably originally 100x120x45mm, crust 35mm or more in centre, just very thin vesicular material on top where not blown
				1	140	smithing hearth slag in form of irregular ball
				8	338	various pieces of dense smithing slag
				8	126	lining slags and small lining fragments
					2746	

Table A (contd.)

context	sample	find	find note	number	total wt (g)	description
77 (fired clay)				12	28	vitrified oxidised lining
				1	8	probable corroded nail c15x12mm head, 20mm long shank
					36	

Table B Metallurgical resides from site 7: gridded / sieved samples

context	weight	grid	bag label	notes
gridded samples of uncertain processing				
56	158	a i	slag	mainly large lumps of floor around shc fragments, also a few very angular flat prills and a couple of spheroids (large)
56	1160	a ii	slag	158 moderately dense slags; 2g 7 "coffee bean" spheroids; 12g dense prills; 18g flats; 20 bubbly flat fragments; 16g small stones; 884g smithing floor
56	144	a iii	slag	mainly smithing floor; 2 isolated "coffee bean" spheroids; 1 flat fragment and one small piece with flowed prills
56	638	a v	slag	small pieces of floor; some slag prills and blebs; lots of broken bubbly flat material; plenty of flats; some corroded iron metal - mainly as sheet
56	24	vi	slag	flat pieces of slag/scale/flat and abundant spheroids
56	64	vi	slag	amorphous fragments of floor and slag, some poor flats and bubbles
56	34	vii	slag	ashy lumps of floor material - looks as if fine matrix would have been very hammerscale-rich
56	1	ix	slag	flat pieces of slag/scale/flat and abundant spheroids
56	22	ix	vit clay	amorphous bits, couple of poor spheroids and a fragment of flat
56	1035	c	slag	26g stone; 11.2g 8 flats; 70g broken slag lump; 76g small slag pieces; many highly porous flowed slags; rest is good smithing floor
56	258	c	s14 slag	1.35g 4 coffee bean spheroids; also 4 spheroidal hammerscale; 29.3g 6 small pieces of smashed shc; 11.6g 6 other small pieces of prilly or lobate slags; rest smithing floor, with one tiny lining fragment
56	232	c	baked clay	fine debris of fired clay and ash with charcoal. 1 strongly vitrified lining/tuyère fragment with rich green glaze
56	286	c	baked clay natural s14	72g fired clay; 44g 3 pieces vesicular slag; 22g 3 slagged lining; 114g stones; 8g worn dense slag nub
56	18.1	d xxvi	slag	poor concreted slag in small pieces; about half of this stone
56	156	e xii		4 pieces of charcoal-rich floor, probably concreted around iron; a rectangular cross-section of iron, like a nail shank, was seen in one piece
56	30	xiii	slag	lots of rather amorphous looking debris, a few poor spheroids
56	88	xv	slag	moderately abundant spheroids and flat material, but dominated by more amorphous material
56	12	xvii	slag vit clay	amorphous material and small flat fragments
56	766	e xvii	vitrified clay	230g 50-60% of small shc; 168g shc frag; 106g 4 other slag lumps; remainder is smithing floor material
56	30	e xvii	slag	very small slag and smithing floor particles
56	814	e xvii	vit clay/slag	22g stone; remainder is lumps of concreted smithing floor, charcoal rich, with some straw, but only small slag pieces
56	512	e xvii		164g gravel; rest is small smithing floor fragments, including 1 small flow lobe frag
56	518	e xvii	vitrified clay	17g of low density dimpled lobes, remainder charcoal-rich smithing floor
56	26	e xvii	slag	lots of rather amorphous looking debris
56	546	e xviii		gravel with ashy clay matrix. Does contain some spheroidal + flake hammerscale, but only tiny slag pieces and almost no concretionary floor
56	560	e xviii	vitrified clay	74g stone; 266g 2 pieces of thin shc in clay floor; rest small slag pieces in clay-rich smithing floor, including one piece of vitrified clay wall
56	1	xviii	slag	bubbly, prill, floor and flake hammerscale

Table B (contd.)

context	weight	grid	bag label	notes
sieved slag samples (5mm)				
56	76	a iii	slag 5mm	slag fragments, bubbles, burnt stones, flats blebs
56	826	a vi	5mm	about 80g of small slag pieces (including 3 "coffee bean" spheroids and 2 flats) - rest is gravel. No smithing floor
56	1380	a viii	slag 5mm	4 substantial pieces of shc; lots of smithing slag; several slagged and melted stones; finer material includes small prills and "coffee bean" spheroids. Several pieces of smithing floor with iron inclusions - 1? Nail head, but two others appear more sheet-like
56	728	d ix	slag 5mm	466g 50% of large shc, dense; 60g smithing slag lump; 4.45g 20 "coffee-bean" spheroids; 25.5g flowed slag pieces, some dense; remainder smithing floor debris
56	786	xiii	slag 5mm	106g 5 small pieces of dense slag; 60g irregular slab of lining slag; 46g 16 pieces of low density nubs and blebs; remainder smithing floor
56	358	e xv	slag 5mm	dark smithing floor rich in slag and scale, but not charcoal and very rich in spheroidal hammerscale; 14g irregular slag nub
56	820	e xvii	slag 5mm	brown fine ashy detritus with lots of scale (subsequently processed with soil samples, see Table 5)
sieved slag samples (3mm)				
56	80	a I	slag 3mm	amorphous material with some flats
56	2	a I	slag 3mm	rather amorphous looking debris
56	234	a ii	slag 3mm	flat pieces of slag/scale/flat and abundant spheroids
56	52	a iii	slag 3mm	flat pieces of slag/scale/flat and abundant spheroids
56	244	a v	slag 3mm	flat pieces of slag/scale/flat and abundant spheroids
56	132	viii	slag 3mm	flat pieces of slag/scale/flat and abundant spheroids
56	66	a ix	slag 3mm	flat pieces of slag/scale/flat and abundant spheroids
14	1050		slag 5mm	7.32g 24 spheroids; 14.4g 32 pieces of flat; 3g pieces of lining slag; remainder smithing floor, amorphous slag and broken bubbly slags. Almost no stone - very rich smithing assemblage.
14	460		s#18, slag 3mm	fantastic assemblage of spheroids (coffee beans) and coarse flake hammerscale
	1510			
63	76	5mm?	s#9 slag	some flats and spheroids but mainly amorphous slag fragments, also glazed pebble and lining fragment
63	72		s#9 slag	flat pieces of slag/scale/flat and abundant spheroids, very rich in scale
	148			
26	126		s#10 slag 3mm	flat pieces of slag/scale/flat and abundant spheroids, flat material more abundant than spheroids?

Table C. Summary of processing of soil samples

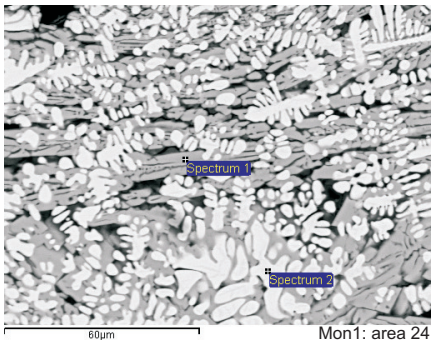
Context	*Grid*	*Sample Notes*	*Sample weight*	*Charcoal notes*	*>200µm sample weight*	*Residue notes*
C56	A IV	somewhat clayey, produced a little bit of charcoal in float, but more seems to be present in residue	8.5kg	a picked sample of 12g a flotation sample of 44g	4.85 kg	Residue very rich in scale. Also some sand/gravel
C56	D XXIV	This was a very charcoal-rich sample	11kg	a flotation sample of 360g	1.20 kg	Residue gravelly, with little slag debris
C56	CI	Very clay rich	11.5kg	very little flot picked large charcoal pieces from slag, 6g	5.32 kg	Residue very rich in scale. Also some sand/gravel
C56	E	lots of slag lumps in clay	7.4kg	no flot at all	4.71 kg	lots of sand and gravel – but v rich in scale; includes small SHC, and other fragments
C56	E XVII	washed sample taken from slag collection not soil samples		a flotation sample of 10g	516 g	Residue gravelly, with little slag debris. Lots of flake hammerscale but masked by non-slag material
C63	*N/a*		9kg	little flot, but did yield possible blackberry pips	3.41 kg	Residue almost pure scale
C14	*N/a*		c8kg	lots of charcoal: a flotation sample of 260g 1g sample picked from slag	3.19 kg	Very scale-rich residue, has some stone and gravel

Appendix 3: Microanalysis

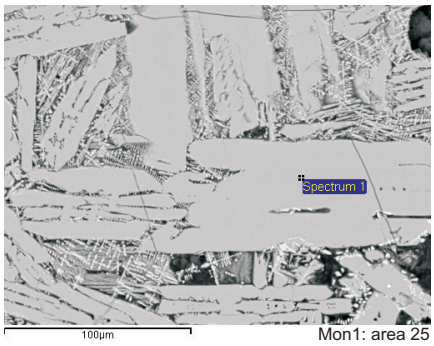
Sample	Site	Spectrum	Analysis notes	All results in atomic%												All results in weight%														olivine							wt% oxides											
				O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	O	Na	Mg	Al	Si	P	S	Cl	K	Ca	Ti	Mn	Fe	*Total*		Mg	Fe	Ca	Mn		Fa	%Ca	Na2O	MgO	Al2O3	SiO2	P2O5	S	Cl	K2O	CaO	TiO2	MnO	FeO	total
1	24	1	fayalite	55.63		4.34	0.23	14.04	0.19				1.1			24.48	30.03		3.56	0.21	13.31	0.2				1.48			46.12	*94.91*		0.29	1.64	0.07	0.00		0.85	4%	0.00	5.90	0.40	28.47	0.46	0.00	0.00	0.00	2.07	0.00	0.00	59.33	96.37
1	25	1	fayalite	54.62		0.88	0	14.72					0.07		0.11	29.59	28.21		0.69	0	13.35					0.09		0.19	53.35	*95.88*		0.06	1.93	0.00	0.01		0.97	0%	0.00	1.14	0.00	28.55	0.00	0.00	0.00	0.00	0.13	0.00	0.25	68.63	98.70
1	26	1	fayalite	55.17		0.99	0	14.68					0.06		0.12	28.98	28.51		0.78	0	13.32					0.08		0.21	52.27	*95.17*		0.07	1.92	0.00	0.01		0.97	0%	0.00	1.29	0.00	28.49	0.00	0.00	0.00	0.00	0.11	0.00	0.27	67.24	97.41
1	27	1	fayalite	56.25		0.89	0.18	14.08					0.08	0	0.14	28.37	30.76		0.74	0.17	13.52					0.11	0	0.27	54.14	*99.71*		0.06	1.92	0.01	0.01		0.97	0%	0.00	1.23	0.32	28.92	0.00	0.00	0.00	0.00	0.15	0.00	0.35	69.65	100.62
1	27	2	fayalite	56.15		1.03	0.13	14.24					0.09	0	0.09	28.27	30.68		0.85	0.12	13.66					0.12	0	0.17	53.91	*99.51*		0.07	1.92	0.01	0.01		0.96	0%	0.00	1.41	0.23	29.22	0.00	0.00	0.00	0.00	0.17	0.00	0.22	68.35	100.59
1	27	3	fayalite	56.86		0.45	0.3	13.8					0.09	0	0.1	28.42	31.32		0.38	0.27	13.34					0.12	0	0.19	54.64	*100.26*		0.03	1.96	0.01	0.01		0.98	0%	0.00	0.63	0.51	28.53	0.00	0.00	0.00	0.00	0.17	0.00	0.25	70.29	100.38
1	27	4	fayalite	57.07		0.45	0.41	13.7					0.1	0.09	0.08	28.1	32.11		0.38	0.39	13.53					0.14	0.16	0.16	55.17	*102.04*		0.03	1.96	0.01	0.01		0.98	0%	0.00	0.63	0.74	28.94	0.00	0.00	0.00	0.00	0.20	0.27	0.21	70.98	101.95
1	27	5	fayalite	56.37		0.51	0.27	13.8					0.09	0	0	28.96	30.63		0.42	0.25	13.17					0.12	0	0	54.93	*99.52*		0.03	1.96	0.01	0.01		0.98	0%	0.00	0.70	0.47	28.17	0.00	0.00	0.00	0.00	0.17	0.00	0.00	70.67	100.17
1	27	6	fayalite	56.28		0.66	0.16	13.85					0.08	0	0.11	28.85	30.68		0.55	0.15	13.25					0.11	0	0.21	54.9	*99.85*		0.04	1.94	0.01	0.01		0.98	0%	0.00	0.91	0.28	28.34	0.00	0.00	0.00	0.00	0.15	0.00	0.27	70.63	100.59
1	28	3	cont fayalite	56.76	0	0.17	1.69	10.52				0	0.31	0.07	0.08	30.21	29.65	0	0.14	1.49	9.65				0	0.41	0.11	0.15	55.09	*97.03*		0.01	1.96	0.02	0.01		0.99	1%	0.00	0.23	2.82	20.64	0.00	0.00	0.00	0.00	0.57	0.18	0.19	70.87	95.51
1	28	4	cont fayalite	56.39	0.57	0.29	2.39	12.59				0.58	0.3	0.1	0.07	26.73	31.43	0.45	0.24	2.25	12.32				0.8	0.42	0.16	0.14	52	*100.19*		0.02	1.95	0.02	0.01		0.99	1%	0.61	0.40	4.25	26.35	0.00	0.00	0.00	0.96	0.59	0.27	0.18	66.90	100.50
3	15	1	mg rich fayalite	56.62	0.2	5.46	0	14.03	0			0	1.31	0	0.13	22.26	32.56	0.17	4.78	0	14.16	0			0	1.88	0	0.25	44.68	*98.48*		0.37	1.53	0.09	0.01		0.80	4%	0.23	7.93	0.00	30.29	0.00	0.00	0.00	0.00	2.63	0.00	0.32	57.48	98.87
3	16	1	mg rich fayalite	57.03	0	5.48	0	13.88	0			0	0.97	0	0.12	22.53	32.8	0	4.79	0	14.01	0			0	1.39	0	0.24	45.24	*98.46*		0.38	1.55	0.07	0.01		0.80	3%	0.00	7.94	0.00	29.96	0.00	0.00	0.00	0.00	1.94	0.00	0.31	58.20	98.36
3	17	1	mg rich fayalite	57.11	0	2.96	0.2	13.82	0			0	0.6	0	0.12	25.18	32.22	0	2.54	0.19	13.69	0			0	0.85	0	0.24	49.58	*99.3*		0.21	1.74	0.04	0.01		0.89	2%	0.00	4.21	0.36	29.28	0.00	0.00	0.00	0.00	1.19	0.00	0.31	63.78	99.13
3	17	3	mg rich fayalite	57.39	0	3.24	0.15	13.87	0			0	0.57	0	0.14	24.64	32.74	0	2.81	0.15	13.89	0			0	0.81	0	0.27	49.06	*99.73*		0.23	1.72	0.04	0.01		0.88	2%	0.00	4.66	0.28	29.71	0.00	0.00	0.00	0.00	1.13	0.00	0.35	63.11	99.25
3	18	1	area -ol	54.99	0.97	1.99	9.58					0.61	1.39	0.07	0.08	30.32	28.91		0.78	1.76	8.84				0.79	1.83	0.12	0.14	55.66	*98.82*		0.12	1.80	0.08	0.00		0.94	4%	0.00	1.29	3.33	18.91	0.00	0.00	0.00	0.95	2.56	0.20	0.18	71.61	99.02
3	20	1	mg rich fayalite	56.9	0	3.82	0	14.04	0	0		0	0.49	0	0.17	24.57	32.3	0	3.3	0	13.99	0	0		0	0.7	0	0.34	48.69	*99.32*		0.26	1.69	0.03	0.01		0.87	2%	0.00	5.47	0.00	29.92	0.00	0.00	0.00	0.00	0.98	0.00	0.44	62.64	99.45
3	20	2	mg rich fayalite	57.09	0	2.66	0	14.03	0	0		0	0.64	0	0.15	25.43	31.62	0	2.24	0	13.65	0	0		0	0.88	0	0.28	49.18	*97.85*		0.18	1.76	0.04	0.01		0.91	2%	0.00	3.71	0.00	29.19	0.00	0.00	0.00	0.00	1.23	0.00	0.36	63.27	97.77
3	21	1	mg rich fayalite	56.82	0	4.34	0.12	14	0.09			0	0.47	0	0.16	24	32.34	0	3.75	0.11	13.99	0.1			0	0.67	0	0.32	47.67	*98.94*		0.30	1.66	0.03	0.01		0.85	2%	0.00	6.22	0.21	29.92	0.23	0.00	0.00	0.00	0.94	0.00	0.41	61.33	99.12
4	21	1	mg-rich fayalite	56.01		3.2	0.45	13.81					0.52	0	0.11	25.91	30.65		2.66	0.42	13.26					0.71	0	0.21	49.49	*97.39*		0.22	1.74	0.03	0.01		0.89	2%	0.00	4.41	0.79	28.36	0.00	0.00	0.00	0.00	0.99	0.00	0.27	63.67	98.50
4	21	2	mg-rich fayalite	56.18		3.02	0.5	12.45					0.56	0	0.08	27.21	30.43		2.48	0.46	11.84					0.76	0	0.15	51.45	*97.57*		0.20	1.76	0.04	0.01		0.90	2%	0.00	4.11	0.87	25.32	0.00	0.00	0.00	0.00	1.06	0.00	0.19	66.19	97.75
4	21	3	mg-rich fayalite	59.96		3.32	0.43	13.47					0.49	0	0.07	22.26	37.98		3.19	0.46	14.98					0.78	0	0.16	49.21	*106.76*		0.25	1.70	0.04	0.01		0.87	2%	0.00	5.29	0.87	32.04	0.00	0.00	0.00	0.00	1.09	0.00	0.21	63.31	102.80
4	21	4	mg-rich fayalite	55.27		2.8	0.58	12.68					0.71	0.11	0.13	27.71	29.14		2.25	0.52	11.74					0.94	0.18	0.23	50.99	*95.99*		0.18	1.77	0.05	0.01		0.91	2%	0.00	3.73	0.98	25.11	0.00	0.00	0.00	0.00	1.32	0.30	0.30	65.60	97.33
4	30	3	fayalite	61.91		1.01	1.32	9.03	0.26	0			0.72	0	0	25.75	33.8		0.84	1.22	8.65	0.27	0			0.99	0	0	49.07	*94.83*		0.07	1.87	0.05	0.00		0.96	3%	0.00	1.39	2.31	18.50	0.62	0.00	0.00	0.00	1.39	0.00	0.00	63.13	86.98
4	35	1	olivine core	56.35	0	10.63	0	14.33	0	0	0		0.91	0	0.13	17.65	34.38	0	9.86	0	15.35	0	0	0		1.38	0	0.27	37.58	*98.83*		0.73	1.20	0.06	0.01		0.62	3%	0.00	16.35	0.00	32.83	0.00	0.00	0.00	0.00	1.93	0.00	0.35	48.35	99.81
4	35	2	olivine core	56.35	0	11.45	0	14.23	0	0	0		0.69	0	0.09	17.2	34.54	0	10.66	0	15.32	0	0	0		1.05	0	0.19	36.81	*98.58*		0.78	1.17	0.05	0.01		0.60	2%	0.00	17.68	0.00	32.77	0.00	0.00	0.00	0.00	1.47	0.00	0.25	47.36	99.51
4	35	5	marginal olivine	56.81	0	5.8	0.28	13.9	0.15	0	0		1.71	0	0.11	21.24	33.4	0	5.18	0.28	14.35	0.17	0	0		2.52	0	0.22	43.59	*99.7*		0.40	1.47	0.12	0.01		0.79	6%	0.00	8.59	0.53	30.69	0.39	0.00	0.00	0.00	3.53	0.00	0.28	56.08	99.87
4	35	6	marginal olivine	58.48	0	4.48	0.24	13.96	0.09	0	0		1.85	0	0.15	20.75	35.69	0	4.16	0.24	14.95	0.11	0	0		2.83	0	0.32	44.19	*102.5*		0.33	1.52	0.14	0.01		0.82	7%	0.00	6.90	0.45	31.97	0.25	0.00	0.00	0.00	3.96	0.00	0.41	56.85	100.66
5	3	1	olivine	56.83		2.23	0.44	12.8	0.12				0.76	0.09	0.11	26.62	31.12		1.86	0.4	12.3	0.13				1.04	0.15	0.21	50.88	*98.1*		0.15	1.79	0.05	0.01		0.92	3%	0.00	3.08	0.76	26.31	0.30	0.00	0.00	0.00	1.46	0.25	0.27	65.46	97.71
5	3	2	olivine	56.45		2.65	0.51	12.79	0.11				0.77	0	0.08	26.64	30.1		2.15	0.46	11.97	0.12				1.03	0	0.15	49.59	*95.56*		0.18	1.77	0.05	0.01		0.91	3%	0.00	3.57	0.87	25.60	0.27	0.00	0.00	0.00	1.44	0.00	0.19	63.80	95.59
5	3	3	olivine	56.25		2.62	0.44	12.93	0				0.77	0.08	0.15	26.75	30.26		2.14	0.4	12.21	0				1.04	0.14	0.28	50.24	*96.71*		0.17	1.77	0.05	0.01		0.91	3%	0.00	3.55	0.76	26.11	0.00	0.00	0.00	0.00	1.46	0.23	0.36	64.63	97.10
5	12	1	olivine	63.24	0	1.2	1.05	9.38	0.21	0			0.97	0	0	23.94	35.7	0	1.03	1.1	9.3	0.23	0			1.38	0	0	47.19	*95.83*		0.09	1.83	0.09	0.00		0.95	4%	0.00	1.71	1.89	19.89	0.53	0.00	0.00	0.00	1.93	0.00	0.00	67.91	86.36
5	15	2	olivine	56.8	0.24	2.88	1.41	14.54	0.09	0.83			4.37	0.07		18.76	32.45	0.2	2.5	1.36	14.58	0.1			1.16	6.25		0.14	37.41	*96.15*		0.22	1.44	0.34	0.00		0.87	17%	0.27	4.15	2.57	31.18	0.23	0.00	0.00	1.40	8.75	0.00	0.18	48.13	96.72
5	17	4	olivine?	60.08	0	2.83	1.71	13.21	0.1	0			2.65	0	0	19.42	36.72	0	2.63	1.76	14.17	0.12			0	4.06	0	0	41.42	*100.89*		0.23	1.56	0.21	0.00		0.87	11%	0.00	4.36	3.33	30.31	0.27	0.00	0.00	0.00	5.68	0.00	0.00	53.29	97.08
5	21	1	olivine	57.41		2.82	0.32	13.64					1.5	0	0	24.31	33.11		2.47	0.31	13.81					2.17	0	0	48.93	*100.8*		0.20	1.70	0.10	0.00		0.90	5%	0.00	4.10	0.59	29.54	0.00	0.00	0.00	0.00	3.04	0.00	0.00	62.95	100.20
5	25	3	olivine	56.98		2.25	2.01	12.3	0.15				1.94	0.09	0.1	24.17	31.22		1.87	1.86	11.83	0.16				2.66	0.15	0.19	46.23	*96.17*		0.16	1.70	0.14	0.01		0.91	7%	0.00	3.10	3.51	25.30	0.37	0.00	0.00	0.00	3.72	0.25	0.25	59.47	95.77
5	29	3	olivine	58.01		4.27	0	13.09					1.19	0	0.12	22.78	34.41		3.85	0	13.63					1.77	0	0.41	47.16	*102.61*		0.30	1.62	0.07	0.01		0.84	4%	0.00	6.38	0.00	29.15	0.00	0.00	0.00	0.00	2.48	0.00	0.53	59.67	99.21
5	29	4	olivine	56.49	0	1.23	0.66	13.23	0				0.25	0.09	0	28.06	31.11	0	1.03	0.62	12.79	0				0.34	0.14	0	53.94	*99.96*		0.08	1.90	0.02	0.00		0.96	1%	0.00	1.71	1.17	27.36	0.00	0.00	0.00	0.00	0.48	0.23	0.00	69.39	100.34
5	29	5	olivine	56.84	0	1.54	0.98	13.45	0.13				0.2	0	0.07	26.79	32.16	0	1.32	0.93	13.36	0.14				0.29	0	0.14	52.92	*101.26*		0.11	1.87	0.01	0.00		0.95	1%	0.00	2.19	1.76	28.57	0.32	0.00	0.00	0.00	0.41	0.00	0.18	68.08	101.33
5	47	1	olivine	55.34		4.74	0.21	14.53					0.44		0.18	24.56	30.65		3.99	0.2	14.13					0.6		0.35	47.48	*97.4*		0.32	1.64	0.03	0.01		0.84	1%	0.00	6.62	0.38	30.22	0.00	0.00	0.00	0.00	0.84	0.00	0.45	61.08	99.59
6	3	1	olivine	57.37	0	0.22	0.59	13.81				0.1	0.06	0.08		27.76	30.39	0	0.18	0.53	12.84				0.13	0.08	0.13		51.34	*95.63*		0.02	1.98	0.00	0.00		0.99	0%	0.00	0.30	1.00	27.46	0.00	0.00	0.00	0.16	0.11	0.22	0.00	66.05	95.30
6	5	1	olivine	56.58	0	0.24	0.49	14.27				0.08	0	0		28.35	29.13	0	0.19	0.47	12.9				0.1	0			50.94	*93.67*		0.02	1.98	0.00	0.00		0.99	0%	0.00	0.32	0.79	27.59	0.00	0.00	0.00	0.00	0.12	0.00	0.00	65.53	94.35
6	1	1	olivine	57.12		0.39	0.37	13.77					0.23			28.12	31.85		0.33	0.35	13.48					0.32			54.73	*101.06*		0.03	1.96	0.02	0.00		0.99	0%	0.00	0.55	0.66	28.83	0.00	0.00	0.00	0.00	0.45	0.00	0.00	70.41	100.90
6	9	2	olivine	55.85		0.36	0.47	13.84					0.24			29.24	28.16		0.28	0.4	12.25					0.3			51.46	*92.84*		0.02	1.96	0.02	0.00		0.99	1%	0.00	0.46	0.76	26.20	0.00	0.00	0.00	0.00	0.42	0.00	0.00	66.20	94.04
6	14	1	olivine	57.51		0.49	1.45	13.19					0.16	0	0	27.2	32.6		0.42	1.39	13.13					0.22	0	0	53.83	*101.6*		0.04	1.95	0.01	0.00		0.98	1%	0.00	0.70	2.63	28.08	0.00	0.00	0.00	0.00	0.31	0.00	0.00	69.25	100.96
7	3	1	olivine	56.65		1.04	1.03	13.41					0	0.18	0.27	27.42	31.55		0.88	0.97	13.11					0	0.31	0.51	53.3	*100.63*		0.07	1.91	0.00	0.02		0.96	0%	0.00	1.46	1.83	28.04	0.00	0.00	0.00	0.00	0.52	0.66	68.57	101.08
7	**3**	**2**	**olivine**	**56.94**		**0.62**	**0.49**	**13.73**					**0.1**	**0.16**	**0.21**	**27.75**	**31.76**		**0.53**	**0.46**	**13.44**					**0.14**	**0.26**	**0.4**	**54.03**	***101.03***		**0.04**	**1.94**	**0.01**	**0.01**		**0.98**	**0%**	**0.00**	**0.88**	**0.87**	**28.75**	**0.00**	**0.00**	**0.00**	**0.00**	**0.20**	**0.43**	**0.52**	**69.51**	**101.15**
7	3	3	olivine	56.44		1.24	0.58	13.7					0	0.12	0.23	27.69	31.23		1.04	0.54	13.31					0	0.19	0.43	53.49	*100.23*		0.09	1.90	0.00	0.02		0.96	0%	0.00	1.72	1.02	28.47	0.00	0.00	0.00	0.00	0.32	0.56	68.81	100.90
7	6	1	olivine	56.99		3.43	0.2	13.78	0.1	0			0.99	0	0.12	24.39	32.83		3	0.2	13.94	0.11	0			1.43	0	0.23	49.04	*100.77*		0.24	1.69	0.07	0.01		0.88	3%	0.00	4.97	0.38	29.81	0.25	0.00	0.00	0.00	2.00	0.00	0.30	63.09	100.66
7	6	3	olivine	56.45		3.74	0.39	13.98	0	0			0.91	0	0.09	24.43	32.03		3.23	0.37	13.93	0	0			1.3	0	0.17	48.4	*99.42*		0.26	1.68	0.06	0.01		0.87	3%	0.00	5.36	0.70	29.79	0.00	0.00	0.00	0.00	1.82	0.00	0.22	62.27	100.15
7	6	4	olivine	57.36		1.04	1.92	13.09					0.52	0.07	0	26.02	31.9		0.88	1.8	12.78					0.73	0.11	0	50.5	*98.69*		0.08	1.89	0.04	0.00		0.96	2%	0.00	1.46	3.40	27.33	0.00	0.00	0.00	0.00	1.02	0.18	0.00	64.97	98.37
9	4	2	olivine	57.28		1.33	1.7	13.21					0.44	0.1	0.11	25.84	31.68		1.12	1.59	12.83					0.61	0.16	0.2	49.88	*98.07*		0.10	1.86	0.03	0.01		0.95	2%	0.00	1.86	3.00	27.44	0.00	0.00	0.00	0.00	0.85	0.27	0.26	64.17	97.85
9	4	1	olivine	57.36	0	1.86	0.23	13.75	0			0	0.41	0	0.19	26.18	32.37	0	1.6	0.22	13.62	0			0	0.59	0	0.37	51.58	*100.36*		0.13	1.83	0.03	0.01		0.93	1%	0.00	2.65	0.42	29.13	0.00	0.00	0.00	0.00	0.83	0.00	0.48	66.36	99.86
9	7	2	olivine	57.18	0	0.96	0.24	13.83	0			0	0.55	0	0.15	27.09	32	0	0.82	0.22	13.59	0			0	0.77	0	0.28	52.92	*100.62*		0.07	1.88	0.04	0.01		0.97	2%	0.00	1.36	0.42	29.07	0.00	0.00	0.00	0.00	1.08	0.00	0.36	68.08	100.36
9	7	4	olivine?	56.54	0.83	0	5.84	10.91	0.15			2.42	2.04	0.29	0.07	20.91	33.05	0.7	0	5.75	11.19	0.17			3.45	2.99	0.5	0.14	42.66	*100.6*		0.00	1.82	0.18	0.01		1.00	9%	0.94	0.00	10.86	23.93	0.39	0.00	0.00	0.00	4.16	4.18	0.83	0.18	54.88	100.15
9	10	1	olivine	56.61	0	1.64	0.33	13.79	0			0	0.57	0	0.18	26.87	31.26	0	1.38	0.31	13.36	0			0	0.79	0	0.34	51.79	*99.23*		0.11	1.84	0.04	0.01		0.94	2%	0.00	2.29	0.59	28.57	0.00	0.00	0.00	0.00	1.11	0.00	0.44	66.63	99.62
9	10	2	olivine	57.76	0	1.18	0.89	13.32	0.11			0.34	1.05	0.08	0.18	25.08	32.89	0	1.03	0.85	13.32	0.13			0.47	1.5	0.14	0.36	49.84	*100.51*		0.09	1.82	0.08	0.01		0.96	4%	0.00	1.71	1.61	28.49	0.30	0.00	0.00	0.00	0.57	2.10	0.23	0.46	64.12	99.41
9	10	4	olivine	57.12	0	1.47	0.16	13.89	0			0	0.53	0	0.2	26.63	31.64	0	1.24	0.15	13.5	0			0	0.74	0	0.38	51.49	*99.13*		0.00	1.86	0.04	0.01		0.95	2%	0.00	2.06	0.28	28.87	0.00	0.00	0.00	0.00	1.04	0.00	0.49	66.24	98.98
9	12	1	area -ol	56.43	0.73	0.66	4.21	13.55				1.28	1.97	0.19	0	20.97	31.61	0.59	0.56	3.97	13.33				1.75	2.76	0.32	0	41	*95.9*		0.06	1.78	0.17	0.00		0.97	8%	0.80	0.93	7.50	28.51	0.00	0.00	0.00	2.11	3.86	0.53	0.00	52.75	96.98
10	2	1	olivine core	56.64	0	4.66	0.14	14.06	0	0		0	0.65	0	0.33	23.52	32.22	0	4.03	0.13	14.04	0	0		0	0.92	0	0.65	46.7	*98.7*		0.32	1.61	0.04	0.02		0.83	2%	0.00	6.68	0.25	30.03	0.00	0.00	0.00	0.00	1.29	0.00	0.84	60.08	99.16
10	2	2	olivine margin	55.77	0	4.46	0.14	14.29	0.1	0		0	0.69	0	0.36	24.19	31.24	0	3.8	0.13	14.05	0.11	0		0	0.96	0	0.7	47.31	*98.3*		0.30	1.63	0.05	0.02		0.84	2%	0.00	6.30	0.25	30.05	0.25	0.00	0.00	0.00	1.34	0.00	0.90	60.86	99.82
10	2	4	olivine	56.45	0.26	2.83	1.93	14.22	0	0		0.36	1.34	0	0.29	22.33	32.36	0.21	2.46	1.87	14.31	0	0		0.5	1.92	0	0.56	44.68	*98.88*		0.21	1.67	0.10	0.02		0.89	5%	0.28	4.08	3.53	30.61	0.00	0.00	0.00	0.00	2.69	0.00	0.72	57.48	99.99
10	**4**	**1**	**olivine**	**56.58**

| | | |

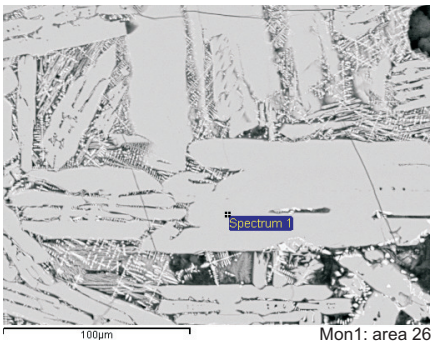
Plate 6



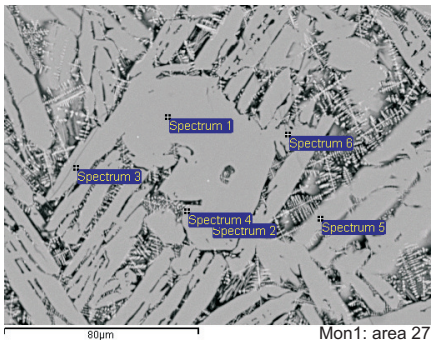
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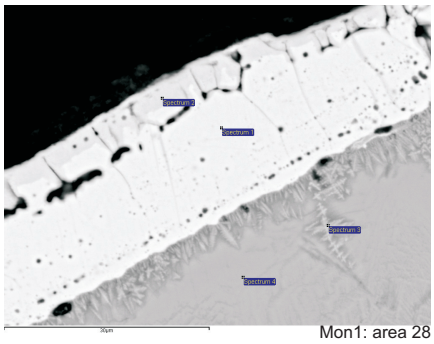
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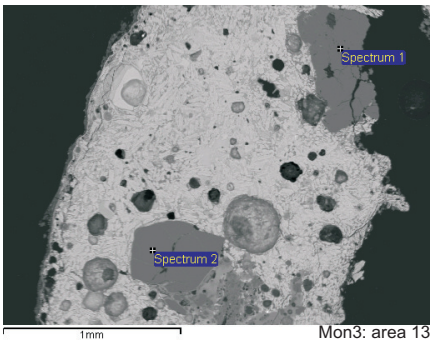


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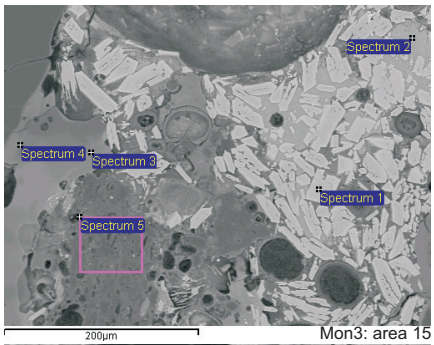


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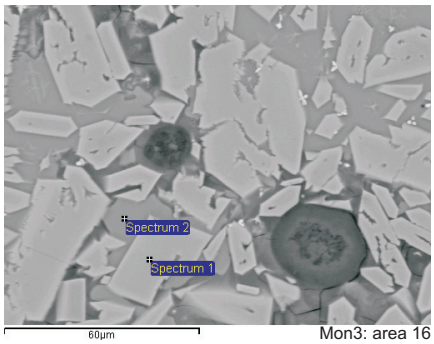

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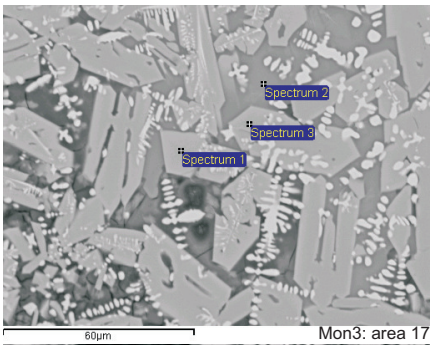
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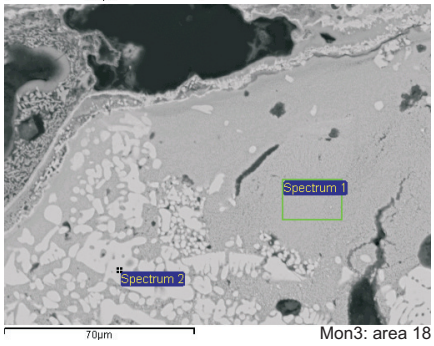
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Mon3: area 16

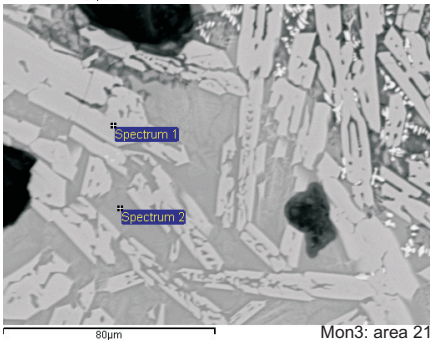


Mon3: area 17



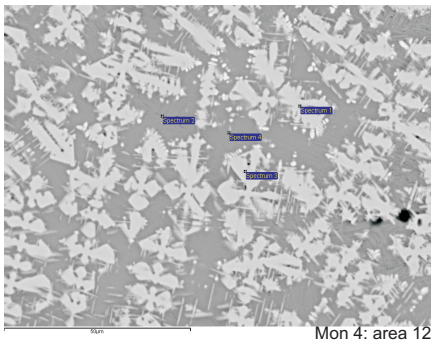
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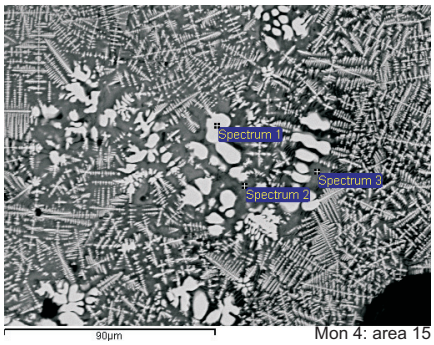

Mon3: area 20



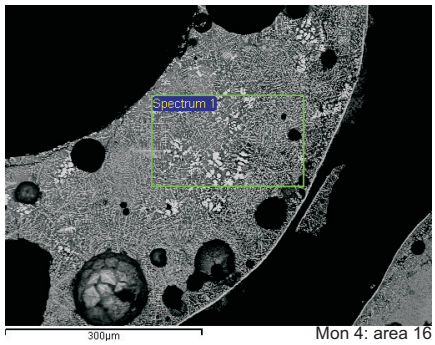
Mon3: area 21

Plate 7

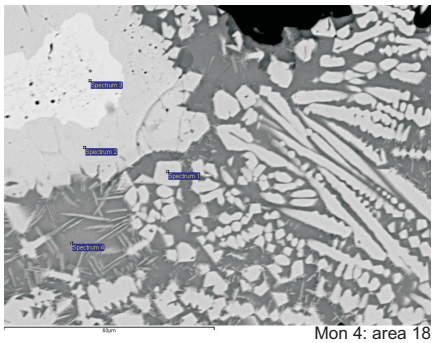

Mon 4: area 12

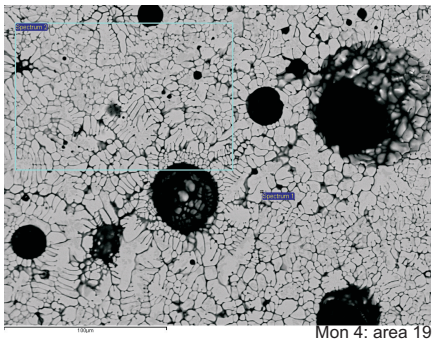


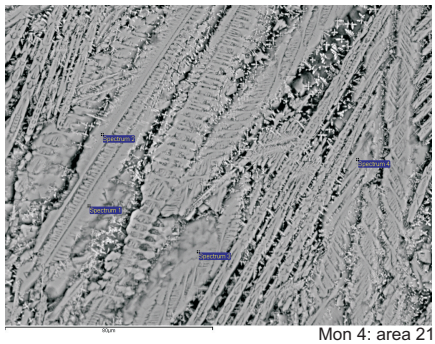
Mon 4: area 15

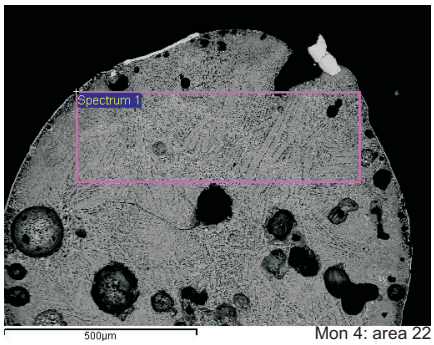


Mon 4: area 16

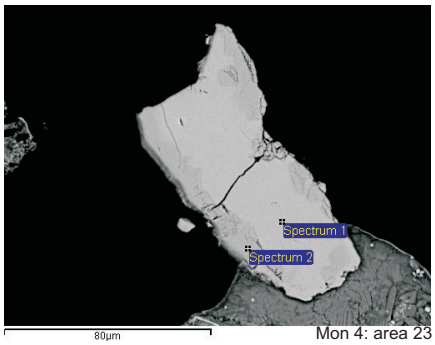

Mon 4: area 18


Mon 4: area 19

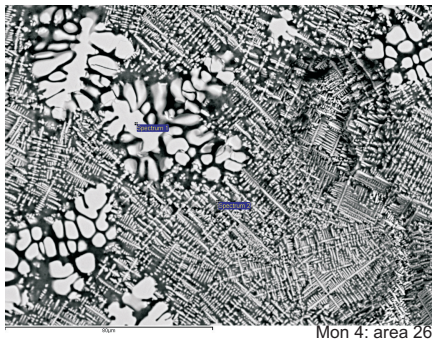

Mon 4: area 21

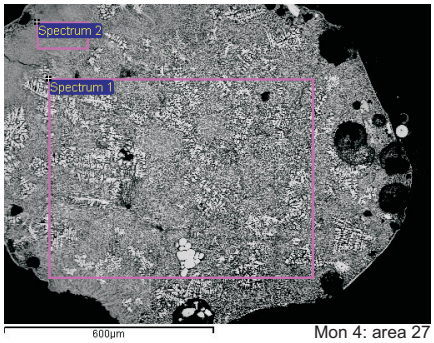


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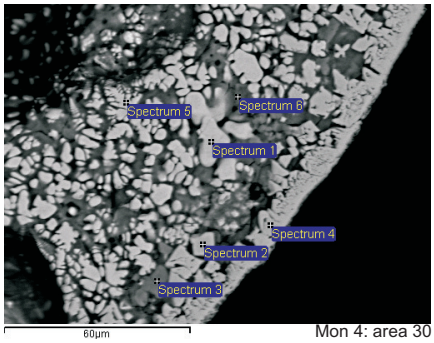


Mon 4: area 23

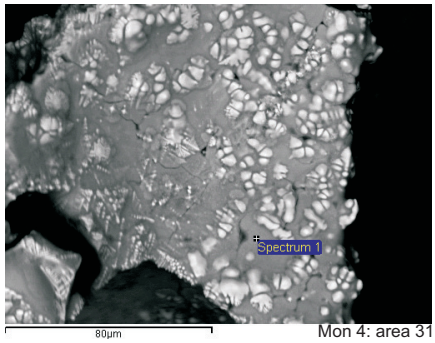

Mon 4: area 26



Mon 4: area 27

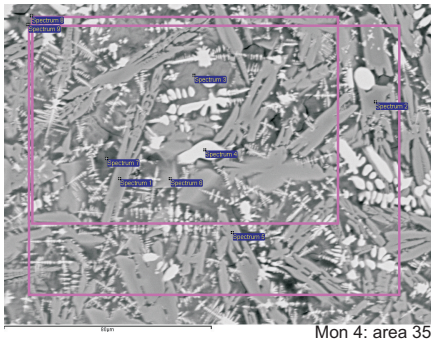


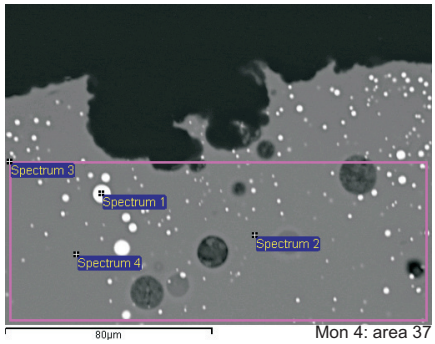
Mon 4: area 30



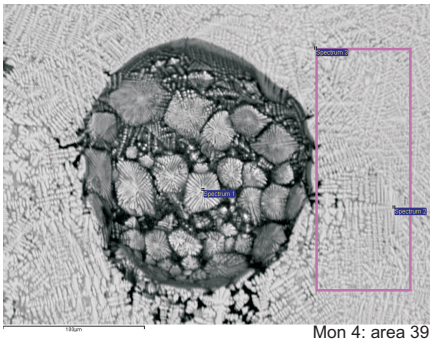
Mon 4: area 31


Mon 4: area 34


Mon 4: area 35



Mon 4: area 37


Mon 4: area 39

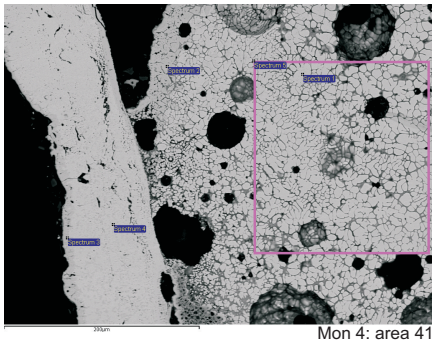
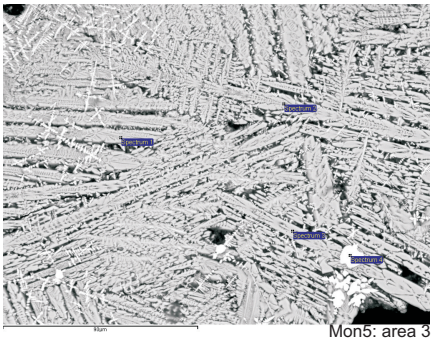
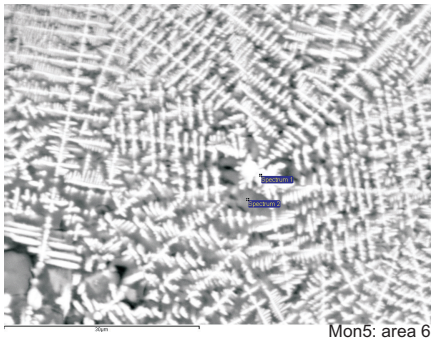
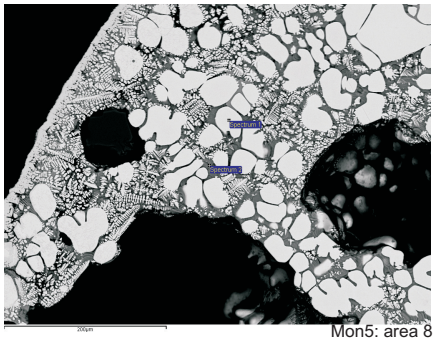
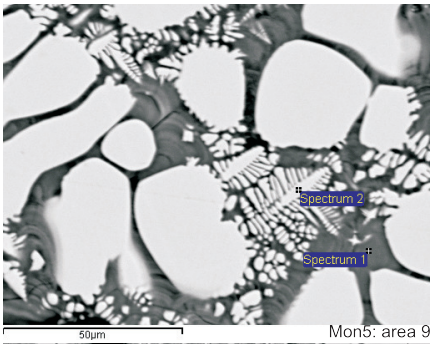

Mon 4: area 41

Plate 8

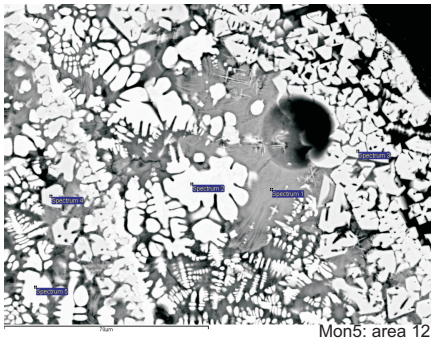

Mon5: area 3

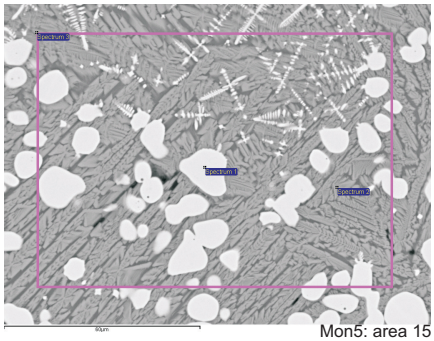

Mon5: area 6

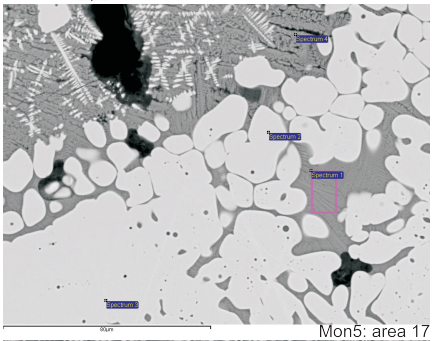

Mon5: area 8

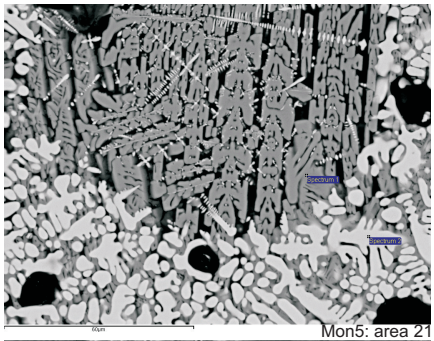


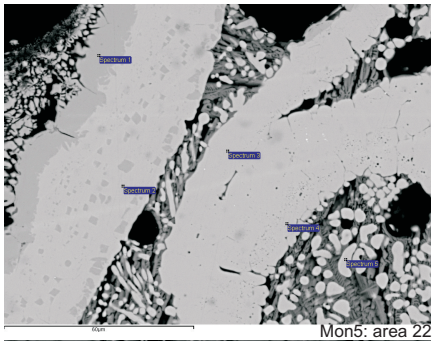
Mon5: area 9

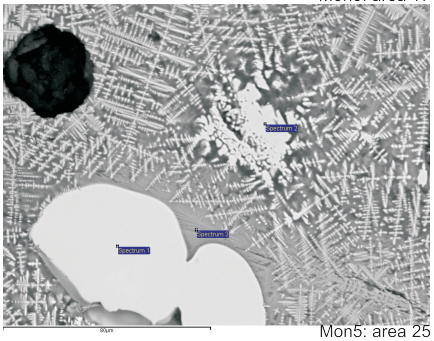

Mon5: area 12

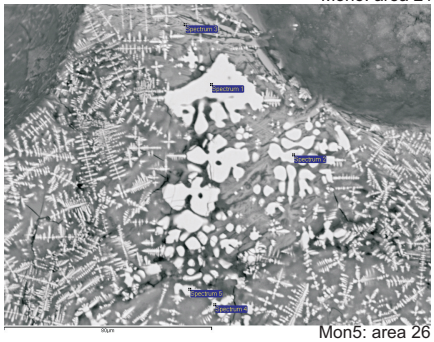

Mon5: area 15

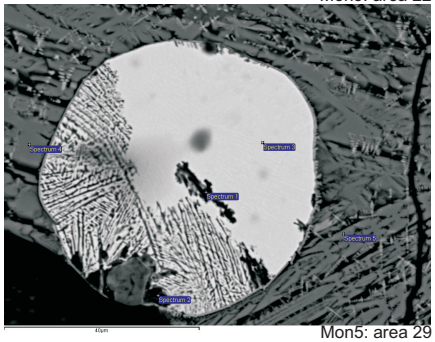

Mon5: area 17

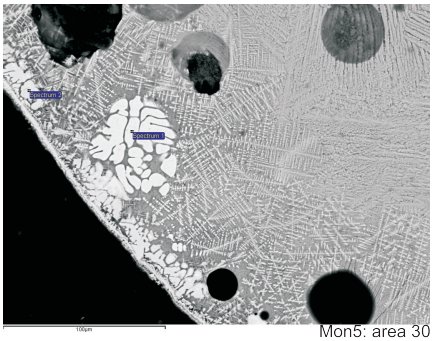

Mon5: area 21

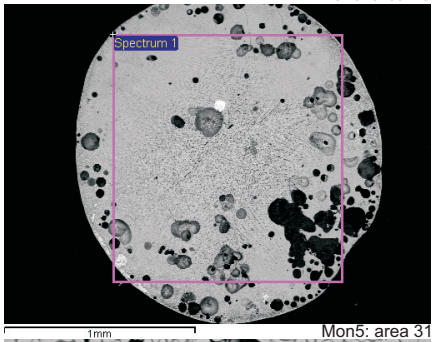

Mon5: area 22


Mon5: area 25

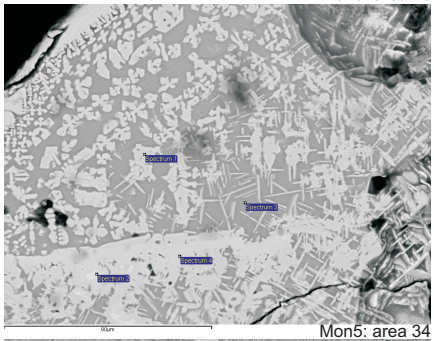

Mon5: area 26

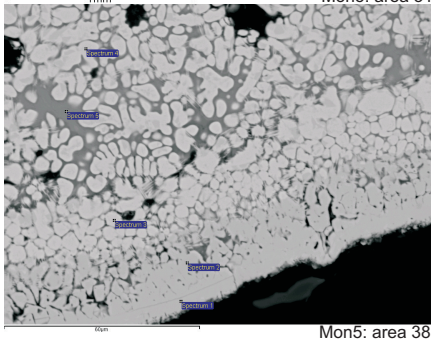

Mon5: area 29


Mon5: area 30



Mon5: area 31


Mon5: area 34


Mon5: area 38

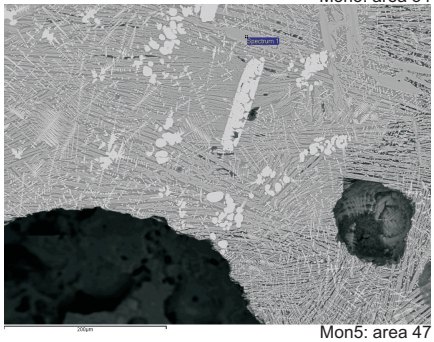
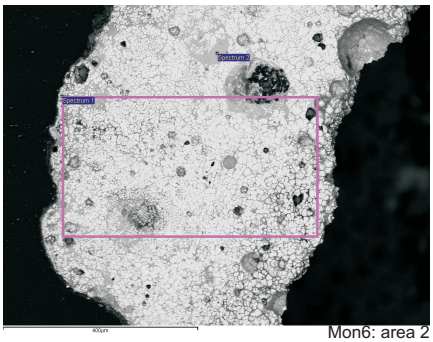
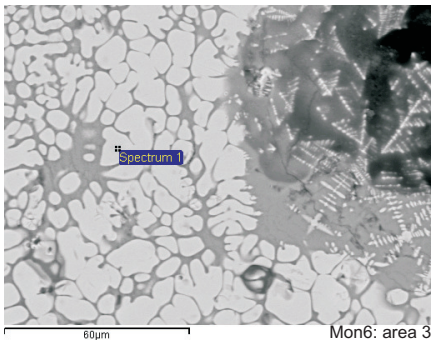
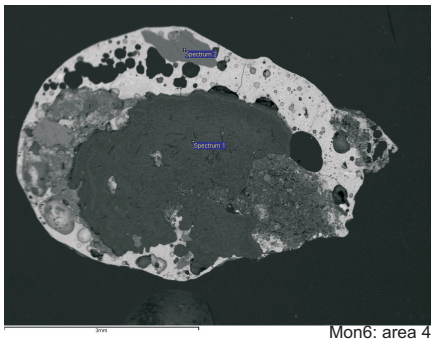

Mon5: area 47

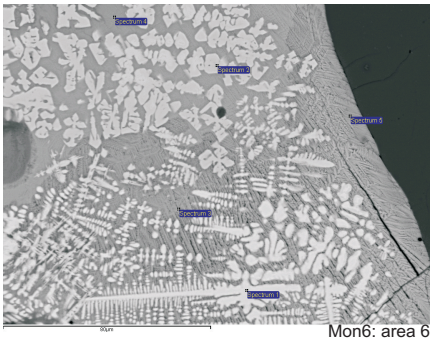
Plate 9

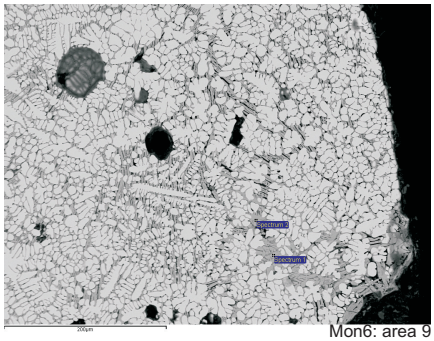

Mon6: area 2

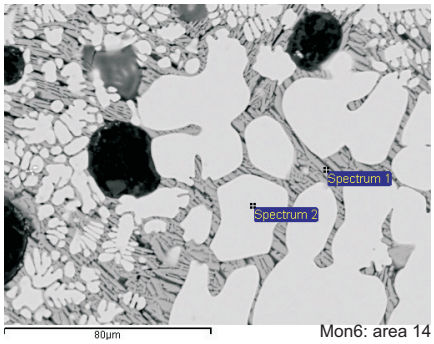


Mon6: area 3

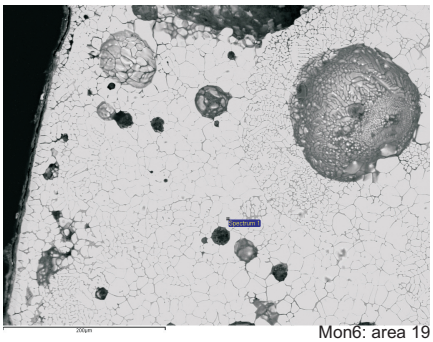

Mon6: area 4

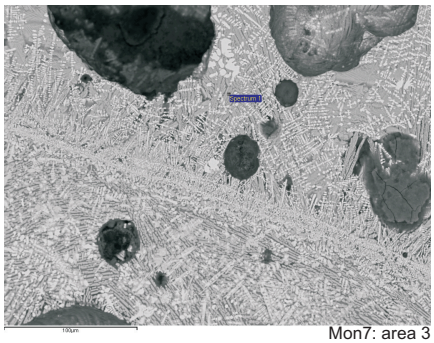

Mon6: area 6

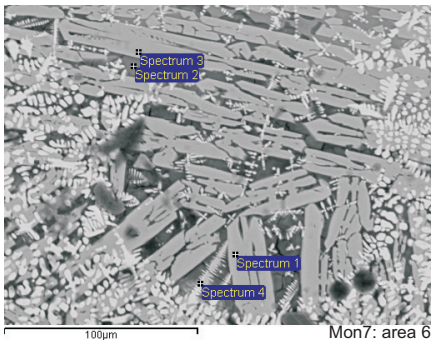

Mon6: area 9



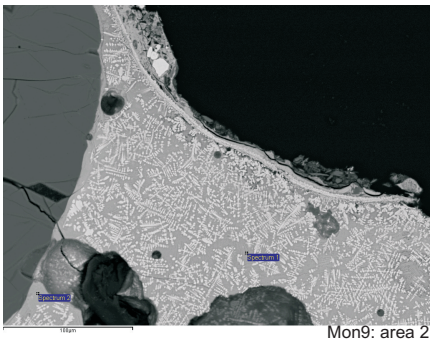
Mon6: area 14

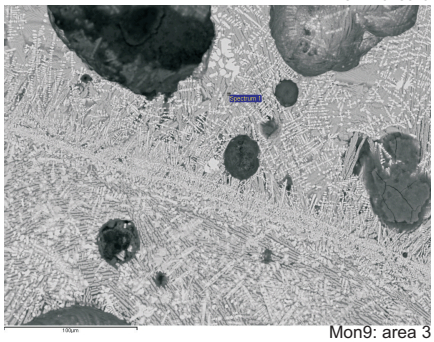

Mon6: area 19

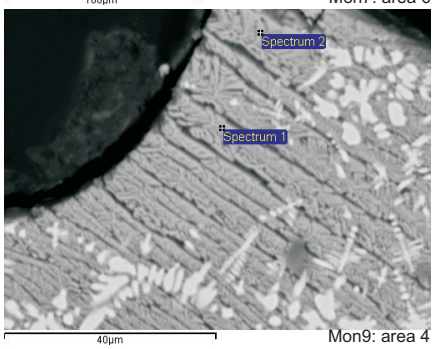

Mon7: area 3



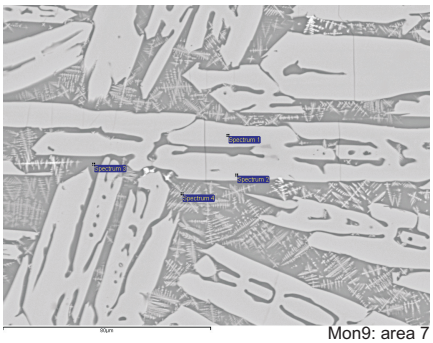
Mon7: area 6

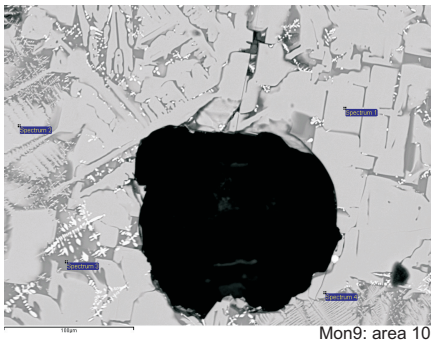

Mon9: area 2


Mon9: area 3



Mon9: area 4


Mon9: area 7


Mon9: area 10

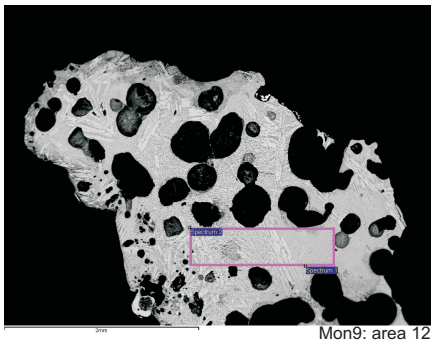
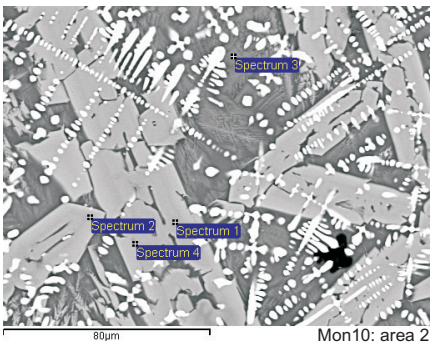
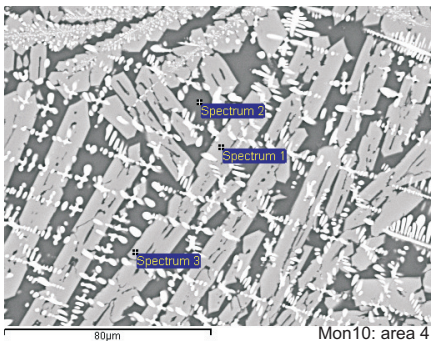

Mon9: area 12

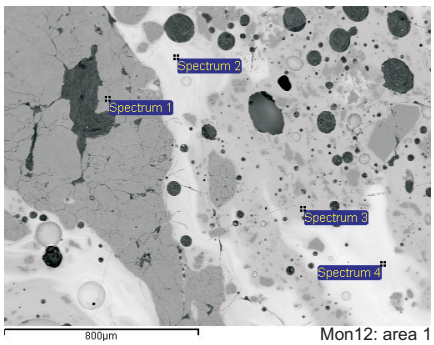
Plate 10



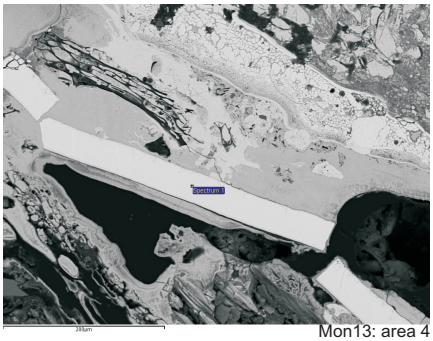
Mon10: area 2

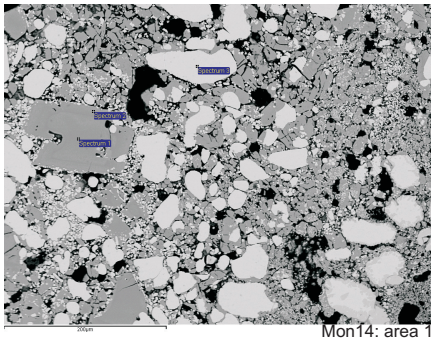


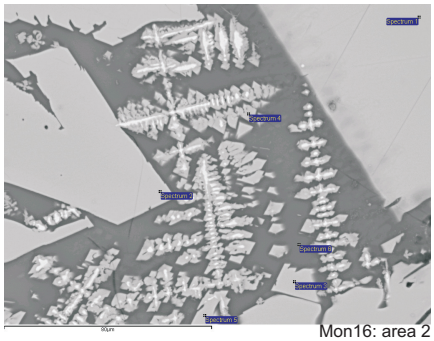
Mon10: area 4

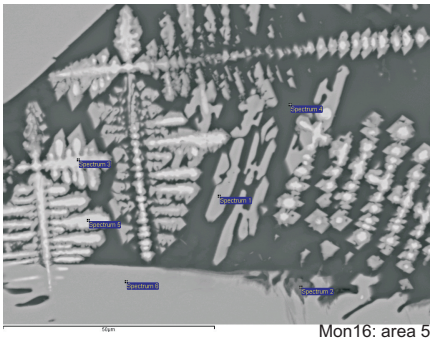


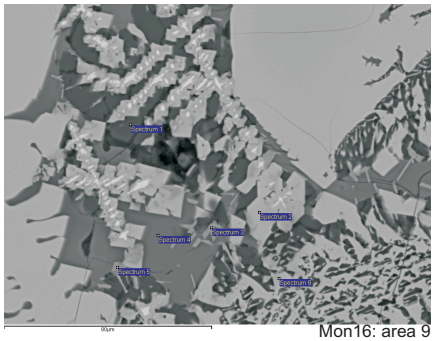
Mon12: area 1

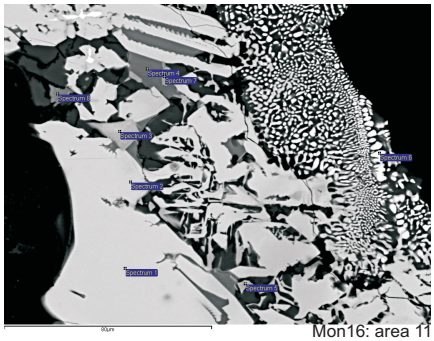

Mon13: area 4

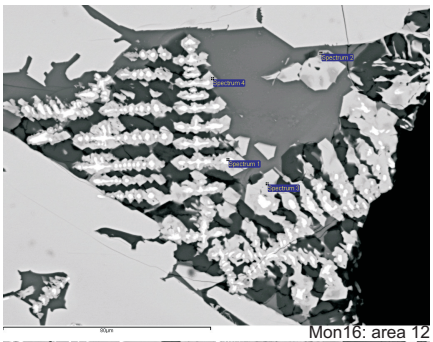

Mon14: area 1

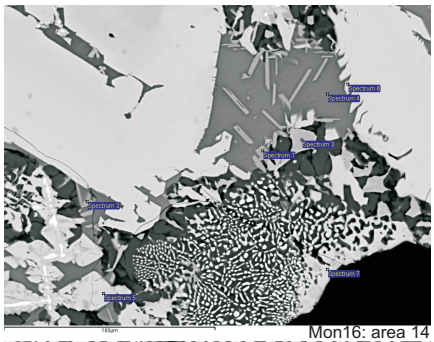

Mon16: area 2

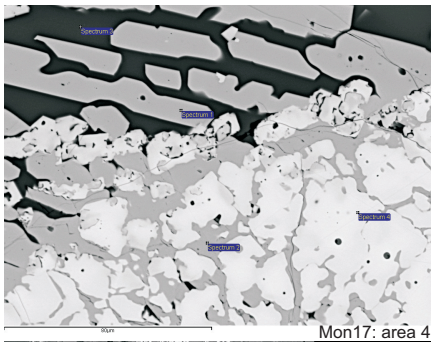

Mon16: area 5

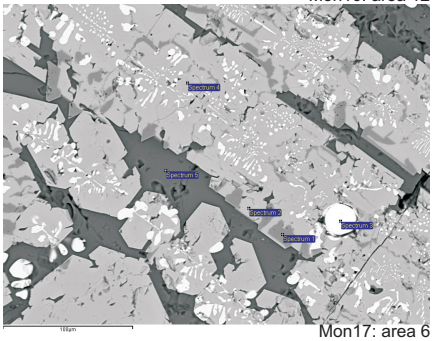

Mon16: area 9

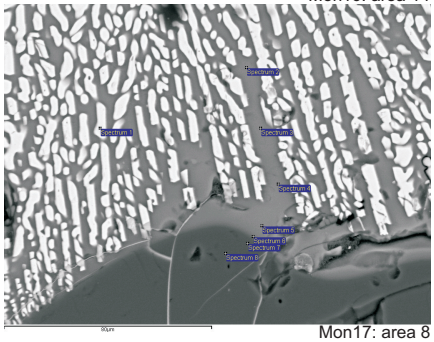

Mon16: area 11

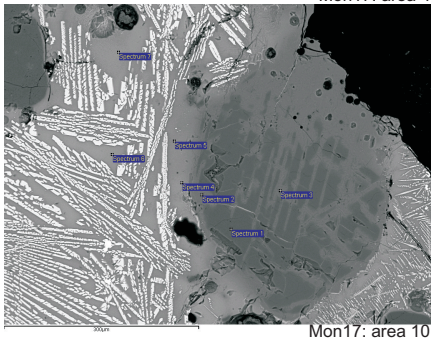

Mon16: area 12


Mon16: area 14


Mon17: area 4


Mon17: area 6


Mon17: area 8


Mon17: area 10

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