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Archaeometallurgical residues from Abbey Street, Southwark, SE1

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Dr T.P. Young

Abstract

Two pieces of slag of rather unusual appearance were submitted for investigation, having been initially identified as pieces of iron ore.

Detailed investigation of one of the pieces showed it to be an iron slag formed of rather equant olivine grains with an overall massive texture. Such a slag would have been formed within a furnace by slow cooling from a high temperature. The most likely point of origin for such material in a smelting furnace would be between the furnace wall and the bloom, just below the blowing hole. The texture is not diagnostic as to whether this would have been from a slag-tapping or non tapping furnace. In detail, the texture comprises moderately equant euhedral manganoan fayalite with a grain size of up to 1mm, locally with a marginal fayalite-hercynite intergrowth, with complex interstitial material involving intergrowths of a more calcic fayalite, rhönite, wustite and leucite with very small areas of glass bearing sulphidic blebs.

Chemical analysis showed that the slag was rich in manganese, indeed the manganese content (7wt% expressed as MnO) was higher than for any iron smelting slags from England in the author's database or in the compilation published by Paynter (2006, 2007). In fact, the manganese content is double the highest values (3.5 wt%) recorded in either of those two sources. The manganese content is, however, well within the range recorded from slags produced during the smelting of bog ores in Ireland (up to 20% MnO) and is similar to that of the experimental smelting slags produced by Crew when smelting bog iron ore from Shropshire.

The aluminium content of the slag was low, with a high silica to alumina ratio (by weight) of 9.9. Similar values occur in many Irish smelting slags and probably indicate a quartz-rich substrate to the ore development. The trace element composition was low and largely unremarkable, probably reflecting the influence of the host sediment, but there is a slightly elevated uranium to thorium ratio – a typical feature of bog iron ores.

Contents

Abstract 1

Methods 1

Results 2

Interpretation 2

Discussion 3

References 4

Captions 5

Table 1: bulk chemical composition 6
Table 2: EDS microanalyses 7
Table 3: EDS interpretation 8

Methods

Electron microscopy was undertaken on the LEO S360 analytical electron microscope in the School of Earth and Ocean 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 thin section for investigation optically and on the SEM was 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 a fused bead on the Wavelength-Dispersive X-Ray Fluorescence (WD-XRF) system in the department of Geology, Leicester University (this also generated analyses for S, V, Cr, Sr, Zr, Ba, Ni, Cu, Zn, Pb and Hf). Whole-specimen chemical analysis for thirty six minor and trace elements was undertaken using a sample in solution on the ThermoElemental X-series Inductively-Coupled Plasma Mass Spectrometer (ICP-MS) in the School of Earth and Ocean Sciences, Cardiff University.

Throughout this report standard mineral terminology is applied to both natural and anthropogenic materials – although artificial phases are no longer strictly considered to be minerals.

The convention adopted in this report is to describe olivine bearing Fe, Mg, Ca and Mn in terms of an olivine on the forsterite-fayalite join (using the notation for instance of Fa95Fo5 for an olivine that is 95% fayalite and 5% forsterite; where Fe/(Fe+Mg) = 0.95) plus figures for the overall atomic percentage replacement by calcium and manganese.

Initial inspection of the supplied pieces showed a granular texture, with the surfaces of coarse euhedral crystal grains revealed on the fracture surface. This texture is unusual in an iron slag, and once the initial suggestion that these were ore samples had been discarded, further investigation was commissioned to determine whether the samples were slags or geological materials. One of the two supplied pieces was taken forward for investigation. The sample was cut, with part archived, part retained for bulk chemical analysis and part employed for the production of a polished thin section. A polished thin section was chosen in preference to the polished block normally used for SEM investigations at GeoArch, because it permitted the additional rapid (and therefore cheap) technique of optical petrography. In fact, optical petrography immediately allowed identification of the material as a slag and further work, including the petrographic investigation of the section on the SEM and bulk chemical analysis, was then commissioned.

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Results

Description of the samples

The submitted material comprised two pieces of slag, both from (27) (<1>, sample 2). The small piece was uniform in its finely granular texture and was selected for further investigation. The larger piece shows a slight gradation of texture from a face with some surface-parallel spalling (possibly close to an original external surface?), through a massive dense granular-textured slag to an opposing, slightly paler, face with some large (up to 7mm) open vesicles.

The main slag type shows a pale, slightly brownish, grey fracture surface with strongly reflective crystal facets, imparting an almost micaceous appearance to the slag. This is a most unusual texture for an iron slag.

Description of the microstructure

The section shows a texture (Plate 1) dominated by equant, euhedral olivine, with a grain size of up to approximately 1mm. EDS analyses show that the olivine grades from cores with a composition of Fa96Fo4 with 1% of calcium and 14% of manganese substitution to rims of Fa100 with 4% of calcium and 11% of manganese substitution. The main olivine shows a localised outer zone bearing a cotectic spinel (approximately 84% hercynite in a solid solution with magnetite and with minor manganese and titanium substitution), probably associated with the calcic fayalite present in the interstitial areas (see below). The texture also includes a low volume of wustite dendrites, mainly seen in the interstitial areas

The interstitial areas are very complex, with several very fine-grained intergrown phases, making EDS analysis difficult.

In many areas a cotectic of leucite and wustite dominates, with intervening areas of calcic fayalite (Fa100 with 11-17% calcium and 10-11% manganese substitution), rhönite, possibly a calcium phosphate and small areas of glass. The rhönite has a composition of approximately

$(Fe_4, Mn_{0.2}, Ti_{0.1}, Al_{1.7})\ Ca_2\ (Al, Si)_6\ O_{20}$

This complex relationship probably indicates the development of two immiscible liquids during the late stages of crystallisation. EDS analysis of the finely intergrown phases is very difficult and there may be other cotectic relationships involved, beyond those currently identified.

Chemical composition

The bulk composition shows a high content of manganese (6.98wt% expressed as MnO), with a correspondingly rather low iron content (53.56wt% expressed as FeO) for a smelting slag. The alumina content is low (2.65 wt%), giving a silica to alumina ratio of 9.1 (Figure 3b).

The phosphorus content (0.58 wt% expressed as P_2O_5) is moderate. Most other elements are present in rather low quantities, suggesting a rather 'clean' ore. The barium content is low compared with many examples of slags from the smelting of bog iron ores with high manganese contents.

The trace elements are also present in rather low to moderate amounts. The upper crust-normalised rare earth elements (REE; normalisation factors after Taylor & McLennan 1981) show a mildly 'humped' profile to the middle REE (Figure 1a). Overall concentrations are mainly just above parity with the upper crustal standard.

Others of the so-called immobile elements show an interesting pattern: yttrium and uranium show high levels compared to, for instance, slags from the smelting of Wealden ores, whereas niobium and thorium are much lower. Such a pattern is, again, suggestive of a bog iron ore source.

Interpretation

The coarse, equant texture of this slag is indicative of slow cooling from high temperature. This implies that the slag cooled within a furnace or hearth. The uniformity of the texture across many tens of millimetres demonstrates that the slag cooled in a homogeneous 'puddle' without any flow.

High manganese contents are often taken as a good indicator of a smelting slag, but may also occur in slags produced during the refining (either by bloomsmithing or remelting) of blooms produced from high-manganese ores. Although the cooling of large smithing slag cakes may be slow, they are rarely as homogeneous as this sample and typically show a characteristic pattern of vertical tubular vesicles.

Remelting slags are poorly known, but appear to resemble smithing slags in most respects.

The most likely interpretation of these slags is as primary smelting slags. Coarse textures have been observed in the furnace slags formed between the bloom and wall below the blowhole. An origin for these slags in such a location would not permit reliable discrimination between an origin within a slag-tapping or non-tapping (slagpit) furnace; such discrimination should be made on the basis of the rest of the assemblage. A slightly arcuate appearance to the zone of distribution of the densest slags in the larger specimen provides a slight supporting suggestion that the pieces may be derived from the 'burr' – the curved nub of slag formed where the fluxing effect of the iron-rich slag on the furnace wall below the blowhole leads to its erosion and the formation of a rounded protrusion of slag into the former wall thickness.

It is noteworthy that the chemical composition of such a 'burr', formed during the smelting of bog iron ores at the Iron Age site of Cherryville, Co. Kildare, Ireland (Young 2007) in a slagpit furnace, is extremely close to that of the present material, including the rather modest iron content. The Cherryville sample also shows equant (or skeletal) olivine with a grain-size of approximately 1mm, with complex leucite-rich interstitial areas.

Provenancing of the ore smelted at the site is hindered by a lack of comparative data – both of potential ores and similar slag.

The major element chemical composition of slags is usually a rather blunt tool for interpreting provenance. The key features of the present material are the low aluminium content, the high manganese content, relatively low magnesium, calcium, sodium and potassium and only moderate phosphorus. The high manganese is suggestive of a bog iron ore origin – but does not prove it; some sideritic ironstones may have a high manganese content. None the less, the high manganese content stands out in comparison to other samples from SE England (Figure 3a).

Amongst the trace elements, the distribution patterns of the immobile elements (e.g. uranium, thorium, niobium, yttrium and the rare earth elements) are capable of providing useful provenancing evidence.

In the present sample the niobium to yttrium ratio is very low and the uranium to thorium ratio somewhat elevated compared with typical sedimentary materials (Figure 3b). These are features observed in bog iron ores and in smelting slags derived from them (e.g. Young 2009b, Figure 8).

The rare earth elements show a slightly humped upper crust-normalised profile (Figure 1a and Figure 2) which is quite different from the generally much more horizontal profiles recorded from most Wealden ores/slags (e.g Figure 1c, Figure 1f).

However, some Wealden ores/slags also show a strongly humped profile (Figure 1b, Figure 1f); these samples however, also have elevated levels of manganese, magnesium, calcium and particularly phosphorus, and also possess a very low silica: alumina ratio.

Poorly-mineralised bog iron ores from Reigate (Figure 1e) showed rather similar profiles to Wealden siderite ores, probably indicating that both sets of material essentially have had their REE profiles determined by the host sediment rather than by the process of mineralisation. The profiles of slags from Hartshill Copse, possibly smelted from bog iron ores, show a humped profile superimposed on an overall inclination with relative enrichment of the heavier REE (Figure 1d).

[Note: It is important to remember, when making comparisons involving both slag and ore analyses, that other elements will tend to be enriched in the slag compared to the ore, because of removal of iron (so the REE profiles of ores tend to be lower than the corresponding slag). Also, the slag composition is derived from a mixing of the ore and furnace materials (with a minor contribution from the fuel ash; Thomas & Young 1999a, b). The furnace clay will typically have a profile close to parity with the standard, so the effect is to move the REE profile of the ore towards parity and to flatten it.]

Discussion

It is clear from the discussion above, that the chemical composition does not provide unambiguous provenancing data. However, the composition does not match either of the ore types from the Weald described above. The manganese content is twice that of any slag recorded by Paynter (2006, 2007) from England or in author's database of English material.

The high manganese content is, however, well within the range of bog iron ore-derived slags from Ireland (the author's database, including the samples given in Young 2008, 2009a, 2009b, 2009c, 2011a and 2011b) and similar to slags produced during the experimental smelting of bog iron ores from Shropshire by Crew (author's unpublished data). Aspects of the trace element content of the slag, as discussed above, are also suggestive of an origin in the smelting of a bog iron ore.

Bog iron ores have not been identified in the London area, but it is clear that suitable environments for their generation would have been available in poorly-drained wet areas. To the west of London bog iron ores have been positively identified as the source of iron for Iron Age smelting at Fleet Hill Farm, Eversley, Berkshire (pers. obs.). This is at the centre of a cluster of similar sites – and it is likely all are associated with bog ores, although they were formerly thought to be have exploited iron ores within the Tertiary sands. These include the sites at Hartshill Copse (Collard *et al.* 2006; Young 2004) and Dunston's Park (Fitzpatrick 1995) close to the River Kennet near Thatcham. Closer to Eversley are the sites at Heckfield (Dungworth 2007), Risely (McDonnell 1984), Baird Road, Arborfield (Hammond, forthcoming) and the former Whitehall brickworks (Pine 2003).

Further east, clusters of sites in the Surrey Heath area and the Staines/Weybridge area (including Brooklands, Hanworth & Tomalin 1977, and Thorpe Lea, Starley 1998) are also possible candidates for sites smelting bog iron ores, although,again, bedrock sources in Tertiary strata have previously been suggested.

To the south, significant volumes of bog iron ore, albeit of very low grade, were recently located at Littleton Manor, Reigate (Young 2010). The Littleton Manor bog iron ore is significant, for it provides direct evidence of bog iron ores formed on or close to the Lower Greensand Group, which has itself been suggested to be a potential ore resource in southern England. The similarity of its geological setting with those of the iron

smelting sites of the Ashford area of Kent (Paynter 2006) may suggest that similar ores should be considered as potential sources in that area too, instead of (or perhaps as well as) sources in the Tertiary sands overlying the chalk, as she suggested.

To the east of London, the early smelting site at Shooter's Hill, Greenwich, is another site for which the ore source has not yet been demonstrated and a bog ore source it possible. Across the Thames estuary in Essex, there are several low-lying iron smelting sites (e.g. in the Blackwater valley), which would again appear contenders to have exploited bog iron ores.

Thus there is considerable evidence, both direct and circumstantial, for the exploitation of bog iron ores in a variety of environmental settings across SE England. That the Abbey Street find probably indicates bog iron ores being exploited much closer-in to London should come as no surprise within that revised view of iron resources in the region.

It may be significant that where local groundwater conditions were suitable for the generation of these resources, such as the Eversley area, then there is a tendency for the resource to have supported multiple smelting sites. It would be desirable, therefore, for a close watch for, and where appropriate analytical investigation of, any further occurrences of iron smelting slags, not only in Southwark, but in the wider region of London.

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Illustration Captions

Figure 1. Upper Crust-normalised rare earth element profiles (normalisation factors after Taylor & McLennan 1981).

a. Slag specimen from Abbey Street, Southwark (this report)
b. Slag specimens from the Weald (WIRG samples, unprovenanced; Thomas 2000)
c. Slag specimens from the Weald (Little Furnace Wood, Mayfield, East Sussex; Young 2011c)
d. Slag specimens from Hartshill Copse, Upper Bucklebury, Berkshire (Young 2004)
e. Bog iron ore samples, Reigate, Surrey (Young 2010)
f. Iron ore specimens from the Weald (Cd2-7: WIRG samples, unprovenanced, Thomas 2000; LFW9a/b Little Furnace Wood, Mayfield, East Sussex; Young 2011)

Figure 2.Bivariate plot of the ratios of the upper crust normalised abundance of gadolinium to lutetium (i.e. the slope of the heavy part of the REE profile) against that for gadolinium to lanthanum (i.e. -1 x the slope of the light part of the REE profile).

On this plot, a flat REE profile would plot at 1,1 and locations with increased values of the two ratios represent increasing 'humped' profiles.

Data groups:
Wealden ores – the profiles in Fig. 1f
Reigate ores – the profiles in Fig. 1e
Wealden slags – the profiles in Fig. 1b
Hartshill Copse slags– the profiles in Fig. 1d
Little Furnace Wood slag – the profiles in Figure 1c
Abbey Street slag – the profiles in Figure 1a

Figure 3. Bivariate plots of:

a) wt% MnO against the silica to alumina ratio (by weight)
b) the niobium to yttrium ratio against the uranium to thorium ratio

Data groups as Figure 2.

Plate 1. BSEM images

a. SOI1. Scale bar 1mm
b. SOI2. Scale bar 70µm
c. SOI 4. Scale bar 300µm
d. SOI5. Scale bar 400µm
e. SOI6. Scale bar 200µm

Plate 2. BSEM images showing locations of EDS analyses.

a. SOI1. Scale bar 1mm
b. SOI2. Scale bar 70µm
c. SOI5. Scale bar 400µm.

Table 1a: Major elements determined by XRF expressed as wt% oxides. Columns in coloured tone indicate data recalculated with iron as FeII rather than FeIII. LOI = loss on ignition, negative value indicates weight gain.

SiO_2	Al_2O_3	Fe_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	LOI	LOI	total
26.25	2.65	59.51	53.56	6.98	0.68	1.68	0.03	0.84	0.13	0.58	-5.93	0.55	99.98

Table 1b: Trace elements determined by ICP-MS expressed in elemental ppm.

Sc	V	Cr	Co	Ni	Cu	Zn	Ga	Rb	Sr	Y	Zr	Nb	Mo	Sn	Cs	Ba
4.2	18.3	22.9	2.16	32.7	37.4	68.2	5.0	34.2	124.8	35.1	110.1	3.53	1.17	0.67	1.30	242.6

Table 1c: Trace elements determined by ICP-MS expressed in elemental ppm (continued)

La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Pb	Th	U
30.59	55.75	7.73	31.09	6.60	1.41	6.65	0.95	5.24	0.98	2.69	0.36	2.21	0.34	2.72	0.26	1.71	2.59	3.99

Table 2: EDS microanalyses (for point locations see Plate 2)

SOI	#	atom%												wt%											
		O	Na	Mg	Al	Si	P	K	Ca	Ti	Mn	Fe	Ba	O	Na	Mg	Al	Si	P	K	Ca	Ti	Mn	Fe	Ba	Total
2	1	54.85		0.96	0.12	14.94			0.33		3.98	24.81		28.24		0.75	0.11	13.51			0.43		7.04	44.59		94.66
2	2	54.26		1.66	0.15	15.13			0.31		4.38	24.11		28.76		1.34	0.13	14.07			0.42		7.96	44.61		97.29
2	3	54.63		1.08	0.15	15.16			0.40		4.12	24.47		29.27		0.88	0.13	14.25			0.53		7.57	45.76		98.40
2	4	53.96		0.60	0.19	15.44			0.43		4.05	25.34		28.84		0.49	0.17	14.48			0.57		7.43	47.27		99.24
3	1	58.95	<		11.73	10.27	0.40	0.11	5.82	0.39	0.67	11.66	<	37.64	0.00		12.64	11.51	0.50	0.17	9.31	0.74	1.46	25.99	<	99.96
3	2	58.31	0.25		11.77	10.98	0.33	0.29	5.58	0.23	0.57	11.68	<	38.94	0.24		13.26	12.88	0.43	0.48	9.33	0.47	1.31	27.24	<	104.57
3	3	58.03	0.21		0.24	13.25	0.53	0.15	4.69	<	2.84	20.05	<	34.03	0.18		0.24	13.64	0.60	0.22	6.89	<	5.72	41.05	<	102.57
3	4	58.38	0.34		1.51	13.16	0.82	0.51	2.82	0.07	2.46	19.95	<	33.60	0.28		1.46	13.29	0.91	0.71	4.06	0.12	4.87	40.07	<	99.37
3	5	60.19	0.76		10.56	14.35	1.72	6.62	2.80	0.15	0.20	2.64	<	42.72	0.78		12.64	17.88	2.37	11.49	4.98	0.31	0.50	6.55	<	100.21
3	6	59.69	0.42		9.90	13.82	1.36	4.34	4.41	0.15	0.33	5.58	<	40.66	0.41		11.38	16.53	1.80	7.23	7.52	0.30	0.77	13.28	<	99.88
3	7	59.01	0.36		9.81	11.04	1.11	1.36	6.07	0.30	0.62	10.33	<	37.61	0.33		10.55	12.36	1.38	2.12	9.69	0.56	1.35	22.97	<	98.91
3	8	59.27	0.39		9.42	13.94	1.23	4.55	4.38	0.15	0.46	6.22	<	38.97	0.37		10.44	16.09	1.56	7.30	7.21	0.30	1.04	14.29	<	97.57
3	9	58.80	0.25		10.86	11.14	0.35	0.45	6.10	0.21	0.67	11.18	<	39.40	0.24		12.27	13.11	0.45	0.73	10.25	0.42	1.54	26.14	<	104.55
3	10	56.62	0.00		0.69	13.86	0.52	0.24	3.63	<	2.97	21.47	<	32.54	0.00		0.66	13.98	0.57	0.34	5.23	<	5.86	43.07	<	102.26
3	12	59.46	1.26		8.37	14.64	1.26	5.89	2.07	0.09	0.31	6.65	<	40.34	1.23		9.57	17.43	1.65	9.77	3.52	0.19	0.72	15.76	<	100.18
3	13	49.43	<		0.28	0.24	<	0.09	0.10	0.22	1.13	48.51	<	21.91	<		0.21	0.19	<	0.10	0.11	0.29	1.72	75.06	<	99.60
3	14	56.72	<		0.19	14.00	0.20	<	1.23	<	3.11	24.55	<	30.94	<		0.18	13.41	0.21	<	1.67	<	5.82	46.73	<	98.96
3	15	58.80	0.86		8.03	13.17	1.49	5.45	2.42	0.11	0.34	9.26	0.06	38.35	0.81		8.83	15.08	1.88	8.68	3.96	0.22	0.76	21.09	0.34	100.02
3	16	58.10	0.68		10.80	15.04	1.70	6.91	3.01	0.09	0.29	3.31	0.07	38.49	0.65		12.07	17.49	2.18	11.18	4.99	0.18	0.66	7.66	0.40	95.96
3	17	59.83	0.70		9.72	14.53	1.29	4.88	4.17	0.14	0.29	4.45	<	40.46	0.68		11.09	17.25	1.69	8.07	7.07	0.27	0.67	10.50	<	97.75
3	18	59.37	0.82		9.72	13.17	1.25	3.05	5.72	0.11	0.43	6.36	<	39.49	0.78		10.91	15.38	1.61	4.96	9.53	0.21	0.98	14.77	<	98.61
3	19	62.86	2.52		9.31	17.08	0.80	4.70	0.69	<	0.17	1.82	0.07	46.57	2.68		11.63	22.21	1.14	8.50	1.27	<	0.44	4.70	0.45	99.60
5	1	55.84	<	<	24.73	0.24	<	<	<	0.51	1.03	17.65		36.29	<	0.00	27.11	0.28	<	<	<	0.99	2.29	40.03		106.97
5	2	55.75	<	0.78	0.12	14.43	<	<	0.37	<	4.00	24.56		29.09	<	0.62	0.10	13.22	<	<	0.48	<	7.16	44.74		95.41
5	3	56.74	0.31	<	8.12	15.02	0.12	7.35	0.09	0.13	0.25	11.86		36.79	0.29	<	8.88	17.10	0.15	11.65	0.14	0.25	0.57	26.85		102.67
5	4	55.77	<	0.15	0.21	14.32	0.18	<	0.99	<	3.30	25.08		29.52	<	0.12	0.19	13.31	0.19	<	1.32	<	6.00	46.34		96.98

Table 4: EDS microanalyses with interpretation

SOI	#	atom% O	Na	Mg	Al	Si	P	K	Ca	Ti	Mn	Fe	Ba			
2	1	54.85		0.96	0.12	14.94			0.33		3.98	24.81		Olivine	Inner	Fa96Fo4 1%Ca and 13%Mn substitution
2	2	54.26		1.66	0.15	15.13			0.31		4.38	24.11		Olivine	Inner	Fa94Fo6 1%Ca and 14%Mn substitution
2	3	54.63		1.08	0.15	15.16			0.40		4.12	24.47		Olivine	Mid	Fa96Fo4 1%Ca and 14%Mn substitution
2	4	53.96		0.60	0.19	15.44			0.43		4.05	25.34		Olivine	Rim	Fa98Fo4 1%Ca and 13%Mn substitution
3	1	58.95	<		11.73	10.27	0.40	0.11	5.82	0.39	0.67	11.66	<	Rhönite		
3	2	58.31	0.25		11.77	10.98	0.33	0.29	5.58	0.23	0.57	11.68	<	Rhönite		
3	3	58.03	0.21		0.24	13.25	0.53	0.15	4.69	<	2.84	20.05	<	Olivine	Interstitial	Fa100 17%Ca and 10%Mn substitution
3	4	58.38	0.34		1.51	13.16	0.82	0.51	2.82	0.07	2.46	19.95	<	Olivine	Interstitial	Fa100 11%Ca and 10%Mn substitution
3	5	60.19	0.76		10.56	14.35	1.72	6.62	2.80	0.15	0.20	2.64	<	Rhönite (mixed)		
3	6	59.69	0.42		9.90	13.82	1.36	4.34	4.41	0.15	0.33	5.58	<	Rhönite (mixed)		
3	7	59.01	0.36		9.81	11.04	1.11	1.36	6.07	0.30	0.62	10.33	<	Rhönite (mixed)		
3	8	59.27	0.39		9.42	13.94	1.23	4.55	4.38	0.15	0.46	6.22	<	Rhönite		
3	9	58.80	0.25		10.86	11.14	0.35	0.45	6.10	0.21	0.67	11.18	<	Olivine	Interstitial	Fa100 13%Ca and 11%Mn substitution
3	10	56.62	0.00		0.69	13.86	0.52	0.24	3.63	<	2.97	21.47	<	Glass		
3	12	59.46	1.26		8.37	14.64	1.26	5.89	2.07	0.09	0.31	6.65	<	Area		Leucite + wustite + ?rhönite + ?apatite
3	13	49.43	<		0.28	0.24	<	0.09	0.10	0.22	1.13	48.51	<	Wustite		
3	14	56.72	<		0.19	14.00	0.20	<	1.23	<	3.11	24.55	<	Olivine	Rim	Fa100 4%Ca and 11%Mn substitution
3	15	58.80	0.86		8.03	13.17	1.49	5.45	2.42	0.11	0.34	9.26	0.06	Area		Leucite + wustite + ?rhönite + ?apatite
3	16	58.10	0.68		10.80	15.04	1.70	6.91	3.01	0.09	0.29	3.31	0.07	Area		Leucite + wustite + ?rhönite + ?apatite
3	17	59.83	0.70		9.72	14.53	1.29	4.88	4.17	0.14	0.29	4.45	<	Area		Leucite + wustite + ?rhönite + ?apatite
3	18	59.37	0.82		9.72	13.17	1.25	3.05	5.72	0.11	0.43	6.36	<	Area		Leucite + wustite + ?rhönite + ?apatite
3	19	62.86	2.52		9.31	17.08	0.80	4.70	0.69	<	0.17	1.82	0.07	Leucite		
5	1	55.84	<	<	24.73	0.24	<	<	<	0.51	1.03	17.65		Spinel		84% hercynite
5	2	55.75	<	0.78	0.12	14.43	<	<	0.37	<	4.00	24.56		Olivine	Core	Fa97Fo3 1%Ca and 13%Mn substitution
5	3	56.74	0.31	<	8.12	15.02	0.12	7.35	0.09	0.13	0.25	11.86		Leucite + wustite		
5	4	55.77	<	0.15	0.21	14.32	0.18	<	0.99	<	3.30	25.08		Olivine	Rim	Fa99Fo1 3%Ca and 11%Mn substitution

Figure 1

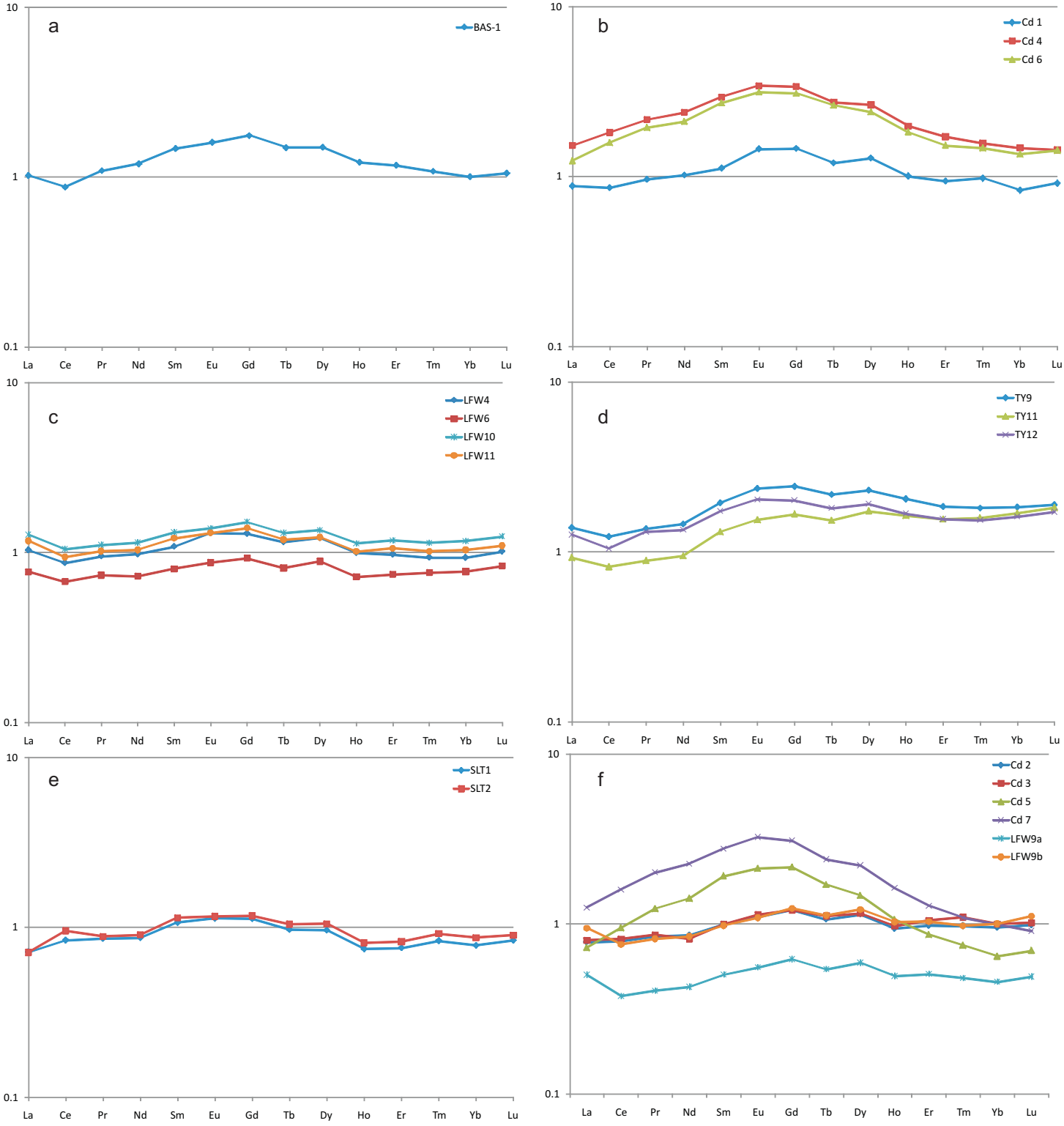

a
BAS-1
b
Cd 1
Cd 4
Cd 6
c
LFW4
LFW6
LFW10
LFW11
d
TY9
TY11
TY12
e
SLT1
SLT2
f
Cd 2
Cd 3
Cd 5
Cd 7
LFW9a
LFW9b
10
1
0.1
La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu

Figure 2

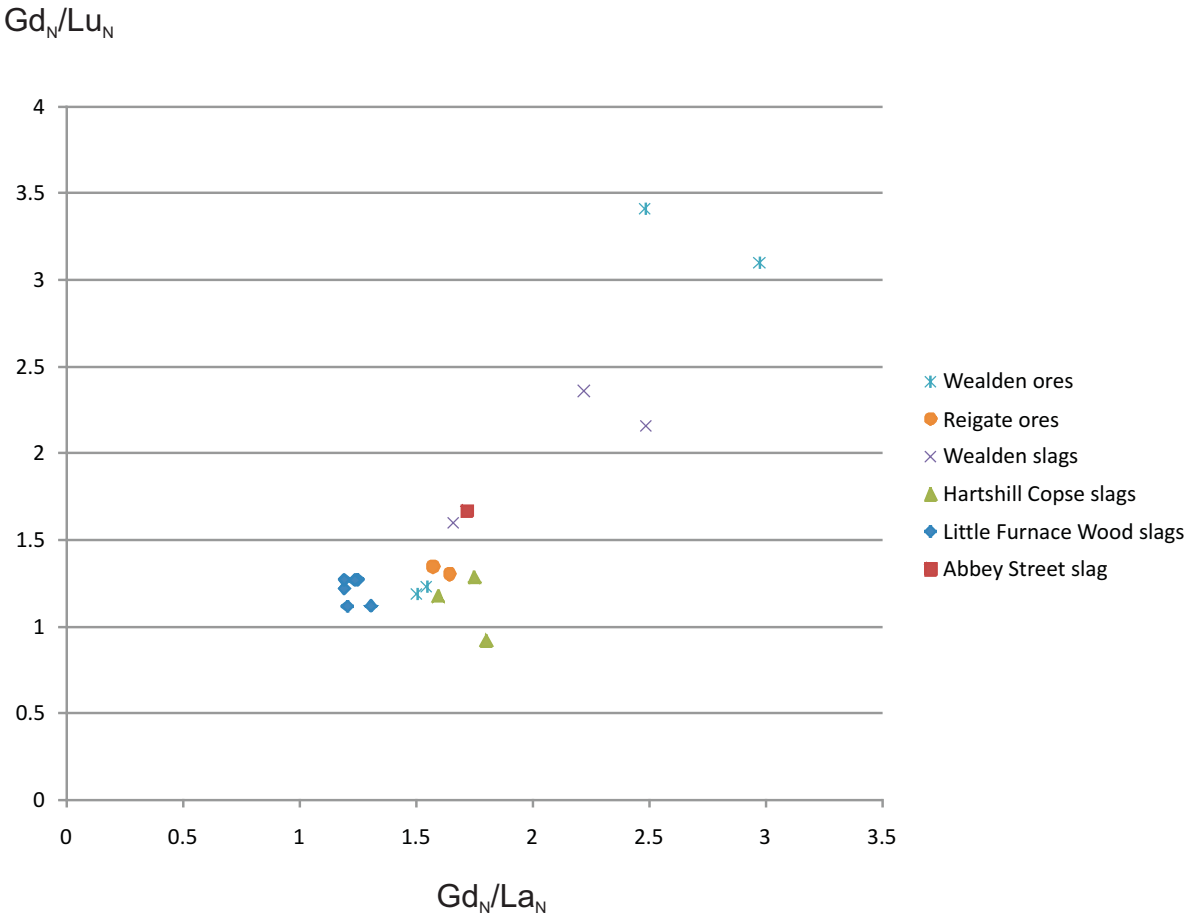
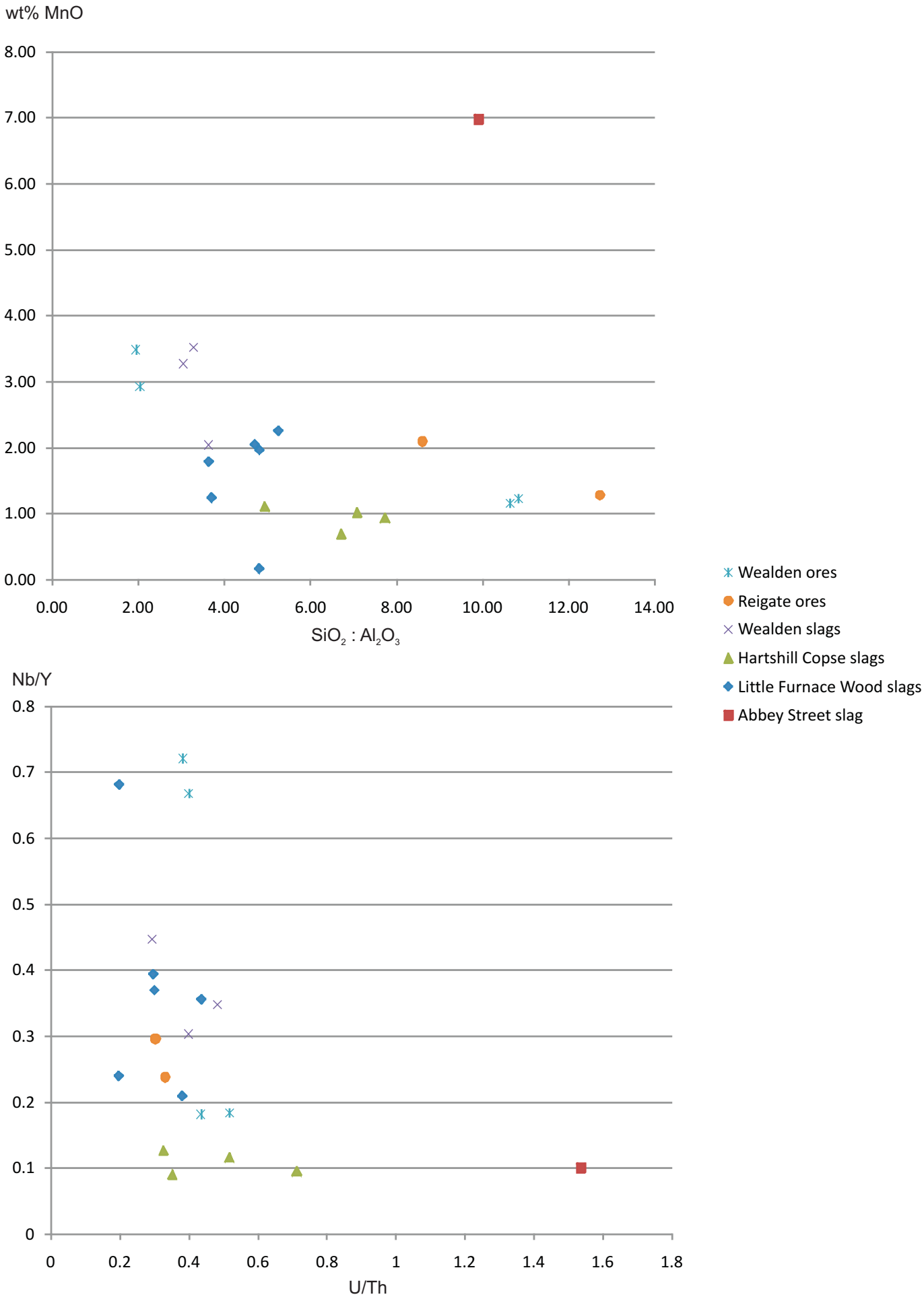
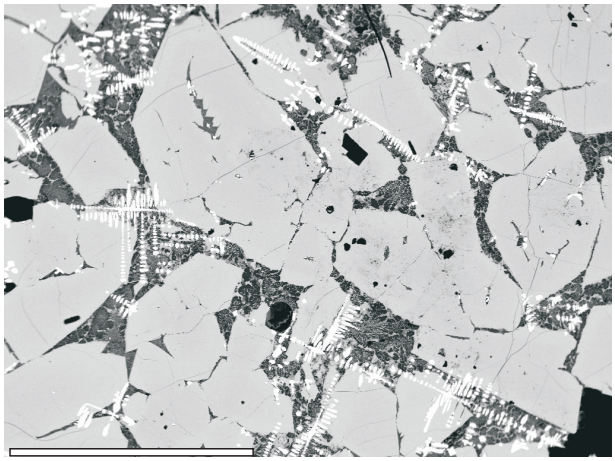

Gd$_N$/Lu$_N$
4
3.5
3
2.5
2
1.5
1
0.5
0
0
0.5
1
1.5
2
2.5
3
3.5
Gd$_N$/La$_N$
Wealden ores
Reigate ores
Wealden slags
Hartshill Copse slags
Little Furnace Wood slags
Abbey Street slag

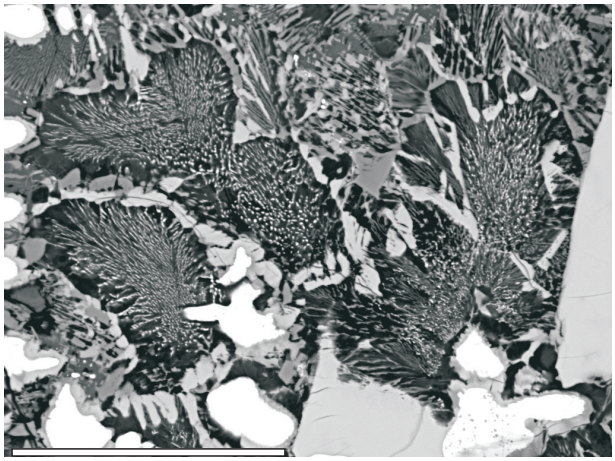
Figure 3


wt% MnO
8.00
7.00
6.00
5.00
4.00
3.00
2.00
1.00
0.00
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
SiO2 : Al2O3
Nb/Y
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
U/Th
Wealden ores
Reigate ores
Wealden slags
Hartshill Copse slags
Little Furnace Wood slags
Abbey Street slag

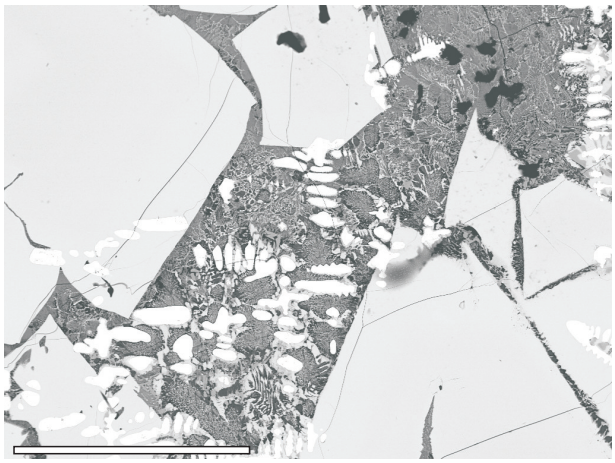
a



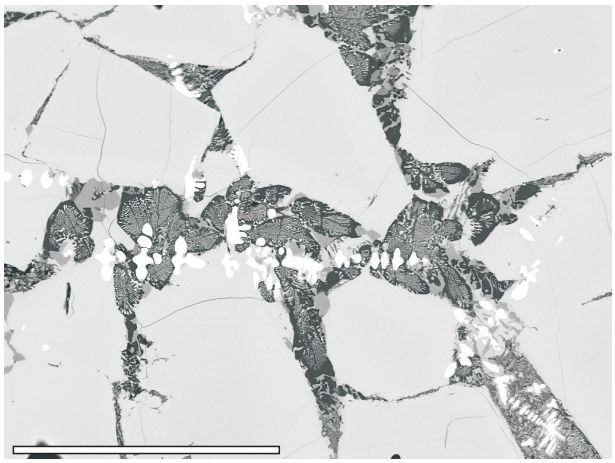
b



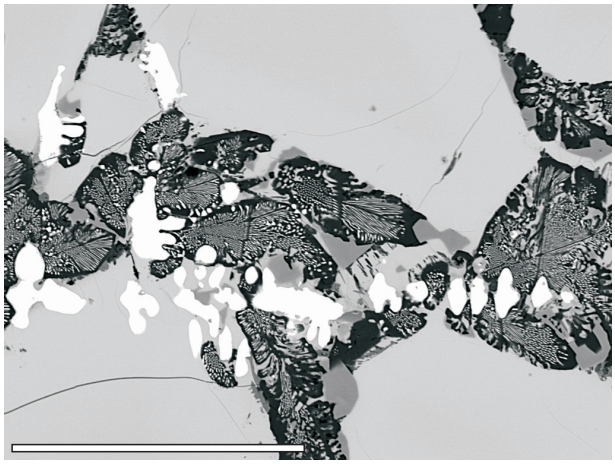
c



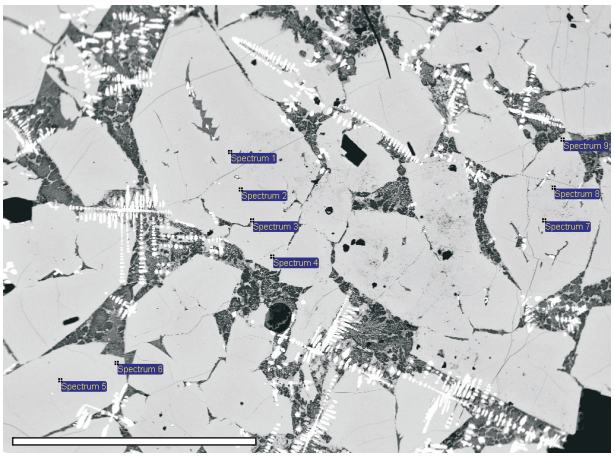
d



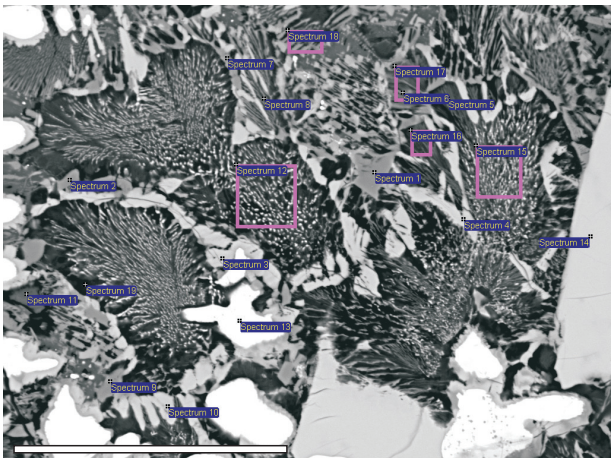
e



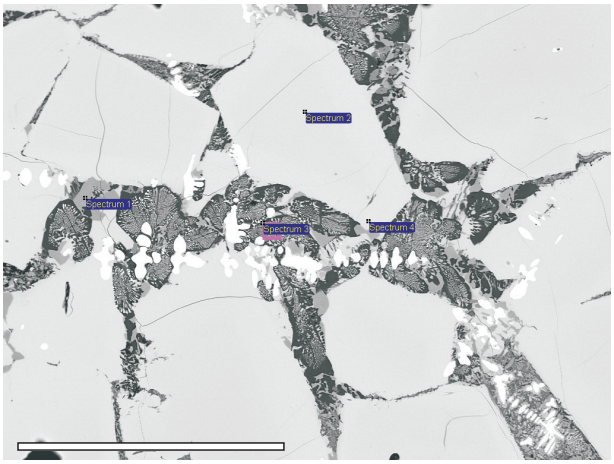
a


Spectrum 1
Spectrum 2
Spectrum 3
Spectrum 4
Spectrum 5
Spectrum 6
Spectrum 7
Spectrum 8
Spectrum 9

b


Spectrum 1
Spectrum 2
Spectrum 3
Spectrum 4
Spectrum 5
Spectrum 6
Spectrum 7
Spectrum 8
Spectrum 9
Spectrum 10
Spectrum 11
Spectrum 12
Spectrum 13
Spectrum 14
Spectrum 15
Spectrum 16
Spectrum 17
Spectrum 18

c


Spectrum 1
Spectrum 2
Spectrum 3
Spectrum 4

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