Centre for Archaeology Report 18/2005

The Metalworking Remains from 14-20 The Butts, Worcester

Eleanor Blakelock

ISSN 1473-9224

The Centre for Archaeology Report Series incorporates the former Ancient Monuments Laboratory Report Series. Copies of Ancient Monuments Laboratory Reports will continue to be available from the Centre for Archaeology (see back cover for details).

Centre for Archaeology Report 18/2005

The Metalworking Remains from 14-20 The Butts, Worcester

Eleanor Blakelock

Summary

67.9 kg of ironworking debris was recovered from pits or ditches, of which the vast majority was iron smelting waste. A large proportion of the iron waste was from Roman contexts although some had been deposited during the post Roman period. The evidence suggests that smelting was probably taking place near to the excavation site and was probably occurring from the same site that the waste from both Farrier Street and Deansway came from. No smithing slag or residues were identified in the ironworking assemblage. The fragment of ore found at the site is similar to others found in the Forest of Dean.

Keywords

Iron
Metal Working-Fe
Technology
Roman

Author's address

English Heritage, Fort Cumberland, Fort Cumberland Road, Eastney, Portsmouth PO4 9LD.

Introduction

An archaeological investigation was carried out by Birmingham Archaeology at 14-20 The Butts, Worcester. The site lies within the historic centre of the Roman and medieval city, with the earliest phase being of Roman date (2nd-4th century). Excavations revealed a possible Roman street and many pits in which 67.9kg of ironworking waste was found.

The site and the surrounding area

The main focus of the Roman settlement in Worcester lay to the south of the site at The Butts and was enclosed by earthwork defences (Burrows and Cutter 2004). Previous excavations in Worcester (Dalwood *et al*. 1994) have revealed that the Roman settlement had a large industrial component. Ironworking waste products were found at Deansway, 500m to the south, dating to the 2nd-3rd century. The focus of the industrial activity seems to have shifted in the 3rd and 4th century to Broad Street, south of The Butts, where furnaces have been found. The excavations at Farrier Street, adjacent to the site, revealed ironworking waste that was also dated to the 3rd-4th century (Dalwood and Edwards 2004, 101).

The evidence for immediate post-Roman activity in Worcester is limited to a few pieces of late Roman pottery and the 'dark earth' that seals the Roman contexts. The large amounts of charcoal, iron slag, daub and animal coprolites in this layer are consistent with household refuse, which possibly was later used for agricultural purposes (Burrows and Cutter 2004).

Excavations at 14-20 The Butts, Worcester, revealed that the earliest phase was a possible Roman road surface, metalled with iron slag, with associated ditches; these features were dated to the late 2nd-4th century. Other features included postholes, a stone-lined well and many pits of varying sizes. The ironworking waste was recovered from secondary deposits in pits and some ditches. There was no evidence for ironworking structures, such as furnaces, but some areas of the site were heavily truncated or totally destroyed by post-medieval activity, dramatically reducing the chances of discovering structural remains. This excavation revealed mostly late 4th century and 5th century pottery as well as iron waste materials in the post-Roman 'dark earth' deposit. This seems most likely to be redeposited Roman waste rather than evidence for post-Roman metalworking (Burrows and Cutter 2004).

Ironworking processes and categories of ironworking waste

There are broadly two processes involved in ironworking: smelting (extracting metal from the ore), and smithing or forging (shaping the object). Both create different kinds of waste that can often be distinguished on the basis of their morphology, as described below. However no smithing slag was identified amongst the assemblage, therefore only the waste produced by the smelting process is discussed here.

Iron smelting took place in bloomery furnaces, which were typically clay-built, rounded structures in the Roman period. Iron ore was fed into the furnace where it reacted to create a spongy mass of iron metal known as a bloom. The waste from this process formed a liquid slag that was often tapped from the bottom of the furnace (Bayley *et al*. 2001).

The ironworking waste from The Butts was classified predominantly using the terms used by Bayley *et al*. (2001). The categories included tap slag, runs, smelting slag, vitrified lining, ore, fuel, iron objects and undiagnostic slag. There is a summary of the main contexts producing ironworking debris in table 1, with a description of the debris by context in the appendix (table 6).

Tap slag and runs were by-products of the smelting process, produced by running slag out of the furnace (tapping) when it was hot and fluid. This waste had a characteristic shape, resembling a flow of lava, and the lower surface may be rougher than the upper one as it comes into contact with the ground. This slag type was not porous and was dark grey in colour. Large numbers of the tap slag and run fragments appeared to be tubular in form.

Smelting slag consisted of large blocks of slag, often with fuel impressions in the surface. These were a similar colour to the tap slag. It had obviously been fluid but did not look as though it had flowed in the same way as the tap slag. The porosity of this slag varied greatly.

Vitrified lining consisted of small fragments of quartz-rich clay that had been subjected to heat. The outer surface was orange/red with a black inner (vitrified) surface. This is most likely to be part of a furnace or hearth structure and the vitrified surface is most likely from the inside of the furnace. Some fragments of vitrified lining had iron slag adhering to them.

Undiagnostic slag did not have sufficient characteristics to be categorised; similar materials may be produced by either smelting or smithing operations.

Description and classification of the ironworking waste from The Butts, Worcester

A total of 67.9 kg of ironworking debris was recovered from the site. Figure 1 shows the relative proportions of the different categories of waste. Over 89% of the waste from the assemblage was tap slag, runs and smelting slag, all produced during iron smelting, and therefore it can be concluded that smelting was the main ironworking process taking place. There was no evidence of smithing activity at the site as no slag with the characteristic morphology typical of smithing slag was identified. Vitrified lining can be produced by both smelting and smithing processes, but since no smithing slag was found, it is most likely to be furnace lining.

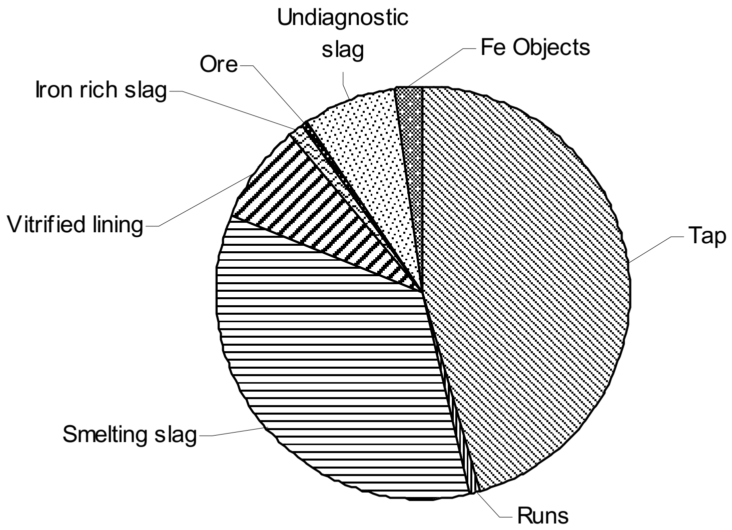

Figure 1: Proportions by weight of different types of ironworking waste from 14-20 The Butts, Worcester.

In table 1, the contexts containing more than 1kg of metalworking debris are listed. The waste from these contexts comprises over 94wt% of the debris recovered from the site. Of this waste over 75wt% was from Roman dated contexts while only 10wt% came from post-Roman contexts and the remainder was undated. Therefore the ironworking activity probably took place largely in the later Roman period. Although some of the contexts appear to be post-Roman, the evidence suggests that it is more likely to be redeposited Roman waste than evidence for post-Roman ironworking (Burrows and Cutter 2004). Most of the metal working debris came from trench E, to the east of the site, in pits that were dated to the 3rd to 4th century. The contents of these pits are similar to the debris found during the excavation of Farrier Street (Dalwood *et al*. 1994).

Table 1: Contexts containing more than 1kg of ironworking waste.

Context	Feature	Trench	Total Waste (g)	Type	Date
4005	400	E	13021	Pit Fill	3rd-4th century
4012	404	E	11427	Pit Fill	3rd-4th century
4015	404	E	10620	Pit Fill	3rd-4th century
4007	402	E	6234	Pit Fill	Roman
1005	-	A	5262	Deposit	post-Roman
4008	400	E	3992	Pit Fill	3rd-4th century
4003	-	E	3088	Unknown	3rd-4th century
4016	407	E	2659	Unknown	Unknown
1011	-	A	2139	Unknown	Unknown
3004	304	C	1937	Ditch Fill	Roman
2004	200	B	1398	Ditch Fill	Roman
1012	-	A	1317	Deposit	Roman
3005	304	C	1232	Ditch Fill	Roman

Material other than slags or vitrified lining found in the assemblage included one piece of iron ore (figure 2), two pieces of charcoal and a rounded quartz pebble that could have been used as a hammer stone. A few iron objects were also found in the assemblage including a piece of unrefined iron, probably a fragment of bloom.

Figure 2: Ore from context 1005.

Research Questions

Previous excavations at Deansway, Worcester have revealed similar debris, and analytical studies of that ironworking debris have been carried out. Samples from The Butts were analysed to compare them with the Deansway material. The source of the iron ore for the Roman ironworking industries at Worcester was also investigated.

Analytical methods

Pieces of tap slag, smelting slag, ore, furnace lining and probable bloom were chosen from contexts that produced large amounts of iron smelting waste. Small samples were taken from each piece and mounted in epoxy resin. They were ground and polished to a 1-micron finish and then coated with carbon. Examination and analysis was carried out using a scanning electron microscope in both backscatter and secondary electron mode. Both modes were used to assess the condition and homogeneity of the samples. The composition of the samples was determined using an energy dispersive spectrometer (with Germanium detector) attached to the scanning electron microscope and calibrated with a cobalt standard. Spectra were collected at 25kV and 2nA for 150 seconds live time. The spectra were quantified using the Oxford Instruments SEMQuant software. A small area (typically 3mm by 2mm) was analysed on each sample. Slag is heterogeneous, often with a coarse microstructure, and small areas may not be representative of the whole sample. To reduce this problem three areas of each sample were analysed. A full table of results are shown in the appendix (table 7)

Analysis of Corning glass standards (table 8) showed close agreement with their actual compositions. A slag standard was also analysed using the SEM, as its chemical composition is similar to the composition of the samples examined in this study. The SEM analysis of the slag sample agreed less well with its quoted composition and suggests that the iron, soda and alumina values determined by EDS may be high and the silica low (see table 9 for the full analytical results and comments).

The bloom sample was etched using nital and then examined under a light microscope. Vickers hardness tests were also conducted on the microstructures within the bloom. A sample of the ore was analysed using X-ray diffraction (XRD).

Results and Discussion

Slag

Two pieces of tap and one piece of smelting slag were analysed. The main elements present were iron and silicon. Of the other elements, there was a relatively high proportion of alumina with only a little lime and magnesia. The tap slag had less iron oxide present but more alumina (Al_2O_3) and silica than the smelting slag. The microstructure of the slag seen in figure 3 was typical, containing predominantly iron oxide (wustite) and iron silicate (fayalite) in a glass matrix. Magnetite was occasionally noted.

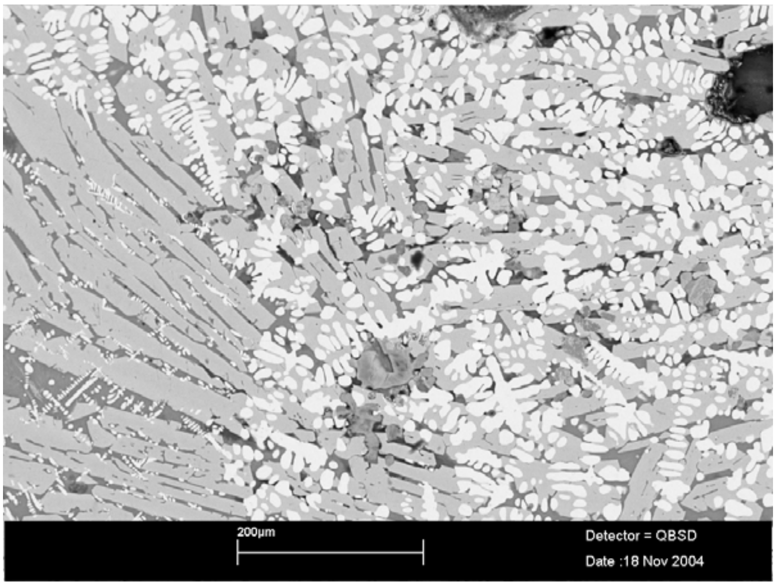

Figure 3: SEM backscatter image of tap slag from context 4012 at The Butts (sample 3) showing the microstructure of the slag which was predominantly iron oxide (white) and iron silicate (light grey) in a glass matrix (dark grey).

Figure 4 compares the composition of the samples from The Butts with other slags from Worcester. Tube slag analysed from the Deansway excavation resembled the tap slag from The Butts, Worcester, both in composition and form (McDonnell and Swiss 2004). The Worcester slag analysed by Morton and Wingrove (1969, 1559) had high proportions of lime and alumina relative to the other gangue elements present in the tap slag. It is unknown where in Worcester this sample originated from and whether it is a tap or smelting slag, although it is very similar in composition to the smelting slag found at The Butts, with a relatively large amounts of iron oxide and low amounts of silica.

Table 2: Chemical composition of slag samples from 14-20 The Butts, Worcester (Normalised, average of 3, data from table 7).

Sample		MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO
3	Tap Slag	0.9	7.1	30.8	0.2	1.6	2.0	0.3	0.2	56.6
5	Tap Slag	0.9	5.4	25.2	0.3	1.0	1.3	0.2	0.1	65.2
4	Smelting Slag	1.0	4.6	18.4	0.2	1.0	1.3	0.1	0.2	72.8

Table 3: Chemical composition of ironworking waste from Worcester analysed by Morton and Wingrove (1969) and the averages for the tap and smelting slag from Deansway, Worcester (McDonnell and Swiss 2004).

	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO
Worcester Slag	1.3	5.9	16.2	nd	nm	3.1	nm	0.2	66.6
Deansway Tap Slag	1.6	4.9	28.0	nd	2.2	2.1	0.2	0.2	59.9
Deansway Smelting Slag	2.0	6.6	31.8	nd	1.2	2.2	0.3	0.2	54.8

nd = not detected nm = not measured

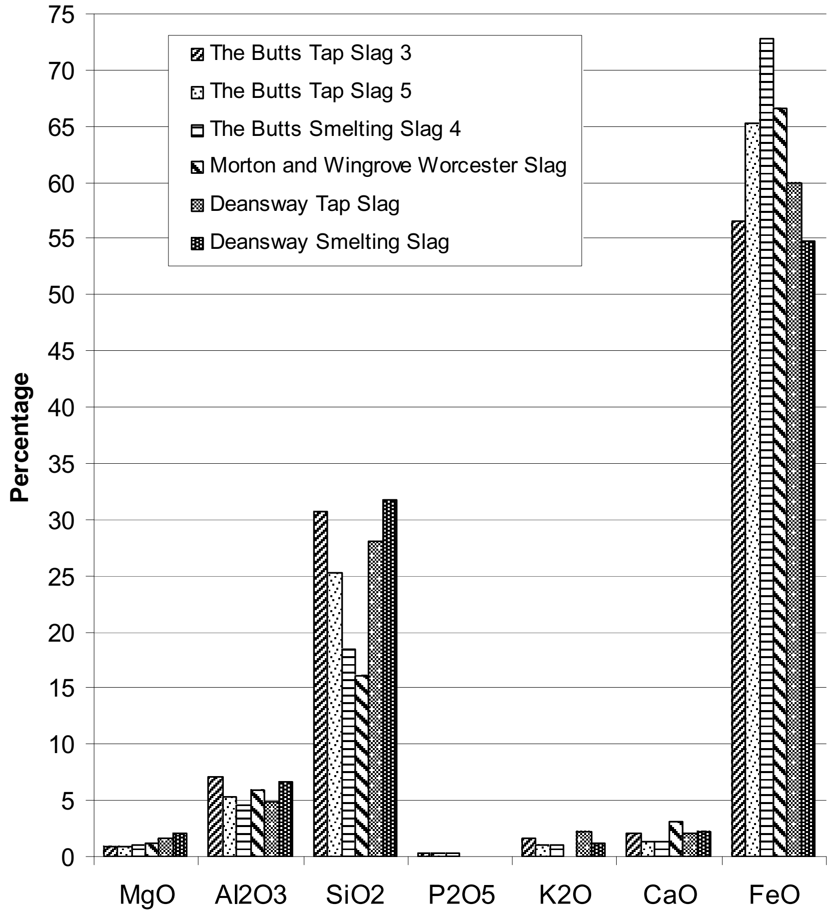

Figure 4: The composition of slag from Worcester (Data from tables 2 and 3).

The minor components within slags vary considerably across sites in different parts of the country. The composition is related to the raw materials, ore and clay lining, and the technological techniques, such as temperature, used during the smelting process. Compared to the concentration ranges in Paynter's study of regional variation in bloomery iron smelting, the Worcester slags have low concentrations of phosphorus and intermediate amounts of lime, magnesia, potash and alumina (Paynter forthcoming). This is typical for slags from the Gloucester, Worcester and Somerset area.

Ore

Goethite ores predominate in the Carboniferous ore-field of the Forest of Dean, which is thought to be the most likely source of iron ore for the smelting sites at Worcester (Fulford and Allen 1992). The chemical composition of these ores can vary considerably between areas within the Forest of Dean ore-fields (Groves 1952, 179). Ore from this source could have been transported up the River Severn to the site at Worcester. Another possible source of ore is the fault-hosted ores of the Worcester Graben in South Gloucestershire.

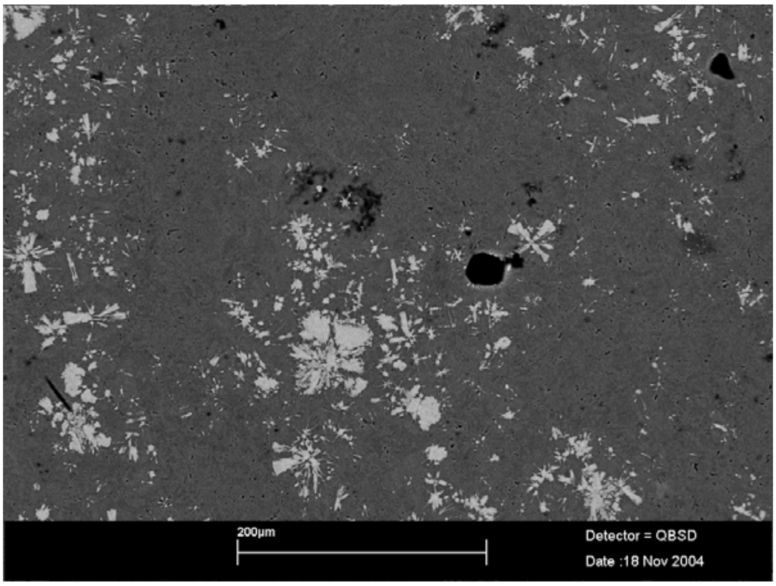

Figure 5: SEM backscatter image of the Worcester ore from context 1005 showing the small light grey haematite crystals in a grey goethite matrix. The black indicates voids within the sample.

XRD showed that the sample of ore from The Butts was goethite with some haematite, and this was confirmed by the SEM images which revealed small haematite crystals in a goethite matrix. Tim Young (pers comm) has identified the ore as stalactitic and indicated that stalactitic ores are very significant in the Forest of Dean, although stalactitic ores also occur in the larger voids elsewhere, for example the Glamorgan ore fields in South Wales. The ore found at Worcester is unlikely to have come from the Worcester Graben as these ores tend to be dominated by botryoidal facies rather than stalactitic facies (Young pers comm: Young and Thomas 1999). Analysis of the ore showed that it contains 97% iron oxide and only very small quantities of silica, alumina and magnesia. The ore found at The Butts was chemically similar to other goethite ores found at Deansway, Worcester (McDonnell and Swiss 2004). The low levels of lime and magnesia in the slag from The Butts are consistent with a high purity ore from the Forest of Dean being used during smelting.

Furnace lining

Analysis of the furnace lining from The Butts revealed that it was a quartz-rich clay containing over 70% silica. This appears to be a typical composition for Roman furnace linings and similar examples have been found during excavations at Westhawk Farm, Kent (Paynter 2002), Snettisham, Norfolk (Chirikure and Paynter 2004) and at the Chesters Villa, Woolaston (Fulford and Allen 1992, 192). The furnace lining also contained high amounts of alumina. Research has shown that the furnace lining may contribute a significant proportion to the overall composition of the slag (Fulford and Allen 1992). As the type of ore thought to have been smelted at the site contains little alumina (see above), the slightly high amounts of alumina present in the slag from The Butts may be derived from the furnace lining.

Table 4: Chemical composition of furnace lining from14-20 The Butts, Worcester (Normalised, average of 3, data from table 7).

	Sample	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**K_2O**	**CaO**	**TiO_2**	**MnO**	**FeO**
1	Furnace Lining	1.8	1.0	12.1	76.8	0.2	2.4	0.2	0.6	<0.1	4.7

Bloom

The bloom was found in context 1005, which is a layer of 'dark earth' sealing a Roman cobbled surface. The bloom fragment weighed 520g and is 100mm by 60mm and 60mm thick. No slag inclusions were found within it but analysis of slag surrounding the surviving metal revealed a similar composition to the slag found at the site (cf. tables 2 and 5), although the slag around the bloom had slightly lower amounts of alumina compared to the tap and smelting slag mentioned above.

Table 5: Chemical composition of slag around the bloom from14-20 The Butts, Worcester (Normalised, average of 3, data from table 7).

	Sample	**Na_2O**	**MgO**	**Al_2O_3**	**SiO_2**	**P_2O_5**	**K_2O**	**CaO**	**TiO_2**	**MnO**	**FeO**
6	Slag around the bloom	<0.5	1.3	4.4	19.8	0.4	0.7	1.3	0.2	0.1	71.6

Although the context from which the bloom was recovered is post-Roman, the evidence suggests that the bloom is more likely to be redeposited Roman material (Burrows and Cutter 2004). The similarity between the chemical composition of the slag associated with the bloom and the smelting slag found in Roman contexts also supports this conclusion.

The bloom was etched with nital to reveal the microstructure of the surviving metal and Vickers hardness tests were also conducted. The microstructure (figure 6) was heterogeneous and included the phases pearlite, bainite and martensite and a phase with Widmanstätten morphology, broad pointed needles (Samuels 1980, 313-315). The Widmanstätten phase is most likely to be ferrite as it was etched by nital and had a Vickers hardness value between 154 and 193. The proportions of these phases and the results of the hardness tests together indicate that the fragment is steel with a carbon content varying from about 0.3 to 0.8%. The bloom fragment had also cooled unevenly; the presence of martensite in the central region indicating rapid cooling whereas the Widmanstätten microstructure of an adjacent region suggested slow cooling (Samuels 1980, 313-315). When the bloom fragment was analysed using the SEM the amount of phosphorus present throughout the sample was below the detection limit.

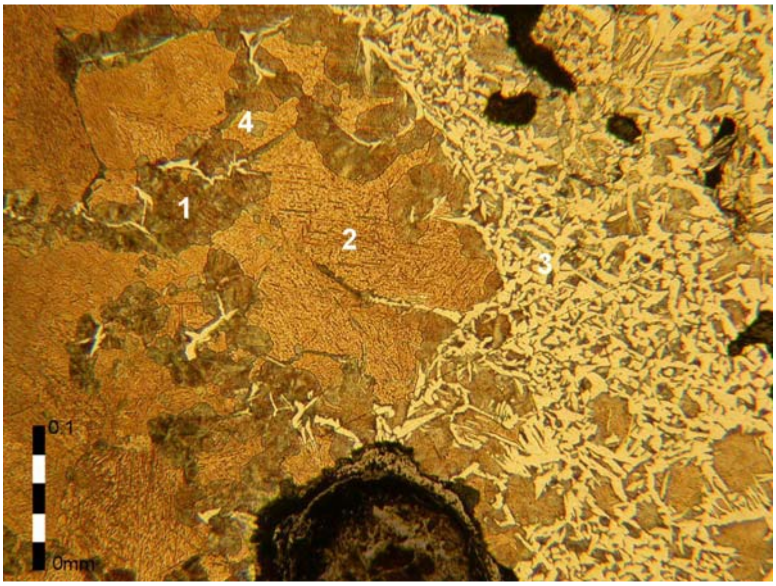

Figure 6: Image of the bloom showing 1) Pearlite forming on grain boundaries, 2) Martensite, 3) Widmanstätten ferrite and 4) Bainite.

Conclusions

Ironworking waste of Roman date was discovered at The Butts, Worcester, but no furnace structures were found, therefore ironworking may not have taken place in the excavation area although it probably occurred nearby. The similar date, chemical composition and form of the slag from The Butts, Farrier Street and Deansway suggests that they were produced using similar raw materials and processes, possibly at the same ironworking centre, perhaps to the north of The Butts.

Both the microstructure and composition of the stalactitic ore suggest that the most likely source is the Forest of Dean. The microstructure of the bloom fragment from the site shows that it is a heterogeneous carbon steel with a carbon content of between 0.3 and 0.8%. The microstructure also indicates that the cooling rate varied across the bloom fragment. The pieces of bloom recovered from Deansway were all ferritic, so the bloom recovered from The Butts appears atypical. However, as this fragment of bloom was found discarded it may not be representative of the iron being produced at the site.

Acknowledgements

I am very grateful to Dr Tim Young who shared his expertise on provenancing ores and assisted with the identification of the ore. I also wish to thank Dr Gerry McDonnell for his assistance in identifying the various microstructures present in the Worcester bloom.

Bibliography

Bayley, J, Dungworth, D and Paynter, S 2001 *Archaeometallurgy*. Centre for Archaeology Guidelines 2001-01. London: English Heritage

Burrows, B and Cuttler, R 2004 *14-20 The Butts, Worcester Post Excavation Assessment and Research Design.* Birmingham Archaeology, University of Birmingham.

Chirikure, S and Paynter, S 2004, Ferrous Waste *in* Lyons A, *Romano-British Industrial Activity at Snettisham, Norfolk*, East Anglian Archaeology Occasional Papers 18, 42-45.

Dalwood, C H, Buteux, V and Darlington, J 1994 'Excavations at Farrier Street and Other Sites North of the City Wall, Worcester 1988-1992'. *Trans. Worcestershire Archaeol. Soc 3rd Series* **14**, 75-114

Dalwood, C H and Edwards, R 2004. *Excavations at Deansway, Worcester 1988-1989 Romano-British small town to late medieval city*. York: Council for British Archaeology. Research Report No 139.

Fulford, M G and Allen J R L 1992 Iron-Making at the Chesters Villa, Woolaston, Gloucestershire: Survey and Excavation 1987-91. *Britannia* **23**, 159-215

Groves, A W 1952. *Wartime Investigations into the Hematite and Manganese Ore Resources of Great Britain and Northern Ireland*. Permanent Records of Research and Development Monograph No. 20.703, Mineral resources Division, Colonial Geological Surveys, Ministry of Supply, London.

Kresten, P and Hjärthner-Holdar, E 2001. 'Analyses of the Swedish ancient iron reference slag W-25:R'. *Historical Metallurgy* **35** (1), 48-51

McDonnell, G and Swiss, A 2004, 'Ironworking residues'. In Dalwood, C H and Edwards, R 2004. *Excavations at Deansway, Worcester 1988-1989 Romano-British small town to late medieval city.* 148-157

Morton, G R and Wingrove J 1969 'Constitution of Bloomery Slags: Part 1: Roman'. *Journal of the Iron and Steel Institute*. Vol 207 1556-1564.

Paynter, S 2002 *The Metalworking Remains from Westhawk Farm, near Ashford, Kent,* Centre for Archaeology Report 84/2002. London: English Heritage

Paynter, S. forthcoming. Regional Variations in Bloomery Iron Smelting Slag of the Iron Age and Romano-British periods.

Samuels, L E 1980. *Optical Microscopy of Carbon Steels*. Ohio: American Society for Metals.

Young, T P and Thomas, G R 1999. 'Provenancing iron ore from the Bristol Channel Orefield: The cargo of the Medieval Magor Pill Boat.' In Pollard, A.M. (ed), *Geoarchaeology; exploration, environments, resources. Geological Society Special Publications* **165,** 103-121.

Appendix

Table 6: Quantities (in g) of different types of waste recovered from 14-20 The Butts, Worcester, by context.

Context	Feature	Date/ Century	Tap Slag	Run Slag	Smelting Slag	Vitrified Lining	Ore	Fuel	Undiagnostic Slag	Iron
1003		Unknown							21	
1004		Unknown								83
1005		post-Roman	1285	76	2063	278	403		488	669
1011		Unknown	140		1662				69	268
1012		Roman	536		718				63	
1018	108	post 2^{nd}	18							
2004	200	post 2^{nd}	873		372				153	
2005	201	Roman	13							
2006	202	Roman	4							
2007	203	Roman	60							
2008	204	Roman	57							
2009	205	Roman	119							
2011	207	post 2^{nd}	393							
2012	208	Roman	10							
2014	210	post-Roman	21							
3000		Natural	10							
	303	Unknown	21		118					
3004	304	2^{nd}	1918						19	
3005	304	2^{nd}	1105			78			49	
3006	305	2^{nd}	118		795					
4003		3^{rd}-4^{th}	615		2044			10		419
4005	400	3^{rd}-4^{th}	5574	121	6371	324		8	623	
4007	402	Roman	2972		2854				408	
4008	400	3^{rd}-4^{th}	2116	49	1827					
4012	404	3^{rd}-4^{th}	6481		4177	119			598	52
4013	405	Roman			248					
4013	405	Roman	30							
4014	406	post-medieval	238		558					
4015	404	3^{rd}-4^{th}	4317		4255				2048	
4016	407	Unknown	1552	257	837				13	
4020	411	Roman	8							
4021	412	Roman	83							
4022	404	Roman	124							
4025	415	post-Roman							17	
4026	416	post-medieval	29							
4032	420	Roman	32							
U/S		Unknown	59						330	

Table 7: Chemical composition of the ironworking waste samples from 14-20 The Butts, Worcester (normalised).

Sample No	Context	Waste Type	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO
1	4012	Vitrified	1.1	1.5	13.6	74.4	0.2	2.6	0.1	0.7	<0.1	5.8
		lining	3.6	0.6	13.0	76.0	0.2	2.3	0.4	0.5	<0.1	3.4
			0.8	0.9	9.8	80.0	0.2	2.3	0.2	0.7	<0.1	5.0
2	1005	Ore	<0.5	0.4	0.4	1.6	<0.1	<0.1	<0.1	<0.1	<0.1	97.2
			<0.5	0.5	0.3	1.3	<0.1	<0.1	0.1	<0.1	<0.1	97.5
			<0.5	0.5	0.5	1.7	0.1	<0.1	0.1	<0.1	<0.1	96.9
3	4012	Tap	<0.5	0.9	6.9	30.6	0.2	1.8	2.1	0.2	0.2	56.7
			<0.5	0.8	6.9	30.8	0.2	1.7	2.1	0.2	0.1	56.6
			<0.5	0.9	7.4	30.9	0.3	1.4	1.8	0.3	0.2	56.4
4	4005	Smelting	<0.5	1.0	4.3	18.2	0.2	1.1	1.3	0.2	0.2	73.2
		slag	<0.5	1.1	4.6	18.3	0.2	1.1	1.3	0.1	0.2	72.7
			<0.5	1.0	4.7	18.8	0.3	1.0	1.1	0.1	0.2	72.6
5	4005	Tap	<0.5	1.0	5.1	24.9	0.3	1.0	1.2	0.2	0.1	65.9
			<0.5	0.9	5.3	25.4	0.3	1.0	1.2	0.2	0.1	65.2
			0.5	0.7	5.7	25.3	0.3	1.1	1.4	0.2	0.1	64.5
6	1005	Slag	<0.5	1.2	4.6	20.1	0.7	0.7	1.2	0.2	<0.1	71.0
		around	<0.5	1.2	4.6	20.2	0.1	0.7	1.2	0.2	<0.1	71.4
		bloom	<0.5	1.6	4.0	19.0	0.3	0.6	1.4	0.2	0.1	72.3

Table 8: Chemical composition of the Corning Glass Standards compared to the analysed results (normalised, average of three).

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	Fe_2O_3
Standard A	14.93	2.78	1.04	69.75	0.14	0.10	3.00	5.25	0.82	1.04	1.14
SEM Analysed A	15.2	2.7	1.0	69.1	0.1	0.2	3.2	5.2	1.0	1.1	1.1
Standard B	17.96	1.09	4.61	64.98	0.87	0.53	1.10	9.04	0.09	0.26	0.36
SEM Analysed B	17.5	1.1	4.5	63.7	0.9	0.7	1.2	9.6	0.1	0.3	0.4
Standard D	1.24	4.07	5.47	56.42	4.06	0.31	11.67	15.28	0.39	0.57	0.54
SEM Analysed D	1.5	4.1	5.4	55.9	4.1	0.3	11.7	15.5	0.5	0.6	0.5

Table 9: Iron Slag Standard (from Kresten and Hjärthner-Holdar 2001, normalised) compared to the SEM result (normalised, average of three).

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
MiniPro conv A122	0.67	0.40	7.38	24.03	0.26	0.07	1.10	1.00	0.33	3.09	61.68
Sandvik conv A123	0.70	0.40	7.33	25.51	0.26	nm	1.00	1.41	0.31	3.11	59.96
SGAB2 ICP A226	0.45	0.47	7.80	25.50	0.31	nm	1.07	1.75	0.33	3.21	59.13
SGAB2 ICP A226	0.56	0.43	7.49	25.50	0.25	nm	1.10	1.58	0.34	3.32	59.42
SGAB2 ICP A226	0.56	0.39	7.67	25.87	0.52	nm	1.07	1.57	0.43	3.14	58.79
Average Slag Standard	**0.59**	**0.42**	**7.53**	**25.28**	**0.32**	**-**	**1.07**	**1.46**	**0.35**	**3.18**	**59.79**
EDS analyses	1.4	0.3	8.0	21.2	0.3	0.2	1.0	1.4	0.3	3.0	62.9
	1.5	0.5	8.5	21.6	0.2	0.3	1.0	1.5	0.3	3.0	61.5
	1.3	0.4	8.0	21.8	0.2	0.3	1.0	1.4	0.3	3.1	62.2
Average EDS Analyses	**1.4**	**0.4**	**8.2**	**21.5**	**0.3**	**0.3**	**1.0**	**1.5**	**0.3**	**3.0**	**62.2**

nm = not measured

The slag standard is from the Viking Age iron production site at Gryssen in Dalecarlia (Kresten and Hjärthner-Holdar 2001). The published original analyses of the standard using different techniques by 9 laboratories resulted in different compositions, some of which had low overall totals. The 6 results selected from those published, to determine an average with which to compare, were those with totals closest to 100% and which included all the oxides of interest. Results that varied considerably from those of the other laboratories for elements of interest were excluded.