Chapter 7: Metalworking Remains

by Sarah Paynter

SUMMARY

Approximately 1.65 tonnes of ironworking waste were recovered from Westhawk Farm. This comprised largely smelting debris, although some smithing slag was also present. Much of the debris was recovered from contexts surrounding two workshops, one pre-dating the other. Both smelting and primary smithing of the product took place in the workshops, and some furnaces, hearths and hammerscale deposits survived. Analysis of the different types of waste has enabled the process of formation of the different types of slag to be modelled. The scale of iron-production at Westhawk has also been estimated and discussed in the context of Wealden iron production in the Roman period.

INTRODUCTION

A large quantity of ironworking debris was recovered during the excavation of Area B. Features thought to be associated with ironworking were identified within two structures, now referred to as Structures I and R. David Starley, from English Heritage's Ancient Monuments Laboratory, visited the site and produced a report (Starley 1998) with a list of recommendations pertaining to the investigation of the metalworking features. In accordance with these recommendations, a high-resolution fluxgate gradiometer survey was conducted over the two areas of interest by Rob Vernon, from the University of Bradford (Vernon 1999).

The quantity of ironworking waste recovered during the excavation of Area B (approximately 1.65 tonnes) indicates that this industry is likely to have been important to the economy of the settlement. Although larger ironworking sites of Roman date are known from the Weald nearby, Westhawk Farm is unusual and important because of the two ironworking workshops within which some features, and in one instance an occupation surface, survived. This report aims to identify the type, location, duration and scale of the ironworking activity at the settlement. The type of activity is determined by identifying the types of ironworking waste produced. The location of the activity is determined by analysis of the spatial distribution of the waste, the geophysical survey data, the descriptions of the excavated features and the examination of occupation deposit samples. The duration of activity is determined by the dating of the deposits of ironworking waste and the workshops themselves. The scale of the activity is approximated from an estimate of the amount of waste produced for the duration of the ironworking activity. Additional information about Roman ironworking technology and the formation of the different categories of waste can be derived through examination of the raw materials, waste and products from these processes.

IRONWORKING PROCESSES AND THE WASTE PRODUCED

Ironworking processes produce characteristic waste products, which can be differentiated on the basis of their shape, colour, density, porosity, surface texture and occasionally chemical composition. A description of various ironworking processes, and the different types of waste that they produce, is given below. The waste from Westhawk Farm was categorised according to these descriptions.

Ironworking processes

Smelting

Smelting is the process of reducing iron ore to produce iron metal. Previous work has shown that iron smelting in this period and area took place in bloomery furnaces, which were typically fairly small, rounded structures with an inside diameter of about 0.3 m and probably with a height of about 1 m. These structures were constructed from clay and had walls about 0.25 m thick (Cleere and Crossley 1985; Crew 1991; Pleiner 2000). Charcoal fuel was used. Some types of ore were roasted prior to smelting to convert the ore to iron oxide and to facilitate crushing into smaller pieces. Air was blown into the furnaces using bellows, generally through one or more small holes near the base, known as blowholes. The furnace would have been lit and allowed to reach full temperature before roasted ore was fed into the top. Additional fuel and ore would have been fed into the furnace for the duration of the smelt. The area near the blowhole would have been the hottest region of the furnace but the temperatures used in the bloomery process were insufficient to melt the iron alloys produced. Therefore, when the iron ore reacted to form particles of iron, these accumulated near the blowhole to form a spongy mass, known as a bloom, which was removed through the top of the furnace or through a tapping aperture. The gangue (non-iron minerals) in the iron ore reacted with some of the iron, and potentially also with the lining of the furnace and ashes from the fuel, to form a liquid slag. The slag was tapped into a pit or down a slope through a hole - sometimes known as the tapping arch - at the base of the furnace. The chemical reactions occurring during smelting can be generalised as:

Ore roasting:

$4FeCO_3$ (siderite ore) + $O_2 \rightarrow$ heat $\rightarrow 2Fe_2O_3 + 4CO_2$

or

$4FeO.OH$ (goethite ore) $\rightarrow$ heat $\rightarrow 2Fe_2O_3 + 2H_2O$

Metal production:

$Fe_2O_3 + CO$ (from burning of fuel) $\rightarrow 2FeO + CO_2$

$FeO + CO$ (from burning of fuel) $\rightarrow$ Fe (metal) + CO_2

Slag production:

$2FeO + SiO_2 \rightarrow Fe_2SiO_4$ (fayalite slag)

Smithing

When removed from the furnace, the iron bloom contained much slag and voids and required consolidation by smithing. This is the process of hammering and shaping iron, generally at red heat, as the metal is then more malleable. The iron was heated in a charcoal-fuelled hearth, which may have been a shallow, walled structure, constructed from clay or stone, either on the floor or at waist height. Bellows blew air into the hearth through a hole in the hearth wall. During smithing the surface of the iron became oxidised and reacted with the materials with which it came into contact, such as the lining of the hearth and ashes from the fuel. When this surface covering was detached from the metal it formed small flakes and spheres of iron oxide and slag, known as hammerscale. Debris from smithing accumulated in the bed of fuel in the hearth and formed a lump of slag known as a smithing hearth bottom. Once hot, the metal was hammered into shape on an anvil, resulting in the loss of more slag and scale, which collected on the floor. Since hammerscale is magnetic it can be detected in archaeological occupation surfaces with a magnet. The smith would form the iron into a billet or bar for subsequent trading.

Primary and secondary ironworking (Fig. 7.1)

The processes of smelting iron ore to form metal and the subsequent smithing to form the bloom into a billet or bar are together known as 'primary ironworking'. The iron billets or bars produced by primary ironworking would then be supplied to smiths at other sites where they were used to produce iron objects by 'secondary ironworking'. In secondary ironworking, bars or billets of iron, or recycled iron, were made into useable objects by further smithing. As this also involved repeatedly heating iron in a hearth and hammering the hot metal into shape, hammerscale and smithing hearth bottom slags were again produced. However, this smithing activity was not associated with smelting. The stages involved in both primary and secondary ironworking are compared in Figure 7.1.

Ironworking waste

Categories of ironworking waste

The ironworking debris from Westhawk Farm was categorised into the classes summarised in Table 7.1 following the Centre for Archaeology *Guidelines* (Bayley *et al.* 2001). The classes and processes that produced each are as follows:

Tap slag *(smelting)*: Dense slag, with a rough lower surface and an upper surface that looks like a lava flow.
Slag-coated clay *(smelting and smithing)*: Clay that formed part of the furnace or hearth lining, with a surface that has reacted with the slag or the ash from the fuel at high temperatures and has developed a

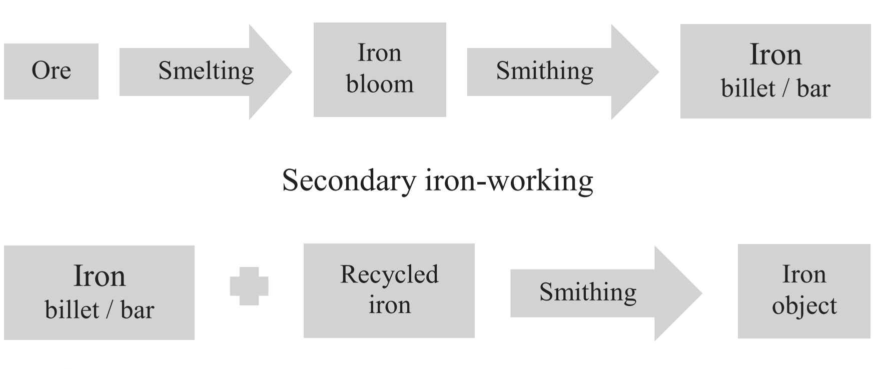

Figure 7.1 Summary of the stages involved in primary and secondary iron-working.

Table 7.1 Metalworking remains: Summary of types of waste produced by primary and secondary iron-working (√ = present, X = absent).

Iron-working Waste	Primary Iron-working	Secondary Iron-working
Tap slag	√	X
Slag-coated clay	√	√
Fired clay	√	√
Ore	√	X
Smithing hearth bottom	√	√
Furnace bottom	√	X
Iron lumps, bar or billet	√	√
Hammerscale	√	√
Runs	√	X
Undiagnostic	√	√
Fuel ash slag	√	√

dark-coloured, slag-like or glassy surface. Furnaces and hearths are hottest near the blowing hole, and pieces of vitrified clay from a furnace or hearth wall with the outline of the blowing hole are sometimes found. This debris is also often referred to as vitrified clay or hearth/furnace lining.

Fired clay *(smelting, smithing and other high temperature processes)*: This can include clay that was sufficiently near the hotter regions of the furnace or hearth to be fired by its heat, but has no identifiable vitrified or slag-coated surface remaining. However, many processes involving high temperatures can result in the production of fired clay and so alone it is not diagnostic of metalworking.

Ore and iron-rich stone *(smelting)*: Any iron-rich stone in the assemblage was categorised as potential ore, although not all of the different types of stone were necessarily smelted. Unroasted ironstone was grey/brown in colour. Roasted ironstone was deep red to metallic grey. Ore that has been heated can be magnetic.

Furnace bottom slag *(smelting)*: If slag accumulates at the bottom of a furnace below the tapping level, a bowl-shaped slag with a level surface and a low porosity is formed. Unlike tap slag it has no flow lines on the surface and occasionally has clay adhering to the bottom. Large lumps of slag with fractured edges, sometimes with protruding flows or runs of slag and often with abundant incorporated fuel fragments, were also categorised as slag from a furnace base that had remained after tapping.

Hammerscale *(smithing)*: Small flakes or spheres of slag and iron oxide, expelled or detached from the surface of iron during smithing. Hammerscale can be produced by primary smithing, during bloom consolidation, or secondary smithing. Hammerscale is magnetic.

Smithing hearth bottom (SHB) *(smithing)*: Spongy lumps of slag containing many small pores with characteristic convex bottom surfaces and concave upper surfaces, produced in the smith's hearth during primary or secondary smithing.

Iron lumps *(smelting and smithing)*: Lumps or fragments of iron including partially consolidated bloom fragments and partially shaped objects.

Undiagnostic slag *(smelting and smithing)*: Much of the slag does not have enough diagnostic features for it to be categorised.

Slag runs *(smelting)*: Slag runs of various sizes, including long slender tubes of slag often in groups or emanating from substantial lumps of slag, produced during slag tapping.

Fuel ash slag *(smelting, smithing and other high temperature processes)*: This material is produced by reaction of plant ashes, for example from charcoal fuel, with siliceous material, such as clay. It is usually vesicular and is lighter-coloured and less dense than the iron-rich slag commonly produced by ironworking processes. Non-metallurgical, high temperature processes can produce fuel ash slag and so alone it is not diagnostic of ironworking. Very little fuel ash slag was found amongst this assemblage.

Charcoal fuel was found in many contexts associated with ironworking. Stores of this fuel are sometimes found in the vicinity of furnaces, and charcoal pits, or platforms, may be found near to where the charcoal was produced. However, no such deposits were identified at Westhawk Farm. Iron pan was also noted in some contexts. Iron pan forms when iron compounds precipitate from solution, forming an orange, iron-rich layer. Iron pan is common in ironworking contexts where there is a large amount of corroding iron-rich material, such as iron lumps or objects, and could also be used as ore. However, it is common geologically and so its presence is not diagnostic of ironworking.

Disposal and reuse of ironworking waste in the past

Many of the large, dense products of ironworking processes, such as tap slag and smithing hearth bottom slags, were removed from ironworking sites and dumped in pits or ditches. Therefore the presence of tap slag does not necessarily indicate that smelting took place in the immediate vicinity, although a very large deposit generally indicates that smelting took place nearby. Slag was also reused, either in antiquity, for example as road metalling, or more recently, for example as ore to be smelted in blast furnaces. Therefore assessments of the scale of metalworking at a site from the amount of waste remaining are likely to be underestimates, since an unknown proportion of the waste will have been removed. In contrast, as hammerscale consists of very small flakes and spheres, it was left to accumulate on the workshop floor where it often formed thick layers. Therefore the presence of hammerscale in an occupation surface indicates that primary or secondary smithing activity occurred in that structure (Bayley *et al.* 2001). Fired clay fragments are fragile and less likely to survive transportation and dumping so, if found, often indicate nearby ironworking activity. Blooms and billets are rarely found, as they were valuable and were processed further.

Identification of ironworking waste

Some 1.4 tonnes of ironworking waste were recovered during excavation in 1998. The waste from 229 contexts, comprising 80% by weight of the slag excavated from Area B, was examined to identify the different types of slag present. Of the ironworking waste recovered in 1999 (which included contexts 7000 to 11150), 94 kg (from 29 contexts) were examined for this report, whereas the waste from 22 boxes, estimated at 150 kg, was not examined. The total amount of ironworking waste recovered from Westhawk Farm was estimated at 1.65 tonnes. The material was sorted into the categories defined above and weighed. Some examples were removed for further analysis. In Table 7.2 the different types of slag and ironworking debris identified in contexts with more than 5 kg are listed, comprising 70% by weight of the total for the site. (A Table giving a full listing of the slag recovered, by context and type, can be found in the archive report on the ironworking debris.) The majority of the metal working waste was deposited during Phase 3 (AD 70-150), Phase 4 (AD 150-200) and Phase 5 (AD 200–250) of the site.

Figure 7.2 shows the percentages by weight of different types of slag represented in the total assemblage. Over half of the assemblage is made up of tap slag, iron-rich stone and furnace bottom slag, all exclusively associated with iron smelting, and therefore the great majority of the slag-coated clay is likely to be waste from smelting furnaces rather than smithing hearths. However, nearly 3.6% by weight of the assemblage is made up of smithing hearth bottom (SHB) slags indicating that some smithing activity took place on the site.

STRUCTURAL EVIDENCE FOR IRONWORKING ACTIVITY

Location of ironworking activity

The distribution of the ironworking waste was studied to determine whether the slag was concentrated

Table 7.2: Metalworking remains: Iron-working debris from contexts containing more than 5 kg of slag categorised by type (weights in kg) (Phase 3 = AD 70-150, Phase 4 = AD 150-200 and Phase 5 = AD 200-250)

Context	Structure	Phase	Tap slag	Ore	Furnace bottom	Slag-coated clay	Fired clay	SHB	Runs	Un-diagnostic	Totals
7773	I	2-3	7.1	0.3	0.0	1.5	0.0	0.0	0.0	0.0	8.9
7866	I	3	2.7	0.0	0.0	0.8	0.0	0.5	0.0	1.4	5.4
1510	I	3	0.1	0.1	5.5	0.0	0.0	0.0	0.0	0.0	5.7
318	I	3	4.0	0.0	0.0	1.6	0.0	0.0	0.1	0.0	6.3
7839	I	3	4.4	0.0	0.0	2.0	0.1	0.0	0.0	0.7	7.2
1156	I	3	1.8	0.0	4.0	2.4	0.0	0.3	0.0	0.5	8.9
319	I	3	3.0	0.0	0.0	1.1	0.0	0.0	0.0	5.8	9.9
481	I	3	3.3	0.0	0.0	3.9	0.0	0.0	0.0	2.8	10.1
8022	I	3	4.1	0.0	0.8	1.1	0.0	6.0	0.0	0.4	12.4
1460	I	4	1.4	0.0	0.0	2.7	0.7	2.7	0.0	0.7	8.1
1206	I	4	2.0	0.0	1.1	5.5	0.0	0.0	0.0	1.5	10.1
1522	I	4	6.7	0.1	0.0	1.4	0.1	0.2	0.2	3.8	13.2
1166	I	4	3.0	0.0	0.0	10.8	0.0	0.0	0.0	0.1	13.9
480	I	4	9.1	0.1	2.8	6.1	0.0	0.0	0.0	0.9	19.1
1126	I	4	41.7	0.1	0.4	22.8	2.1	1.6	0.0	5.8	74.4
1193=1225	I	4	50.9	0.0	4.2	47.7	5.4	6.8	0.1	5.0	120.1
1082=1106	I	5	42.8	0.3	2.1	18.6	4.2	1.0	0.0	5.5	74.5
676	I	6	0.5	0.0	1.1	1.0	0.0	3.3	0.0	0.0	5.9
7623	P	3	3.7	0.0	1.0	2.6	0.0	0.0	0.0	0.0	7.3
7471	P	4	4.5	0.0	0.0	1.3	0.0	0.0	0.0	1.5	7.3
8449	P	4	6.2	0.2	0.0	11.8	0.1	0.0	0.0	0.7	19.1
1157	R	3	0.4	0.0	0.0	6.1	1.2	0.0	0.0	0.0	7.6
1585	R	4	0.6	0.1	0.0	0.4	0.0	0.0	0.0	4.3	6.9
1222	R	4	7.0	0.2	0.0	1.5	0.2	1.0	0.0	0.8	10.6
922	R	4	11.3	1.3	0.8	13.9	0.0	0.0	0.9	0.7	29.0
1356	R	4-5	102.4	10.8	3.0	62.4	3.6	0.2	4.0	11.3	197.7
1219	R	5	1.4	0.1	0.0	1.7	0.0	0.0	0.0	1.7	5.1
1331	R	5	4.1	0.0	0.0	1.6	0.0	0.0	0.1	0.1	5.9
1231	R	5	3.0	0.1	3.1	0.5	0.0	0.0	0.1	0.8	7.7
1216	R	5	2.2	2.7	0.0	1.2	0.2	0.0	0.0	3.4	9.7
1258	R	5	5.6	0.7	1.8	7.3	0.0	0.9	0.1	2.1	18.5
1257	R	5	5.5	0.3	0.0	2.7	0.0	0.0	0.0	10.9	19.3
1332	R	5	14.8	0.4	0.6	6.3	0.0	4.1	0.0	1.1	27.5
1265	R	5	40.4	2.1	0.0	9.4	0.3	0.2	1.6	7.6	61.5
1217	R	5	57.3	2.9	0.3	24.4	1.1	6.0	2.4	10.2	104.7

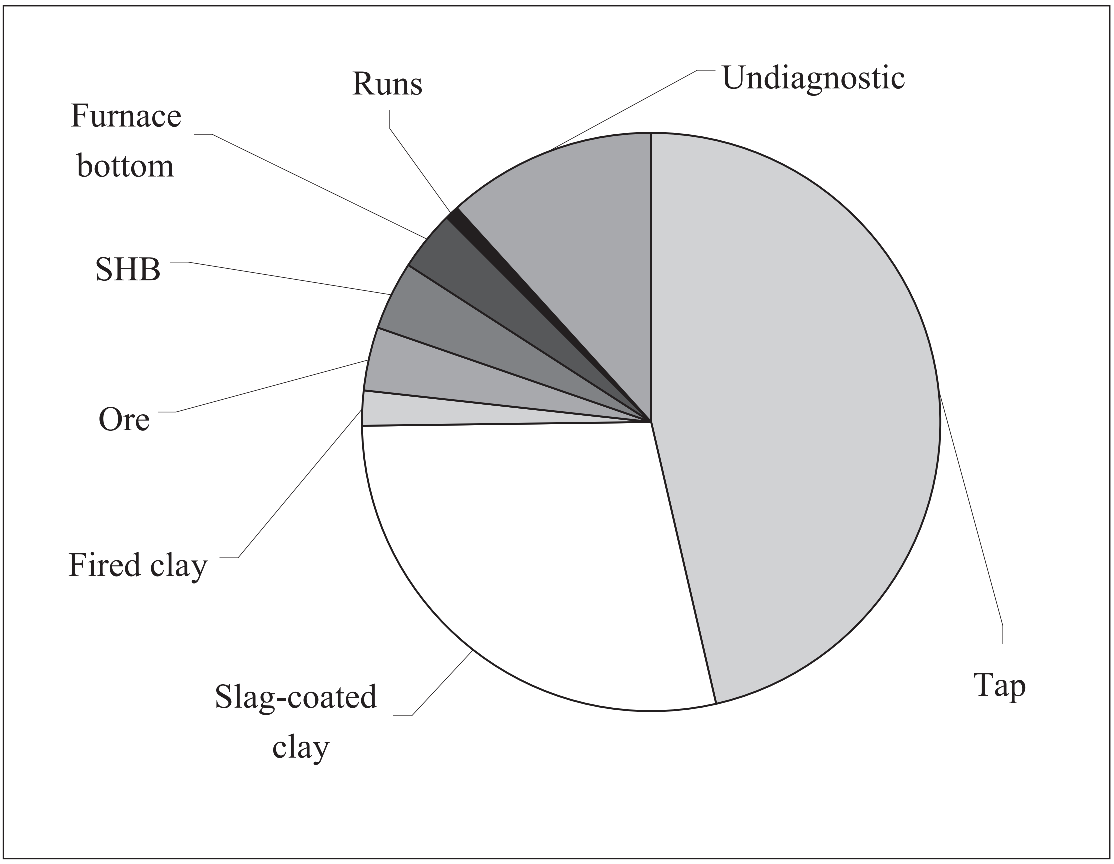

Figure 7.2 Pie chart showing the relative proportions of different types of iron-working debris for the contexts listed in Table 7.2.

in particular areas. The contexts containing in excess of 5 kg of ironworking waste (listed in Table 7.2 and marked on Figure 7.3) are largely concentrated around two structures: structure R and structure I. The remains of features associated with metalworking, such as furnaces, were identified in these structures, which were therefore interpreted as workshops. The layout of the workshops is discussed below. Some metalworking waste and a large iron billet were also found in the vicinity of structure P, but no ground-level metalworking features or metalworking occupation deposits were identified within that structure.

Structure I

Figure 7.4 shows the proportions of the different types of waste recovered from contexts containing more than 5 kg of slag in the vicinity of structure I (see Table 2). The vast majority was smelting waste, although some smithing slags were also identified.

Structure R

Figure 7.5 shows the proportions of the different types of waste recovered from contexts containing more than 5 kg of slag in the vicinity of structure R (see Table 2). As with Structure I, the vast majority was iron smelting waste with some smithing slags also identified.

Structure P

Figure 7.6 shows the proportions of the different types of waste recovered from contexts containing more than 5 kg of slag in the vicinity of structure P (see Table 2). Again virtually all of the waste was from smelting.

Duration of ironworking activity

Many contexts, and particularly those associated with structure I, contained little pottery that could be closely dated. Consequently the contexts are dated largely by stratigraphic associations. These indicate that structure I was probably built in the early 2nd century (in Phase 3; *c* AD 70-150) and was used into, but not for the duration of, Phase 4 (*c* AD 150-200). Examination of the pattern of iron production across the Weald by Cleere and Crossley (1985, 62-63) highlighted a shift towards ironworking at sites in the High Weald between AD 120 and 140, with which this evidence is consistent. Structure R was probably in use from the early 3rd century until AD 250, which is consistent with the evidence

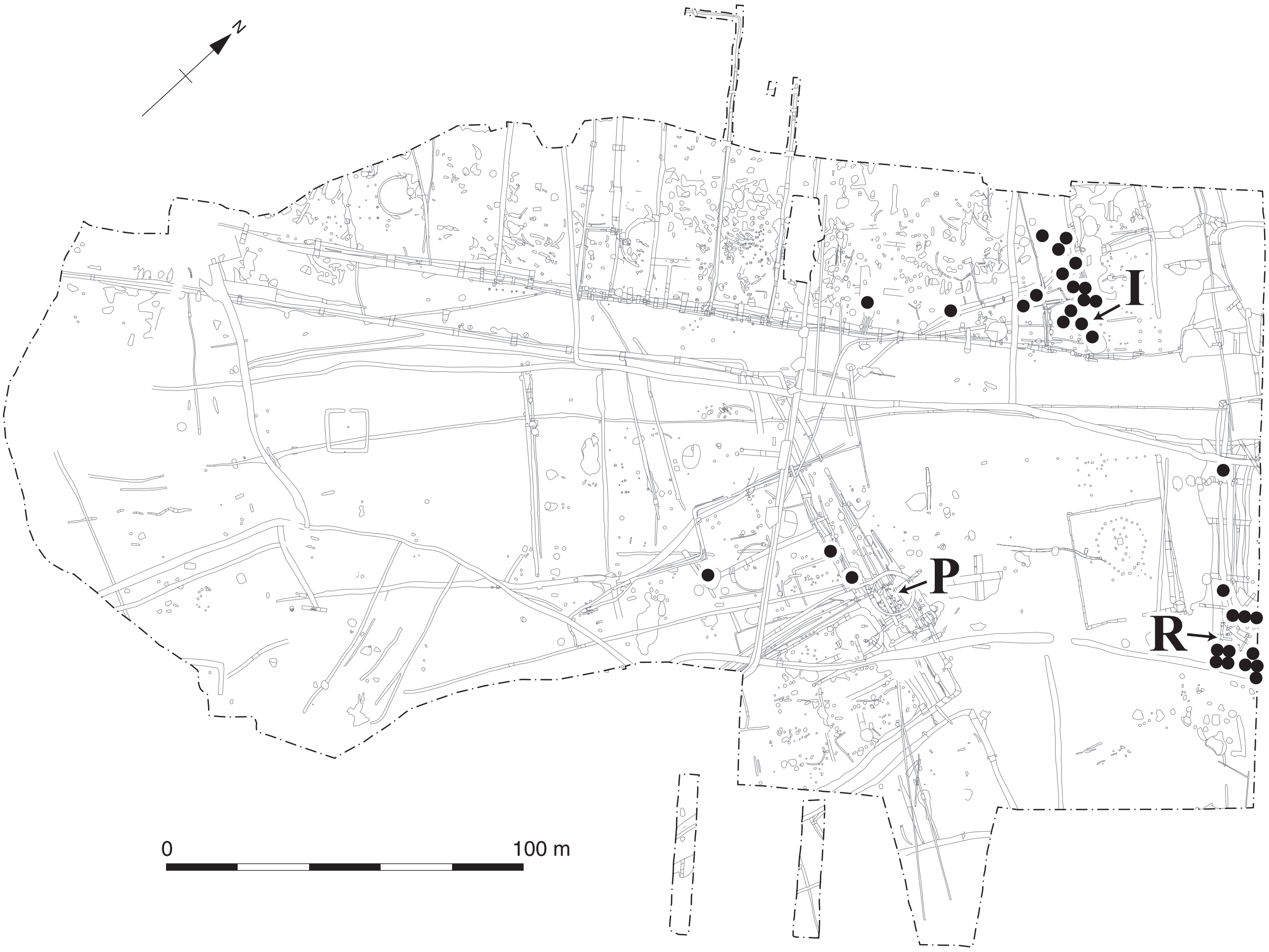

Figure 7.3 Location of contexts with more than 5 kg of iron-working waste recovered.

for the cessation at the same date of smelting activity at other Wealden sites. Other evidence, such as the almost complete absence of coins and pottery from the second half of the 3rd century at the site, suggests that the settlement itself was largely abandoned at this time. The major deposits of ironworking waste surrounding structure I are largely from Phase 4 and the waste in the vicinity of structure R is largely from Phase 5 (*c* AD 200-250). It has been assumed that the periods of iron smelting activity in both structure I (*c* AD 110-160) and structure R (*c* AD 200-250) were of approximately 50 years duration (*c* AD 110-160). This leaves a gap between the ironworking activity based in these two workshops. It is possible that some ironworking took place on the site of structure R prior to the construction of that workshop or, as is discussed later in this report, that other ironworking structures are present in the unexcavated portions of the site. The geophysical survey highlighted several areas with strong readings, potentially resulting from industrial activity, in Area A; therefore an estimate of the duration of ironworking activity for the site as a whole, based only on the activity in structures R and I, is likely to be an underestimate.

The waste in the vicinity of structure P is from contexts assigned to Phases 3 and 4, while the structure itself has been assigned to Phase 5, contemporary with structure R. Although ironworking waste and an iron billet were found in the vicinity of structure P, no smelting furnaces, hearths or occupation deposits associated with ironworking activity were identified in that area. It is likely that the waste deposited at structure P was produced in a workshop elsewhere on the site. However, the concentration of slag in the vicinity of the structure suggests that there is a link of some kind between structure P and the ironworking activity at the site.

Features associated with ironworking activity

Structure I (*Fig 7.7*)

Structure I lay within a rectangular enclosure defined by ditches and gullies, and beam slots aligned with the ditches. Internal features included eight postholes. The enclosure is at the top of a gradual incline, which slopes towards the south-east. The occupation spreads survive less well than in structure R. At the top of the slope there was no post-medieval subsoil

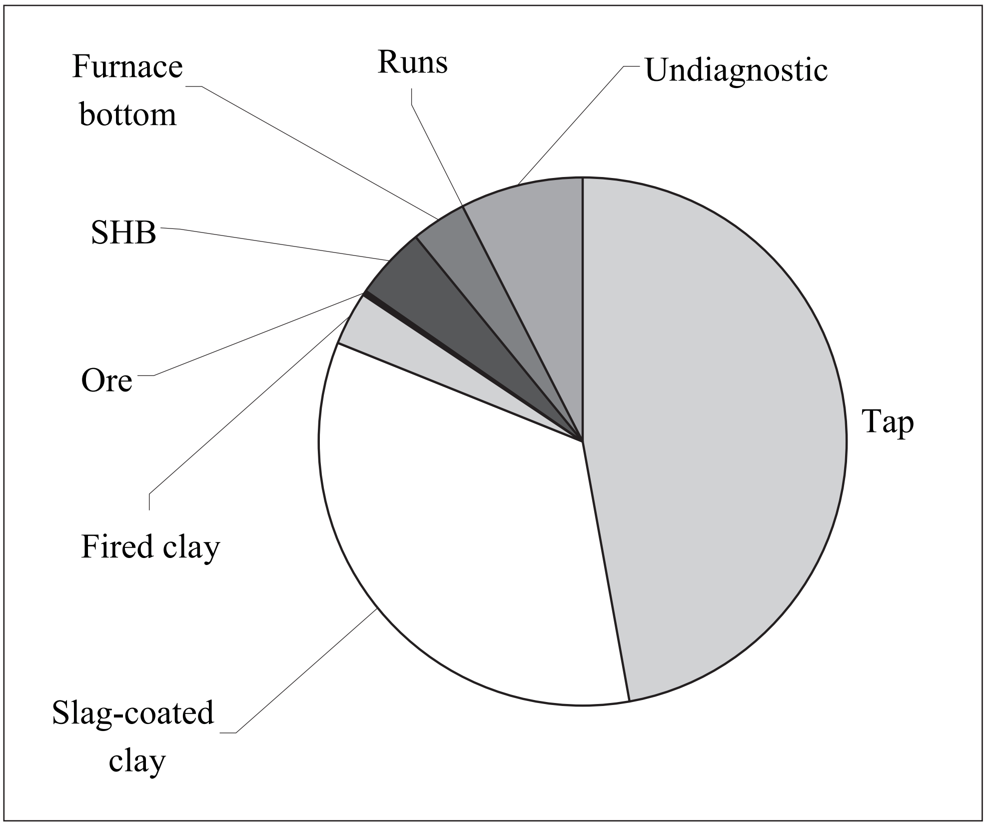

Figure 7.4 Pie chart showing relative proportions of different types of iron-working debris from contexts in the vicinity of Structure I (total 350 kg).

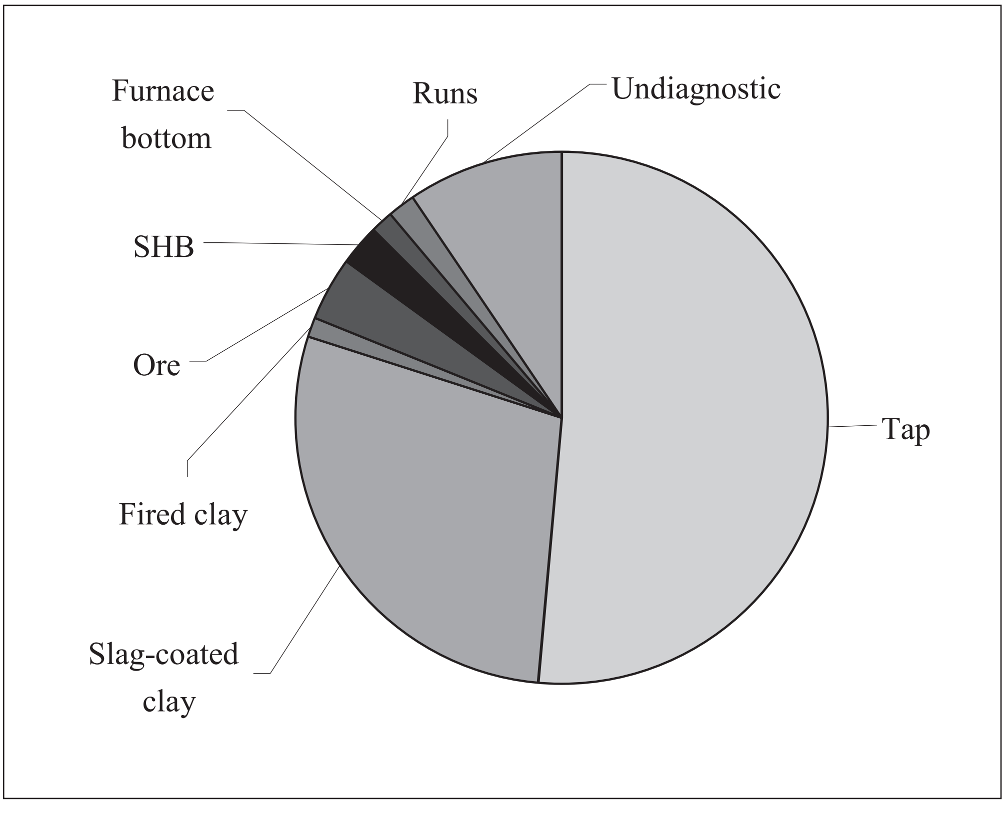

Figure 7.5 Pie chart showing relative proportions of different types of iron-working debris from contexts in the vicinity of Structure R (total 490 kg).

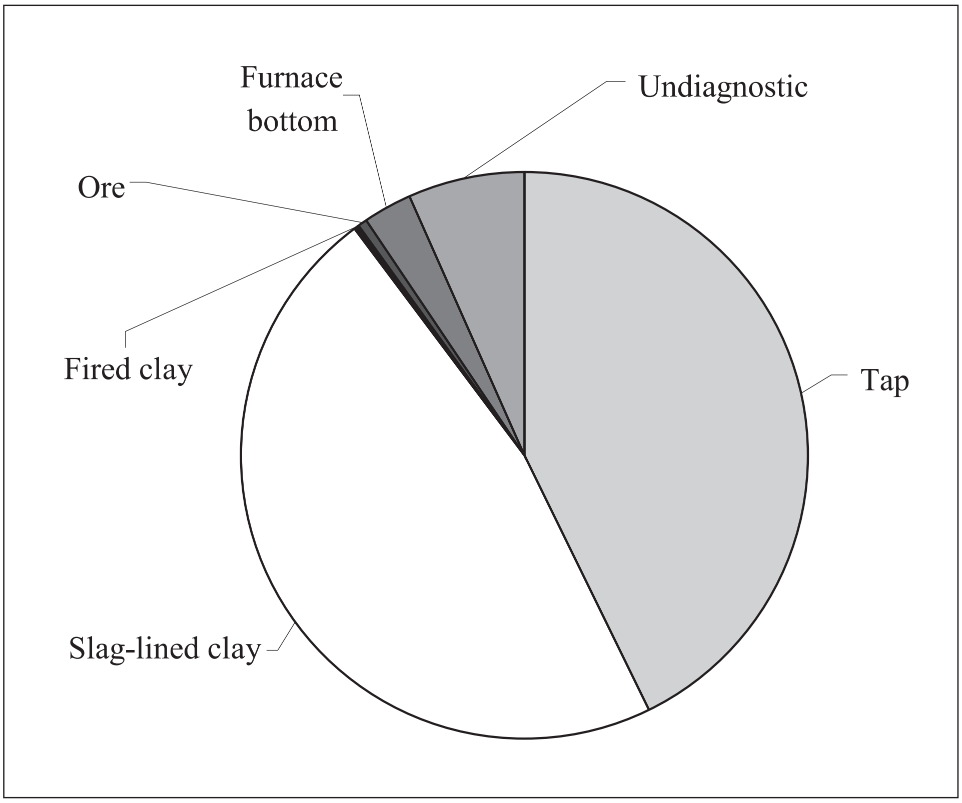

Figure 7.6 Pie chart showing relative proportions of different types of iron-working debris from contexts in the vicinity of Structure P (total 34 kg).

and the modern topsoil directly overlay the natural Wealden clay.

The structure appears to have been partitioned into two working areas. In the north-west working area were two rounded features, 1525 and 1511, with fired clay linings, likely to be the bases of bloomery furnaces. Feature 1525 was 0.46 m in diameter and 0.14 m in depth, with moderate to steeply sloping sides. It was heavily truncated and contained a very charcoal-rich fill. Feature 1511 had similar dimensions (0.7 m diameter) and contained a complete furnace bottom slag (1510) weighing 5.5 kg. This was 0.26 m in diameter and 80 mm deep at its thickest point and bowl-shaped, with a very thin layer of reduced-fired, grey clay adhering to the bottom. The average overall diameter of these furnaces at the base is 0.6 m and the internal diameter, indicated by the furnace bottom slags (a second complete furnace bottom was found in context 1225 nearby) is about 0.26 m. Therefore, the walls of these furnaces were about 0.17 m thick. Experiments by Crew (1991) have indicated that this wall thickness ensures adequate heat retention in the furnace. The furnaces were to the west of the building, side by side and approximately perpendicular to the slope of the land. The slag tapped from the furnaces may have flowed downhill in a south-easterly direction, though no evidence for this survives. Also in this area was a crescent-shaped feature, 1523, which was 1.2 m in diameter and 0.3 m deep with moderate 45º sloping sides. Although this feature contained ironworking debris there were no signs that the debris was *in situ* or that the feature had been fired to high temperatures.

Several features in and around structure I were identified as possible ore roasting pits at the time of excavation. Pit 1549, which was 0.4 m long and 0.14 m deep, and nearby pit 1551, which was 0.3 m long and 0.1 m deep, both contained roasted iron-rich stone, deep red in colour. The fill of pit 1581, which was oval, 0.64 m long and 0.08 m deep, was also described as deep red, but no iron-rich stone from the fill was found amongst the assemblage and neither was any unworked or burnt stone listed for this feature. All of these pits are on the north-west edge of the enclosure, near to each other and to the furnaces. Feature 1494, a posthole situated to the south of the structure, also contained entirely iron-rich stone. Although one or more of these features may have been used for ore roasting, no evidence of heating was observed in the features themselves. Therefore the roasted ore may have been dumped or stored in these areas and not necessarily roasted there. Rounded features interpreted as ore roasting areas have been found at early Wealden sites (Cleere and Crossley 1985, 35) and large elongated roasting pits, 2.5 m long by 0.8 m wide, were found at Bardown in the Weald.

In the south-east working area of structure I was pit 316, which had a diameter of 0.46 m and depth of 0.4 m and contained a large, upright, 0.4 m diameter storage jar. This is one of several large pots of ‘Belgic’

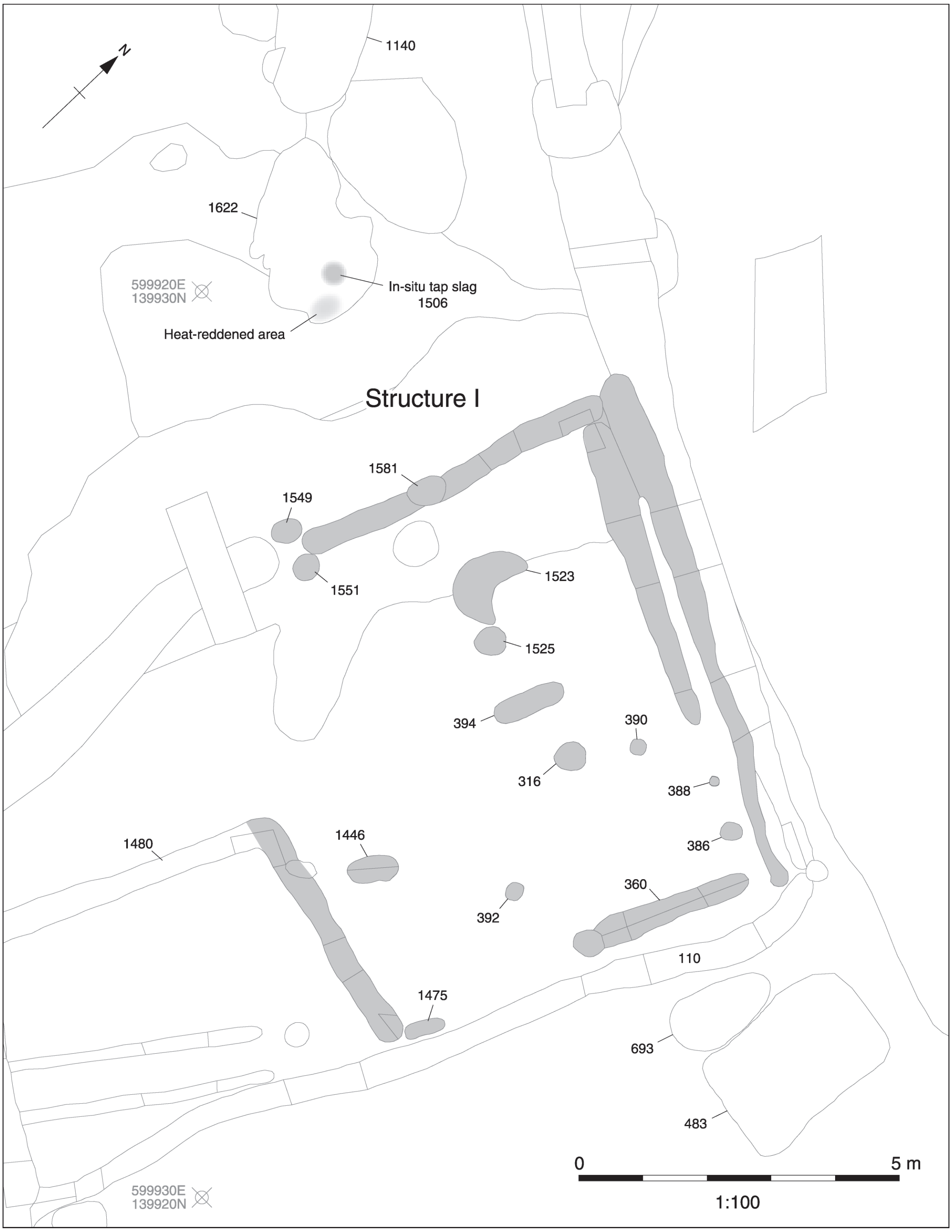

Figure 7.7 Plan of Structure I.

tradition decorated with combing found across the site. The pit contained some consolidated hammerscale, indicating that smithing probably took place in structure I. Although only a small amount of hammerscale was found within the structure, and always in cut features, this was not unexpected given the poor survival of occupation spreads in this area. A shallow oval feature (1446) 0.88 m long and 0.08 m deep in this working area was described as another ore roasting pit. However, no iron-rich stone was found amongst waste from this feature, although there were many rusty agglomerates containing small flecks of charcoal and a small amount of hammerscale, typical of smithing debris. There were also small dribbles of slag.

Features outside the enclosure to the east included two large pits, 483 and 1226, and two smaller pits, 693 and 1461, which were full of ironworking debris. To the west of the structure, there was a feature (1622) within the base of which was an unexcavated, thin deposit of silt (1516). An area approximately 0.5 m by 0.7 m at the south-east end of the silt was fire-reddened with a large piece of tap slag adjacent to it. The tap slag (1506) weighed 4.5 kg and had a flow direction away from the fired clay patch. A photograph of this area gives the impression that this slag was *in situ*. However, this feature is at a distance from structure I, where the two probable furnaces were located, while the direction of flow of the tap slag was up the slope from the fired clay. These factors suggest that this slag may have been dumped rather than created *in situ*. Furthermore, the burnt area differs in size and shape from the furnaces and it seems unlikely that the burnt patch constituted the remains of a furnace. However, this cannot be conclusively established with the evidence available.

Structure R *(Figs 7.8-7.9)*

Structure R lies at the north-east edge of the excavated Area B and continued into the unexcavated Area A. Fortunately the majority of the structure appears to have been included in the excavated area. However, the geophysical survey detected strong readings in Area A at the north-east side of structure R, which probably correspond to pits and gullies full of ironworking debris. As exposed structure R had at least six posts, and again appears to have been partitioned into north-east and south-west sections where different ironworking activities took place. The boundary between the two areas lay on the line between postholes 1465 and 1484.

At the south-west end of structure R there were a series of rounded features, in intercutting groups, arranged in a row, the majority of which were the basal remains of bloomery furnaces (Fig. 7.8). The first group consisted of feature 1455 (sides slope at 70°, 0.6 m by 0.5 m by 0.15 m deep), which was cut by 1451 (sides slope at 45°, 0.55 m by 0.55 m by 0.1 m deep), which in turn was cut by 1449 (sides slope at 60°, 0.8 m by 0.6 m by 0.11 m deep) (see Fig. 3.45, section 310). In feature 1455, reduced-fired, grey clay was found with 80 mm of oxidised-fired, reddened clay beneath and feature 1451 also had a layer of red, oxidised-fired clay at the base. Feature 1449 had a charcoal-rich fill but there were no signs that the clay had been fired.

The second group consisted of feature 1443 (sides slope at 80°, 0.7 m by 0.5 m by 0.24 m deep), which was cut by 1438 (sides slope at 70°, 0.9 m by 0.8 m by 0.25 m deep) (see Fig. 3.45, section 309). In feature 1443, 60 mm of red, oxidised-fired clay was found, followed by a layer of fill and another 50 mm thick layer of oxidised-fired clay. Feature 1438 had not been fired and contained a very charcoal-rich fill.

The third group consisted of feature 1425 (sides slope at 70°, 0.6 m by 0.4 m by 0.15 m deep), which was cut by 1428 (sides slope at 60°, 0.65 m by 0.65 m by 0.18 m deep) which in turn was overlain by feature 1423 (sides slope at 60°, 0.5 m by 0.5 m by 0.1 m deep) (see Fig. 3.45, section 306). Feature 1425 had a fire-reddened base, 1428 had a greyish-red base and 1423 had a grey, reduced-fired base with a layer of red, oxidised-fired clay beneath. Feature 1383 was fourth in the row (sides slope at 60°, 0.6 m by 0.4 m by 0.05 m deep) and had oxidised-fired, reddened edges (see Fig. 3.45, section 298).

Cuts 1455, 1451, 1443, 1428, 1425, 1423 and 1383 are likely to be the remains of repeatedly reconstructed bloomery furnaces. The layer of oxidised-fired, reddened clay with a layer of reduced-fired, grey clay above, in features 1455, 1428 and 1423 is very characteristic of furnaces, where high temperatures are combined with reducing conditions inside, and oxidising conditions increase with distance from the interior. In features 1383, 1425, 1443 and 1451 only the oxidised-fired, reddened clay layer was identified; presumably the reduced-fired, grey zone has not survived. The furnace remains are all rounded with diameters of approximately 0.6 m. An internal diameter of 0.2-0.3 m was estimated for these structures at the time of excavation (Starley 1998), so a wall thickness of 0.15 to 0.2 m is again indicated. The furnaces are aligned across the slope of the land at the south-west end of the building and slag from the furnaces may have flowed downhill in a south-westerly direction. Features 1449 and 1438 are shallow, fairly large pits with charcoal-rich fills, but there is no evidence that the pits were exposed to high temperatures. Although in close proximity to the furnaces, and therefore likely to be related to smelting activity, these pits cut the first and second furnace groups, and so must post-date them. There were no similar pits cutting the third and fourth furnace groups. This may indicate that the furnaces were constructed and used one at a time or in pairs rather than all at once, and that the third and fourth furnace groups were in operation after the first and second groups. There is little indication as to the purpose of the shallow pits, although if they are assumed to cut older furnaces, their function may be associated with the construction or operation of the newer ones.

A large oval pit, 1233, 1 m in diameter, situated at the north-east edge of the enclosure alongside the row of furnaces, contained a high concentration of charcoal and several kilos of waste including 0.75 kg of iron-rich stone (plus unworked stone). Pit 1233 occupied a similar position to feature 1581 in structure I at the edge of the enclosure next to the furnaces and, given the similarities between the layouts of workshops R and I, may have had a similar function, perhaps for ore preparation.

The north-east working area within the structure contained an occupation layer, 1585, with an extremely high concentration of hammerscale, so thickly deposited that in areas it had become consolidated into large lumps of smithing pan (Fig. 7.9). The south-west edge of the hammerscale deposit 1585 was more or less straight and coincided with postholes 1465 and 1484. Within the north-east area

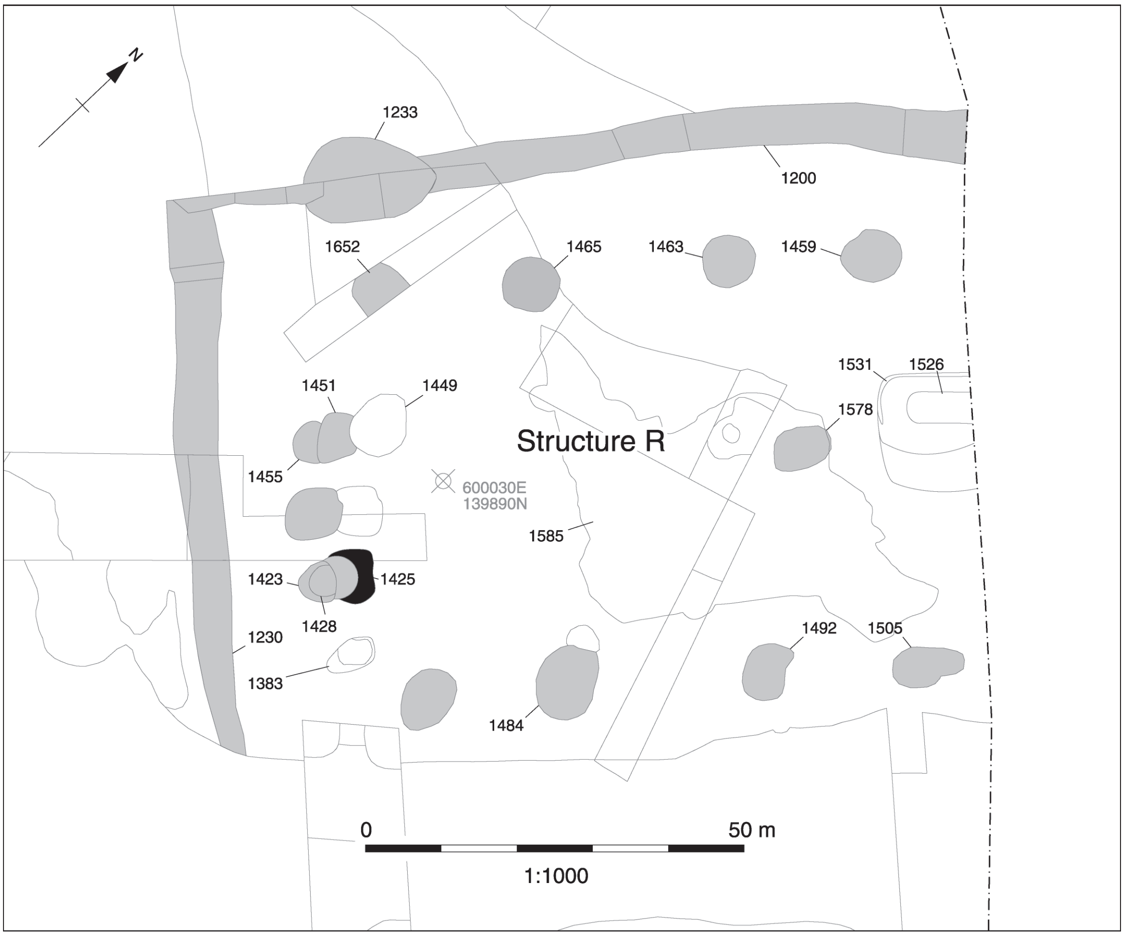

Figure 7.8 Plan of Structure R.

were a small pit 1636 containing a large upright jar and a sub-rectangular feature 1578 with a flat base and almost vertical sides, measuring 0.5 m by 0.7 m by 0.18 m deep. Although the latter feature had fire-reddened edges and a charcoal-rich fill, the base was not reddened. The occupation spread within this working area was sampled at 0.5 m intervals across a grid, although feature 1578 was excavated prior to the sampling. Only the area of the floor visibly rich in hammerscale was sampled, rather than the entire occupation surface of the structure plus a small area outside, that is generally recommended. However, the results (Fig. 7.9) show that the limits of the deposit were estimated accurately and so it is likely that little data has been lost. The samples were sieved to remove particles greater than 3 mm in size, and then processed using a magnet to separate the magnetic hammerscale and heavily fired clay fragments from the remaining residue (Mills and McDonnell 1992). The magnetic fraction present was expressed as a weight percent of the total. A plot of hammerscale concentration across the sampling grid shows the change in concentration from low levels (light) to high concentrations (dark) (Fig. 7.9).

Very high concentrations of hammerscale were detected (up to 90% by weight) indicating that smithing took place in this section of the structure. The highest concentrations were in the north-west half of the workshop near to the large pot and feature 1578, which strongly suggests that an anvil was situated in this area and that a hearth was also nearby. The sharp decrease in concentration of hammerscale to the right of the spread coincides with feature 1578 (labelled H in Figure 7.9) which was excavated prior to sampling. The trough in the hammerscale deposit, extending towards the east and west, is likely to be a result of individuals treading the deposit across the floor as they left the area towards the eastern corner. The proximity of the large pot and feature 1578 suggest that both were involved in the smithing process. The large pot may have held water for use by the smith, for example for cooling tools. Feature 1578 may be the remains of a ground-level smithing hearth. The internal dimensions of the feature (0.5 m by 0.7 m) are comparable to smithing hearths of the period identified elsewhere (Pleiner 2000, 218-227; Tylecote 1990; Salter 1997). The feature would also have been big enough to take the large billets potentially produced at Westhawk (the billet recovered on the site was 0.32 m long), and to have produced the large smithing hearth bottom slags found near structure R, the biggest of which was 0.19 m in diameter.

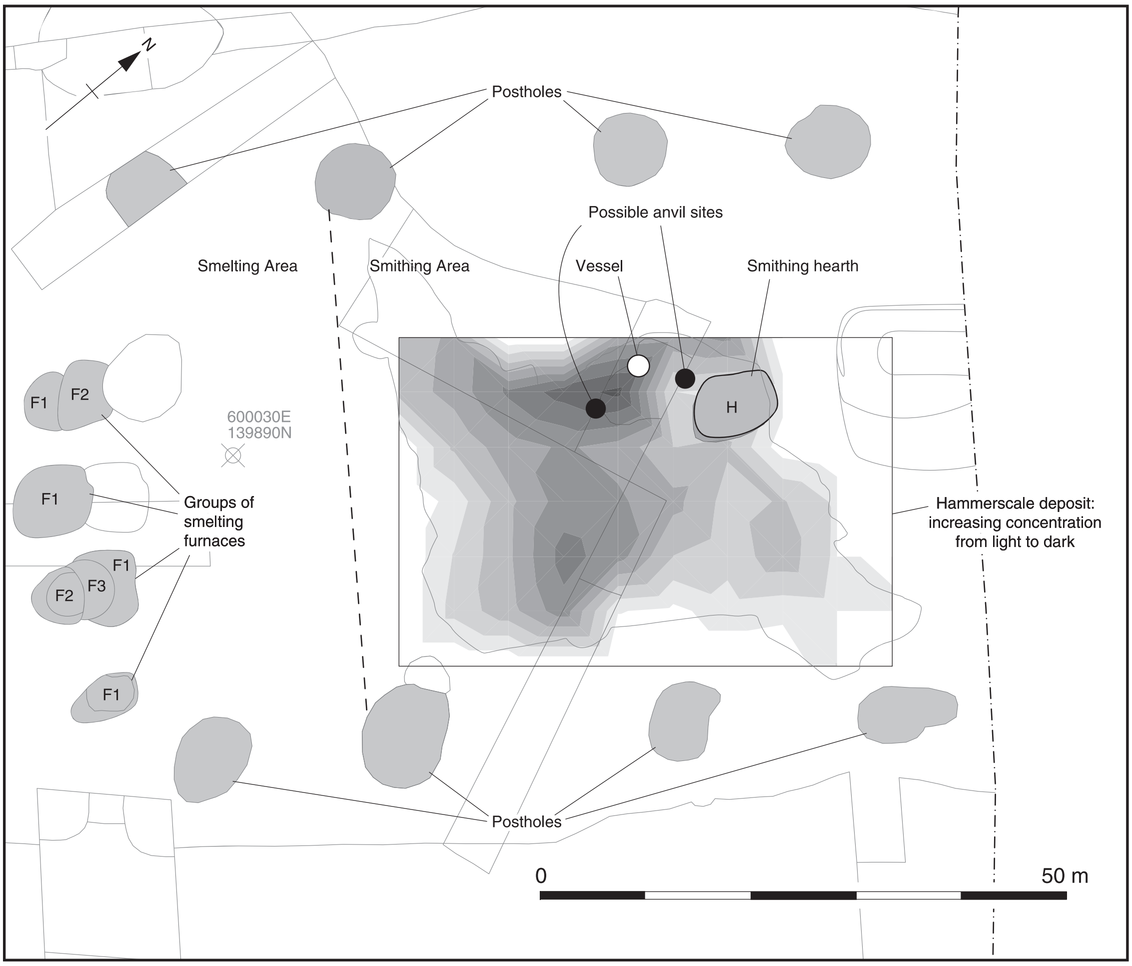

Figure 7.9 Plot of hammerscale distribution in Structure R, in relation to other features, including the furnaces and potential hearth. (Darkest tone shows highest concentration).

The anvil, possibly set on a tree stump, appears to have left no diagnostic mark.

A further series of fired features were identified at the north-east edge of the excavated area within the structure (see Fig. 3.45 section 331). Feature 1526 was subrectangular, with near vertical sides and a flat base, and measured 0.7 m by 0.33 m and 0.48 m deep. It had a slightly fired, reddened base and cut feature 1531, which had a flat base, a diameter of 1.1 m and was 0.2 m deep, with sides sloping at 60°. The base of this feature was slightly fire-reddened. Feature 1531 cut feature 1530, which was oval-shaped, vertical-sided and flat-based and measured 0.6 m by 0.4 m and 0.2 m deep. The base and sides of this feature were heavily fired and reddened. These features were filled with clay and some charcoal, but little slag. Interpretation of these features is difficult as they lay at the edge of the excavated area. They had been used for high temperature processes, but little indication remains as to what these processes may have been. These might be the remains of additional primary smithing hearths and elongated features similar to these have been interpreted as such elsewhere (Pleiner 2000, 223). However, the features are 2 m distant from the area with the highest concentrations of hammerscale and therefore the anvil. Hearths are generally situated near to the anvil for convenience and also to ensure that the object looses the minimum of heat between hearth and anvil (Schmidt 1997, 198-208). Elongated ore roasting hearths have been identified at Roman sites, as mentioned previously, but no ore was found in these features.

Parallels between Structures I and R

Structures R and I are both thought to have been in use for similar periods of up to 50 years and therefore the intensity of ironworking activity for each structure might be anticipated to be roughly equivalent. Structure R contained four probable furnace bases, some with evidence of repeated reconstruction. It is likely that there were furnaces other than the two identified in structure I but that the features have not survived. Like the structure R furnaces these would have been used and repeatedly relined. Approximately 44% of the total ironworking waste by weight from the site was from contexts near structure I.

There are similarities in the layouts of structures I and R, in that both were partitioned with the probable remains of furnaces in one area and a large sunken pot in the other. Although no occupation spread survived in structure I, some smithing pan (consolidated hammerscale) was found in the cut for the pot. Therefore it appears that in both enclosures smelting took place in one area and smithing of the products in the other. This workshop layout can be compared with that of other Roman smelting workshops. The workshop discovered at Woolaston, Gloucestershire (Fulford and Allen 1992, 173, fig. 10) was a post-built structure, with two parallel rows of padstones. It measured 16.5 by 8.2 m and therefore much larger than the post-built structure R at Westhawk Farm. Four groups of heavily-fired, rounded features were identified as furnaces, two groups at each end of the building (F24, F324, F311 and F312: ibid., figs 11 and 12). In the south-east half of this structure, there were three stone settings (F30, F316 and F317: ibid., figs 16 and 15) with evidence of *in situ* breaking of the stones interpreted as ore crushing units. Features F30 and F317 were lined with quartz-rich stone, such as sandstone, which would have been resistant to high temperatures. A fourth feature, a shallow pit (F325: ibid., fig. 14) may originally have been a similar stone setting. The entire lower part of an upright pot (F26) was found near to feature F30, and feature F317 yielded joining sherds of a pot. At Westhawk Farm large ceramic vessels have been found in the workshop areas used for smithing. If features F317 and F30 at Woolaston were the remains of stone-lined hearths used for primary smithing this would be consistent with the presence of the large pots, the surrounding concentrations of charcoal, the proximity to the furnaces and the fracturing of the stones themselves. However, this interpretation of the Woolaston features is tentative since no hammerscale was found in the vicinity of these settings, although it was sought.

Another Roman ironworking structure was excavated at Lenham, Kent, very near to Westhawk Farm (Philp 1994). Postholes were identified forming three sides of a building, within which were three fire-reddened features identified as hearths, a number of features full of ironworking slag and the lower half of a large pot (0.45 m diameter), sunken into the floor. By analogy with Westhawk, it is likely that smithing and possibly smelting took place in this workshop. The finds from the area were dated from AD 50-200 with the majority being of 2nd-century date. The well-preserved bases of two repeatedly reconstructed smelting furnaces, containing *in situ* furnace bottom slag of identical dimensions to those from Westhawk, were also found, some 20 m from the posted structure in an area otherwise reduced by ploughing. Over 30,000 pieces of slag were recorded from the site, but these were not investigated further.

MATERIALS AND THEIR ANALYSIS

The ironworking waste from Westhawk Farm included fragments of furnace lining, quantities of iron-rich stone and charcoal, large amounts of tap slag and smithing slag and some furnace bottom slag. Examples of the end products, in the form of fragments of unrefined iron blooms and a complete refined iron billet, were also recovered. This assemblage provides an opportunity to investigate the compositional relationships between the raw materials, waste products and products of iron smelting and smithing. Detailed examination of the ironworking waste has also provided information on how the different types of by-product may have formed.

Samples were analysed using X-ray fluorescence spectrometry (XRF), energy dispersive spectrometry (EDS) or X-ray diffraction (XRD). Both XRF and EDS determine the elemental composition of a sample while XRD identifies the compounds present. The XRF spectrometer analyses an area of just under 0.5 mm in diameter. Using EDS, areas as large as several millimetres (mm) in width or as small as tens of microns (μm) could be selected for analysis. For bulk analyses, larger areas were analysed to obtain a more generalised result.

Raw Materials

Clay

The furnaces and parts of the smithing hearths were constructed from very quartz-rich clay, which is ideally suited to these high temperature applications because of the refractory properties of quartz. The clay was either selected because of its high quartz content or was quartz-tempered before use and is likely to derive from sand formations in the Lower Greensand or from sandy deposits on the crest of the North Downs, near to the site. The ore smelted at Westhawk Farm probably also derives from the latter deposits (see below). Heavily quartz-tempered clay was also used for lining or constructing furnaces at other Roman smelting sites (Fulford and Allen 1992; Crew 1998). The quartz grains in the furnace clay are angular and are generally less than 150 μm in diameter, although some grains up to 0.5 mm in size were observed. The fabric has a friable, sandy texture. As a result of its iron oxide content the clay has a grey colour when reduced-fired and a red colour when oxidised-fired. All of the vitrified or slag-coated clay, regardless of thickness, colour, phase or origin (structures R, I or P) had a similar appearance and composition. Samples of slag-coated clay from contexts near structures I and R were analysed and the results are compared in Table 7.3.

The heavily vitrified, black surfaces of the fired clay pieces probably originally formed part of the internal walls of furnaces and were subjected to very high temperatures. The fragments were dumped when the furnaces were destroyed, relined as part of a repair, or rebuilt altogether. Many of the pieces are likely to derive from areas near a blowing-hole, where the temperature would have reached its maximum. At high magnifications the black vitreous surface of the lining can be seen to consist of quartz

Table 7.3 Metalworking remains: Composition of quartz-rich, slag-coated clay used for furnace construction, analysed by EDS, average of 3 analyses, normalised (see Table 7.15).

Context	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
1332	0.05	0.43	9.08	83.81	0.79	0.10	1.35	0.50	0.81	0.03	3.06
1225	0.00	0.54	10.07	83.48	0.20	0.22	1.13	0.32	0.94	0.05	3.06

grains and some crystallising silica polymorphs (all mid-grey) surrounded by an iron-rich glassy matrix (lighter grey) with some bubbles (black). In many areas, dispersions of sub-micron, spherical droplets (white) in an iron-rich, glassy matrix were observed (Fig. 7.10). Those large enough to be analysed were found to be iron, often containing several weight percent of phosphorus.

Samples of slag-coated clay lining from contexts near to structures R and I were analysed (Table 7.4). The vitrified surface was formed by the reaction of the clay with ashes from the charcoal fuel and the slag in the furnace and was enriched in iron, calcium, potassium and phosphorus oxides and depleted in titanium, aluminium and silicon oxides relative to the original clay composition. The slag provided the majority of the iron and manganese oxides and some of the phosphorus oxide while the clay provided the majority of the silica, alumina, titania and some of the potash. Larger amounts of potash, lime, magnesia and phosphortus oxide relative to iron oxide were detected in the clay lining compared to the tap slag. This suggests that the contribution of the fuel ashes to the formation of the vitrified lining was significant relative to the small contribution that the ashes made to the formation of by-products such as tap slag.

Furnace and hearth construction

Some pieces of furnace lining had delaminated into parallel-sided slabs. This may be an indication of successive relining of the furnaces, resulting in weak bonding between linings where previous vitrified surfaces were overlain. Alternatively the lamination could have been as a result of the reactions occurring during furnace use. A concentration gradient of different elements was observed through the thickness of the lining fragments, caused by the reaction zone at the lining surface extending inwards during the temperature cycling of the furnace with each smelt. This resulted in the formation of successive layers within the lining, each with different compositions and microstructures, some of which may have been weaker than others.

Some Roman bloomery furnaces were constructed from clay blocks (Crew 1998) with layers of increas-

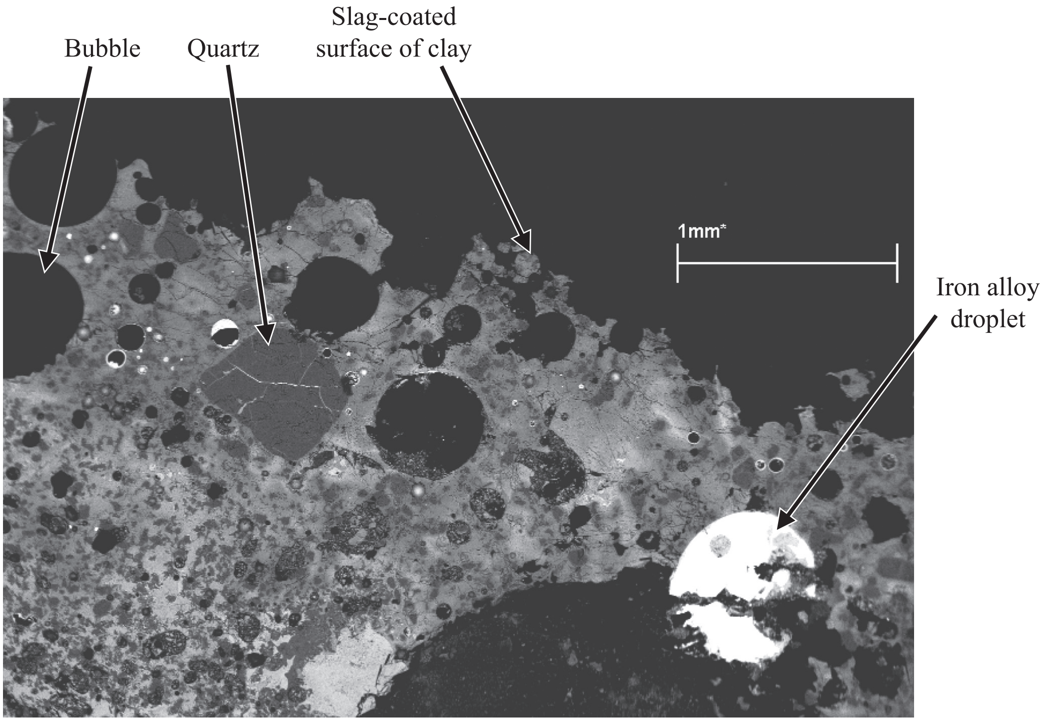

Figure 7.10 SEM back-scattered electron image of the cross section of a piece of furnace lining from context 480.

Table 7.4 Metalworking remains: Composition of different regions of the vitrified surface of slag-coated clay from context 480, analysed by EDS, normalised.

Area	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
Surface (bulk)	0.20	0.54	5.60	74.54	0.90	0.04	4.79	1.93	0.48	0.17	10.81
5.5mm from surface (bulk)	0.38	0.30	6.31	79.16	0.44	0.00	1.24	0.40	1.07	0.08	10.62
Glassy matrix, near surface	0.64	0.58	7.53	66.39	1.29	0.00	7.47	3.01	0.85	0.26	11.98
Dispersion near surface	0.37	0.66	7.28	69.22	1.24	0.11	6.17	3.72	0.72	0.29	10.21
Dispersion second area	0.57	0.85	8.05	57.87	1.97	0.11	3.23	2.49	1.02	0.18	23.65
Matrix of dispersion area	0.66	0.75	8.38	61.52	1.21	0.23	3.37	2.38	0.97	0.17	20.35

ingly siliceous clay used to line the furnace internally. By contrast, the majority of the furnace lining fragments from Westhawk Farm, including very large ones, had no shaped edges and it is therefore probable that the clay was moulded directly to form the basic furnace structures. However, many shaped fragments of slag-coated clay with one or two original edges were also found among the assemblage. All of these had formed part of the inner furnace or hearth wall because they had vitrified and blackened surfaces. Interpretation of these shaped, slag-coated clay fragments is complicated by the fact that debris from both smelting and smithing structures is likely to be included in the waste from the site. Although debris from smithing hearths is generally found to be less blackened and vitrified by slag than debris from smelting furnaces (McDonnell 1986), the hearths at Westhawk Farm would have been used for refining slag-rich iron blooms and so it cannot be assumed that this distinction would apply. For this reason hearth and furnace debris could not be confidently differentiated. Examples of the shaped fragments were found in contexts near workshops R and I and also near to structure P (particularly in context 8449), indicating that, whatever their function, it was common to all of the workshops. The form of the surviving edges indicated that the fragments derived from several groups of differently shaped clay pieces, which may have been used for different applications, and these are described below.

The first group of fragments had two perpendicular (but rounded and uneven) edges, with a varyingly rounded corner. One piece had finger impressions along the edge where it had been pushed into position while plastic. The pieces were generally more than 50 mm thick although none survived to full thickness or sufficiently intact to conclusively establish their function. Possibilities include that they are fragments from near the blowing-hole of a furnace or hearth as the area near the blowing hole was the hottest zone and therefore required frequent repairs. Sometimes replaceable blowing-hole plates were used, consisting of a block of clay with one or more holes through which the bellows blast entered the furnace or hearth. The use of a replaceable plate enabled damaged blowing-holes to be replaced in their entirety by inserting a fresh plate with little disruption to the rest of the furnace or hearth. However, no surviving blowing-hole fragments were found among the assemblage and so this possibility could not be investigated further.

The second group of clay fragments also had one, or more rarely two, original edges. These differed from the previously described blocks because some of the edges were sharp and extremely straight with a glassy green surface. From the flow of the vitrified surfaces on these fragments, it appeared that the very straight edges had frequently formed the base, but occasionally the side, of the piece when in use. Some of the fragments with two original sides were wedge-shaped with a straight, glassy edge forming the base although the second edge was generally less defined and blackened with slag (Plate 7.1). These fragments may have been set against a temperature-resistant flat surface, such as a slab of stone or a tile to produce the straight bases observed. Alternatively the flat edges may have been necessary in order to ensure that a number of blocks could be fitted together. The fragments examined were flat, rather than curved, and one small-angled wedge survived to its full thickness of about 50 mm. These observations suggest that the flat-edged clay fragments, including the wedge-shaped pieces, may have been used to form smithing hearth structures since the hearth was probably not rounded (the possible hearth feature in structure R is sub-rectangular) and the wall thickness could have been less than that of the furnaces. However, there are other alternatives, including that a number of the shaped clay fragments may have formed a furnace-tapping aperture. Fragments of shaped clay blocks with one glazed surface and occasional finger marks have also been found on other Wealden smelting sites (Cleere and Crossley 1985, 50), and were tentatively interpreted as having been used to block the tapping aperture when this was not in use.

Charcoal

Oak was the main species of charcoal from ironworking contexts (see Challinor. Chapter 9 below), but no evidence was found of coppicing. Oak constituted a large proportion of the hardwoods of the Wealden forest and also provided good quality charcoal (Tylecote 1990, 225; Cleere and Crossley 1985, 37). At the Roman ironworking site at Woolaston (Fulford and Allen 1992, 190-91) the identified charcoal consisted mostly of oak and hazel. There, small branches between 7 and 18 years old had been cut, probably in

Plate 7.1 Wedge-shaped fragment of slag-coated clay, with a flat edge at the bottom of the picture, a reasonably flat edge at the top of the picture and the point of the wedge in the foreground.

the autumn and/or winter, and left to dry for some time before being burnt. Similarly, studies of charcoal production practices found that charcoal producers using traditional forest kilns (Kelley 1986) generally burnt wood between April and November. However, although ironworking was dependent on the availability of charcoal, the seasonality of charcoal production does not necessarily mean that ironworking was also a seasonal activity, as charcoal could have been stockpiled until it was required. Compositional data for the ashes of oak are given in Table 7.5. However, these data can only be used as a guide since the compositions of plant ashes vary with many factors including the geology of the region where the plant grew, the season and the part of the plant ashed. Ashes from charcoal are likely to have made a varying contribution - predominantly of lime, potash and some phosphorus oxide - to the composition of the different types of ironworking waste discussed in this report.

Ore

Iron-rich stone, potentially intended for use as ore, was recovered from contexts in and around the ironworking structures at Westhawk. Some of the material had been heated in an oxidising atmosphere, suggesting that the ore was roasted prior to smelting. Samples were analysed using XRD, EDS and XRF spectrometry to determine the compounds present and the compositions of the stone. The samples ranged from more silica-rich ferruginous sandstone to iron-rich ironstone, although it appears that these two extremes are end-members of a continuous series and that all of the stone may have derived from the same source. The unroasted examples were orange/brown/grey in colour, either nodular or tabular in form, and the minerals present were hydrous iron oxides (goethite and lepidocrocite) and quartz. The quartz grains were present in widely varying amounts and were angular and generally small (less than 200 µm in diameter), although some coarser-grained examples were also observed. Roasted examples were red to metallic grey in colour and consisted of haematite and varying amounts of quartz in the coarser sandstone examples and haematite plus magnetite in the iron-rich, fine-grained examples. Some of the concretionary nodules were found in association with flint nodules or small flint chips (Plate 7.2). Flint nodules had been used along with ironworking slag for metalling the road through Westhawk (see above).

The compositions of some potential ore samples from Westhawk are given in Table 7.6. The analyses have been presented in two groups: ferruginous

Table 7.5 Metalworking remains: Composition of ashed oak, from Wolff (1871).

Sample	Na_2O	MgO	Cl	SiO_2	P_2O_3	SO_3	K_2O	CaO	FeO
Oak bark	0.0	1.4	0.1	2.0	0.0	0.7	8.0	87.8	0.0
Oak bark	2.3	6.9	0.5	0.5	4.8	0.6	8.3	75.6	0.4
Oak wood	5.7	4.5	0.0	0.8	3.5	1.2	8.4	75.4	0.5

sandstone, which contained a considerable proportion of quartz grains ($Si0_2$); and ironstone, which contained little or no quartz. The varying quartz content between samples is illustrated by the change in silica content of the analyses; some ironstone contained virtually no silica or alumina. The heterogeneity of the stone, in particular the coarse sandstone, made it necessary to conduct relatively large numbers of analyses in order to obtain representative compositions. In addition to the tabulated analyses, four other samples from each category were screened to ensure that the analyses were representative. EDS analyses of fragments of ironstone from contexts 1548 and 1356 detected on average 91% iron oxide (FeO) by weight, 0.6% phosphorus oxide (P_2O_5), 4.5% silica (SiO_2) and 0.6% manganese oxide (MnO).

There are a number of possible sources of ore at varying distances from Westhawk Farm. The site is situated on an outcrop of the Weald clay and the main form of ore utilised in the Weald was clay ironstone, which generally occurs as nodules between 0.05 and 0.25 m in diameter, but also in layers in the Wealden beds. The predominant constituent of the ironstone nodules is siderite (iron carbonate). At Shadoxhurst, 3 km south-west of the site, thin nodular ironstone beds have been noted. Siderite seams, up to 0.13 m thick, have also been mapped on British Geological Survey Sheet 304 (Tenterden) near High Halden, Woodchurch and Bethersden, all about 8 km from Westhawk Farm (Worssam 1985). However, although siderite could have been obtained locally, no siderite was identified in the site assemblage.

A second potential source of ore is a concretionary form of iron-rich stone, which is also found in the Weald, formed by weathering of iron-rich minerals such as siderite. The siderite is oxidised in successive layers, broken off and dispersed in the soils or incorporated in river gravels. In the Weald the greater permeability to water of river terrace gravels than of clays can also lead to the formation of large, thick masses of concretionary iron pan (Worssam 1985, 13-14). Hydrous iron oxides, goethite or lepidocrocite, are the most common alteration products of siderite (Deer *et al.* 1992). However, no conclusive evidence for the utilisation of this type of ore was found at Westhawk.

Two other possible sources of ore, which could both be described as ferruginous sandstone, have been mentioned in past studies of the Wealden iron industry (Worssam 1985, 9-10, 14-15). These are the Lower Greensand ironstone and the ironstone of the Lenham Beds and the ‘Sand in Clay-with-flints’.

The sandy ironstone that occurs in the Folkestone Beds within the Lower Greensand is known as carstone and contains a significant quantity of silica in the form of quartz grains. The Lower Greensand was deposited when the area became a shallow sea; some beds contain phosphatic nodules (Gallois 1965), which may have been formed by replacement of the original matter by calcium phosphate during a long exposure on the sea floor (Chatwin 1961). Although the carstone may have been smelted elsewhere in the region, this stone is unlikely to have been exploited at Westhawk since little carstone is found in the vicinity of the site (B Worssam, pers. comm.).

The ironstone of the Lenham Beds and the ‘Sand in Clay-with-flints’ is found along the North Downs between Detling and Folkestone. These sands are the remains of a Pliocene deposit that was laid down on the floor of a sea. Little is known about the sands or whether ironstone derived from them may have a significant phosphorus content. However the discovery

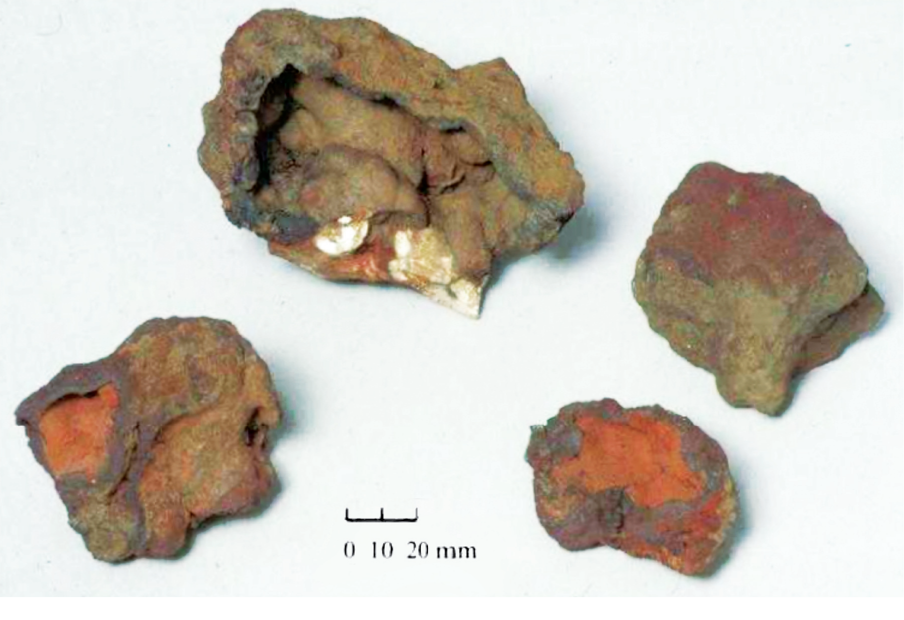

Plate 7.2 Roasted ferruginous sandstone nodules and pieces, one (top centre) with associated flint (the white areas).

Table 7.6 Metalworking remains: Composition of ironstone samples measured by XRF, the number of analyses is given in brackets (see Table 7.16).

Type:	*Ferruginous Sandstone*	*Ironstone*	
Context:	**1332** (average 9)	**1548** (average 4)	**1356** (average 2)
Description:	Orange nodule, fine	Red nodule, fine	Red nodule, fine
FeO	57.5	89.3	95.7
Al_2O_3	6.6	3.0	0.9
SiO_2	33.6	5.9	1.9
P_2O_5	0.9	0.7	0.5
K_2O	0.2	0.1	0.0
CaO	0.2	0.2	0.2
MnO	0.5	0.6	0.5
SO_3	0.3	0.2	0.4
TiO_2	0.4	0.1	0.0

of bloomery slag on the summit of the Downs above Hollingbourne suggests that Lenham Beds sandstone may nonetheless have been smelted in bloomery furnaces (Worssam 1985, 15). A Roman smelting site has also been identified at Lower Runhams Farm, Lenham (Philp 1994) and a bloomery smelting site has been identified at Chapel Farm, Lenham Heath (Worssam 1985, 14). Dr Worssam has kindly identified the iron-rich stone from Westhawk as being derived from the Lenham Beds of British Geological Survey Sheet 288 (Maidstone) or from the 'Sand in the Clay-with-flints' of Sheets 289 (Canterbury) and 305/6 (Folkestone and Dover). The presence of flint in some of the samples proves that they are post-Cretaceous and is consistent with the stone being from these Pliocene deposits.

In summary, although all of the ore used at Westhawk probably derived from two deposits - the Lenham Beds or the 'Sand in Clay-with-flints' - it ranged from ferruginous sandstone, containing about 50% silica by weight, to ironstone, containing about 85% iron oxide. The lower and higher iron content stone were probably intentionally combined in each ore batch to ensure that the batch had an intermediate iron content overall and would produce a reasonable yield of iron metal. The sandstone would also contribute a large proportion of the silica required to produce fluid iron silicate slag during smelting. Although the slag is a waste product, its formation influences the progression of other reactions in the furnace and fluid slag separates more easily from the iron bloom (Pleiner 2000). The ore was roasted prior to smelting.

Smelting slags

Tap slag

Samples of tap slag from three contexts, 1332, 319 and 480, were analysed. The tap slag from contexts 1332 (near structure R) and 319 (near structure I) consisted predominantly of fayalite laths in a glassy matrix. Some wustite (FeO) was also present but these dendrites were scarce and very fine. The iron content of the slag from context 480 was found to be higher and this slag consequently contained more wustite. The microstructure of each flow of slag was coarser towards the base, as a result of slower cooling, and successive flows of slag could therefore be distinguished. Although the tap slag was relatively homogeneous (Table 7.7) some compositional variation was observed; for example, the base of one slag cake (319, see Table 7.17) was richer in alumina, silica and potash but depleted in iron oxide.

The smelting slag from Westhawk was found to have a high phosphorus content, suggesting that the ore smelted at Westhawk was phosphorus-rich. Variable but significant levels of phosphorus oxide were detected in samples of potential ore (Table 7.16), the highest being 3.4% by weight in ferruginous sandstone. Examination of data on the composition of bloomery smelting slag from other sites in England has revealed five with phosphorus-rich bloomery slag, three of which are in Norfolk and two in North Yorkshire (Tylecote 1962a; Chirikure and Paynter forthcoming; McDonnell 1986). Additional sites are likely to be found in the future as more material is analysed, particularly from these areas. Two Roman

Table 7.7 Metalworking remains: Composition of tap slag, measured by EDS, average of 6 analyses for each sample, normalised (see Table 7.17).

Context	Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
1332	Tap (R)	0.6	0.4	6.6	26.5	1.9	0.1	0.7	2.6	0.3	0.6	59.5
319	Tap (I)	0.1	0.5	6.8	24.7	1.6	0.1	0.9	2.1	0.3	0.5	62.6
480	Tap (I)	0.1	0.4	6.3	21.8	2.0	0.2	0.4	1.9	0.2	0.3	66.5

Table 7.8 Metalworking remains: Composition of phosphorus-rich tap slag from Ashwicken and West Runton, Norfolk and Baysdale and Ouse Gill, Yorkshire, compared with the composition of low-phosphorus Roman tap slag from selected other sites.

Site	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO	Ref
Ashwicken	nm	1.4	3.3	21.8	1.8	nm	0.0	0.4	nm	0.5	70.8	A
West Runton	nm	0.5	9.6	26.3	1.8	0.1	0.0	1.5	nm	3.1	57.3	B
Baysdale	0.3	4.1	9.7	27.4	2.5	0.5	2.2	10.4	0.6	1.3	41.1	C
Ouse Gill	0.4	4.2	9.6	30.9	1.8	0.5	2.4	11.3	0.6	1.2	36.2	
Snettisham	0.1	0.2	1.98	24.1	1.4	0.2	0.3	1.3	0.1	0.5	69.8	D
Camerton	nm	0.3	6.9	13.0	0.6	0.4	nm	2.3	0.4	nm	76.2	E
Wilderspool	nm	0.0	2.1	29.6	0.3	nm	nm	1.7	nm	nm	66.2	
Sharpley Pool	nm	1.1	6.0	32.8	0.0	0.0	nm	1.9	nm	trace	58.2	F
Worcester	nm	1.3	6.0	16.5	0.0	0.0	nm	3.1	nm	0.2	72.8	
Woolaston	nm	1.8	4.6	23.5	0.2	nm	1.8	2.2	0.3	0.2	65.5	G

nm = not measured.

References: A: Tylecote 1962a, B: Tylecote 1962b, C: McDonnell 1986, D: Chirikure and Paynter forthcoming, E: Tylecote 1990, F: Morton and Wingrove 1969, and G: Fulford and Allen 1992.

sites, Snettisham and Ashwicken, are situated on the Lower Greensand in Norfolk. Ferruginous sandstone nodules derived from the Lower Greensand carstone were probably smelted at these sites (Chatwin 1961; Tylecote 1962a; Chirikure and Paynter forthcoming). The third Norfolk smelting site, West Runton, is on the coast near Cromer. Tylecote (1962b) describes a sandy, ferruginous conglomerate in that area, sometimes containing flint or shells as well as nodules of hydrated iron oxides. This stone may be derived from Pliocene and Pleistocene Crag deposits, which extend over the eastern part of Norfolk. Therefore types of ore similar to that from Westhawk (nodules of hydrous iron oxides with varying quartz grain contents derived from sandy deposits) were probably smelted at the Norfolk sites. However, ironworkers at the North Yorkshire sites are likely to have utilised ore composed of the mineral siderite, for example Jurassic ironstone or ironstone from the Coal Measures. The slag from these sites can be further distinguished by the increased concentrations of lime and magnesia resulting from the substitution of Fe^{2+} by Ca and Mg in the ore. Phosphorus-rich smelting slag could also be produced when bog iron ore was smelted, as demonstrated by research at the Iron Age settlement of Snorup in Denmark (Høst-Madsen and Buchwald 1999). The compositions of phosphorus-rich tap slag from these sites are given in Table 7.8, where they are compared to the lower phosphorus compositions of tap slag from some other Roman sites.

Furnace bottom slag

Samples from bowl-shaped furnace bottom slags from contexts 1510 and 1225 near structure I were examined (Plate 7.3). The microstructure consisted of fayalite laths and wustite in a glass matrix. The composition of the slags varied from surface to base resulting in microstructural variations. There was a relatively sharp boundary in the microstructure between the lower and upper halves of the slag. Towards the top of the slag the concentration of iron oxide was higher and the concentration of the other components was correspondingly lower. Large fayalite laths and wustite were plentiful and the upper half of the slag also had the greatest porosity. The

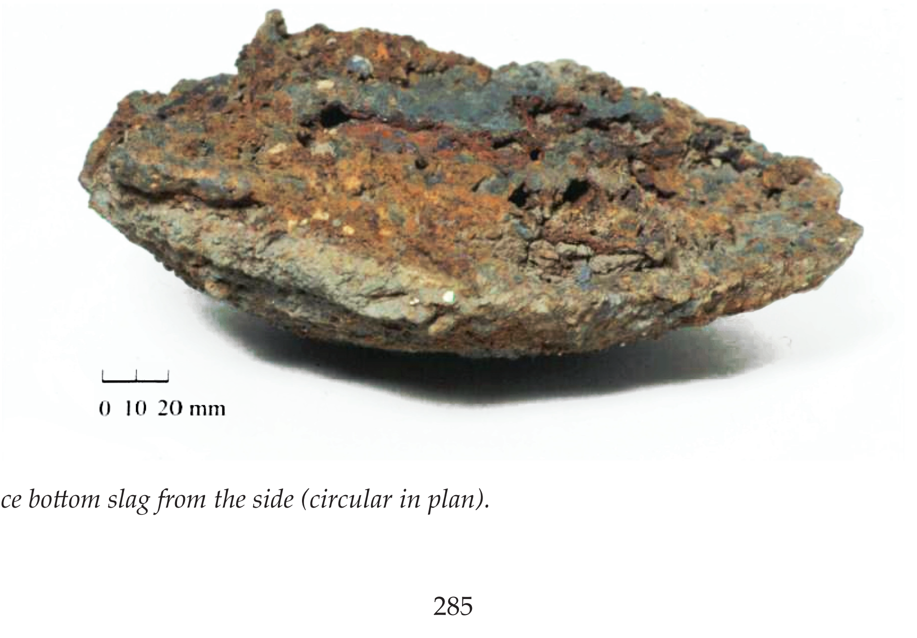

Plate 7.3 Furnace bottom slag from the side (circular in plan).

Table 7.9 Metalworking remains: Composition of furnace bottom slags, measured by EDS, average of 7 (1510) and 5 (1225) analyses, normalised (see Table 7.18).

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
Furnace Bottom (1510)	0.13	0.42	3.84	20.31	0.91	0.20	0.57	1.57	0.17	0.08	71.52
Furnace Bottom (1225)	0.14	0.16	4.41	23.66	0.80	0.05	0.82	1.66	0.23	0.20	67.64

lower half contained less wustite (and finer dendrites), but more glass, with very little wustite present at the base of the slag.

These samples were analysed (Table 7.9) and were found to have a higher ratio of iron oxide to silica (SiO_2) and of silica to alumina (Al_2O_3) overall than the tap slags. The furnace slags also contained slightly less phosphorus oxide (P_2O_5) than the tap slags, but still more than the equivalent slag from bloomery sites producing low-phosphorus smelting slags (cf Fulford and Allen 1992, table 9). These compositional variations indicate that the tap slag and furnace slag formed in slightly different environments. For example, differences may be a result of changes in the atmospheric conditions between regions of the furnace. Fulford and Allen (1992, 194) noted that 'massive slags', which they often found attached to tap slag, were also noticeably richer in iron oxide and depleted in other constituents. They also detected magnetite in these slags, indicative of a relatively oxidising atmosphere. These massive slags are likely to have been the equivalent of the Westhawk furnace bottom slags. The Westhawk furnace slags had also reacted to some extent with the siliceous lining at the furnace base, as a result of prolonged contact at high temperatures, and this was reflected in the decreased iron oxide content and scarcity of wustite dendrites towards the slag base.

Products

Unrefined blooms

Two fragments of blooms from the slag assemblage were sectioned and examined. The first (1333) was predominantly ferritic with occasional small patches of pearlite, indicating a low overall carbon content. The average of eleven EDS analyses showed that the bloom contained 0.3% phosphorus oxide (P_2O_5) by weight. The detection of phosphorus in the metal is to be expected as there are very high levels in the slag within the bloom and analysis of the slag within this bloom showed 7.32% of phosphorus oxide by weight (Table 7.10). The slag remaining in the bloom is the remains of smelting slag, and it would be expected that the composition of the bloom slag and the smelting slag would be broadly similar. This is so with the exception of the increased phosphorus content of the slag in this bloom fragment. In addition, the iron content of the bloom slag is slightly higher, and the alumina and silica contents consequently lower, than that of the smelting slag. Høst-Madsen and Buchwald (1999) also noted phosphorus oxide enrichment of the slag in a bloom relative to the tap slag from the same site. They attributed this to phosphorus dissolving in the metal and then later partitioning between the metal and the slag with which it was closely associated, resulting in phosphorus enrichment of the slag in the bloom.

The second bloom fragment (1259) was probably rejected because it still contained particles of ore, fuel and regions with a high proportion of partially reacted quartz grains (less than 100 μm and angular) as well as slag and ferritic iron. The particles of ore were interpreted as such, rather than as corrosion products formed in voids, because of the presence of tiny crystals nucleating around the perimeter of each particle, indicating that the particles were present when the bloom was hot (Fig. 7.11). As a result of the smelting process, and corrosion of the bloom since it was discarded, the ore fragments are likely to have been converted to iron oxide (haematite or magnetite) or hydrous ferric oxide (goethite) regardless of their original composition. Consequently a total of *c* 74% iron oxide (FeO) by weight was detected by analysis (the data in Table 7.11 are normalised). The ore fragments were up to about 1 mm in diameter with a plate-like appearance and the outline of euhedral crystals, probably goethite, could be seen in some. No quartz grains were observed in the ore fragments, suggesting that the quartz has already reacted to form the surrounding iron silicate slag or that little was originally present.

The slag comprised dendrites of wustite, fayalite laths and a glassy matrix, with occasional crystals of hercynite ($FeAl_2O_4$). The regions containing large concentrations of quartz grains may derive from detached furnace lining or from ferruginous sandstone added as part of the ore batch. The iron metal within the bloom fragment contained less than 0.05% phosphorus oxide by weight (four EDS analyses) and the associated slag contained correspondingly less phos-

Table 7.10 Metalworking remains: Composition of slag within a partially refined bloom from context 1333, measured by EDS, average of 6 analyses, normalised (see Table 7.19).

Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
0.09	0.51	2.09	12.84	7.32	0.38	0.77	1.46	0.09	0.35	74.10

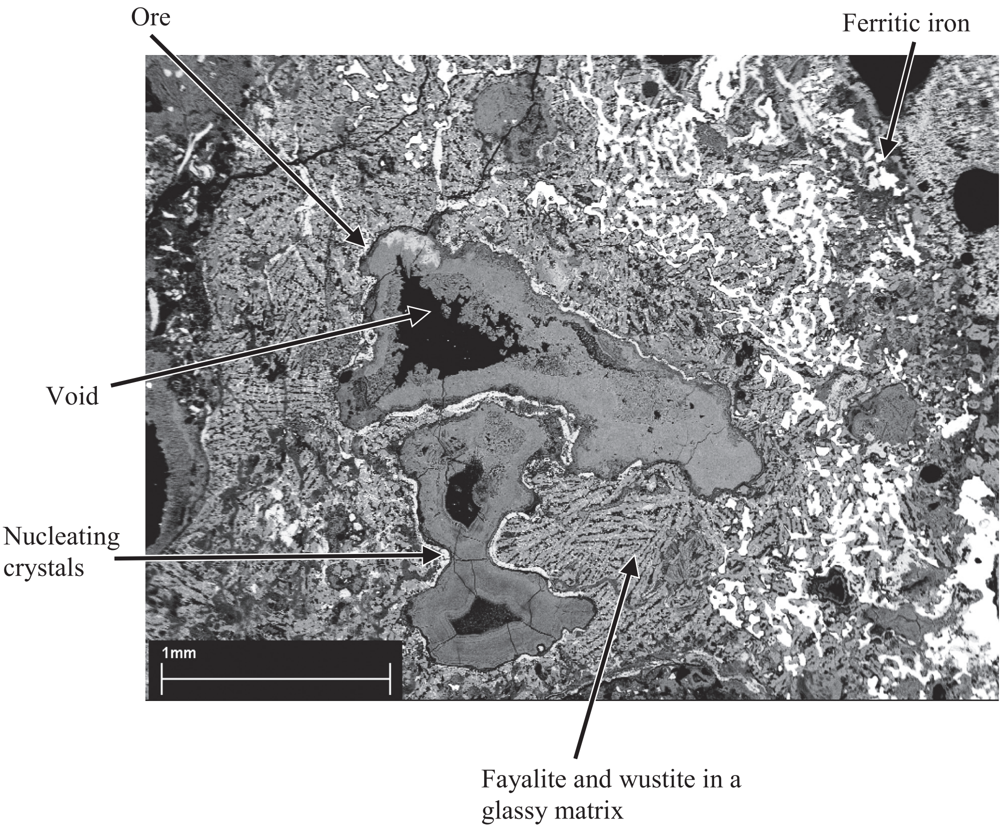

Figure 7.11 SEM back-scattered electron image of unrefined bloom, showing areas of ferritic iron (white), ore (mid-grey) and central voids (black) surrounded by nucleating crystals (white) and slag comprised of wustite (light grey) and fayalite (mid-grey laths) in a glass matrix (dark grey).

phorus (Table 7.11) than the previously described bloom fragment (Table 7.10).

Refined billet

A refined billet (SF905; see Scott, Chapter 5, cat. no. 2; Fig. 5.10) was found in context 7009, during cleaning of a layer above structure P, a circular structure that probably dates to *c* AD 200-250. The billet weighed 4.46 kg and was 0.32 m long, with a maximum width of 75 mm and a thickness of 55 mm. The longitudinal section of the billet (both parallel and perpendicular to the base of the billet) was trapezoid shaped with rounded vertices. A sample of the billet was examined metallographically and analysed using EDS (Table 7.12). A value of 0.11% of phosphorus by weight was detected in analyses of approximately 4 mm^2 areas of the billet selected as they contained very little slag (standard deviation 0.04%, average of four analyses). This level of phosphorus is intermediate between the levels detected in the bloom fragments, suggesting that the phosphorus content of the iron produced at Westhawk was variable. The variation in phosphorus content within the billet sample demonstrates the heterogeneity of the iron. This amount of phosphorus would slightly increase the hardness of the iron (Tylecote 1990, 145).

The billet appeared to be very well consolidated and the few slag inclusions remaining were analysed (Table 7.12). The majority of the larger slag inclusions consisted only of glass or of glass with fayalite. The fayalitic slag inclusions were very iron-rich and consequently contained little phosphorus oxide. The smaller inclusions contained wustite dendrites in addition to fayalite and glass and also contained the highest concentration of phosphorus oxide. The

Table 7.11 Metalworking remains: Compositions of different regions within theterogeneous discarded bloom fragment, measured by EDS and normalised.

Area	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
Quartz-rich region	0.81	0.28	2.96	33.23	1.44	0.18	0.46	0.09	0.13	0.00	60.42
Fuel-rich region	0.63	0.09	1.73	13.41	1.32	0.24	0.22	0.12	0.09	0.00	82.15
Slag (average of 3)	0.26	0.49	7.81	21.63	2.02	0.15	1.22	1.78	0.28	0.65	63.71
Ore (average of 3)	0.56	0.14	0.27	0.36	0.21	0.52	0.01	0.39	0.05	0.12	97.36

Table 7.12 Metalworking remains: Compositions of slag inclusions sampled from billet (SF905, context 7009), measured by EDS and normalised (see Table 7.20).

Slag	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
Fayalite and glass (average of 3)	0.35	1.71	8.45	0.38	0.11	0.31	0.91	0.11	0.29	87.38
Wustite, fayalite, glass (average of 5)	0.73	4.49	24.01	1.14	0.56	1.12	3.28	0.28	0.92	63.48
Glass (average of 3)	0.88	5.30	30.59	0.81	0.42	1.48	4.22	0.45	1.26	54.60
Overall average	0.67 ± 0.22	3.95 ± 1.5	21.56 ± 9.4	0.84 ± 0.4	0.40 ± 0.3	1.00 ± 0.5	2.89 ± 1.4	0.28 ± 0.1	0.84 ± 0.4	67.58 ± 14.0

compositions of the slag inclusions and the smelting slag from Westhawk were approximately similar although the concentration of phosphorus oxide in the inclusions was slightly less than that detected in the tap slag analysed from the site.

The compositions of the Westhawk billet and the slag inclusions it contains are consistent with the billet having been produced at Westhawk, although the slag contained slightly less phosphorus than the smelting slag from the site. The varying phosphorus contents of the billet and bloom fragments suggest that the products of Westhawk ranged from ferritic to phosphoric iron.

Smelting summary

The ore used at Westhawk was probably concretionary ironstone with a varying quartz content, ranging from silica-rich ferruginous sandstone to ironstone with a low silica content. The ore was derived largely from the Lenham Beds or from the 'Sand in the Clay-with-flints' no more than 10 miles from the site. If the more iron-rich stone was combined with the more silica-rich stone in appropriate proportions the ore batch would have had a sufficiently high iron content overall for a good yield of iron metal. The gangue from the ore is likely to have provided a large proportion of the silica from which the tap slag formed. The ore was roasted before being smelted. Analyses of the ore detected widely varying levels of phosphorus oxide of up to 3.4% by weight.

As a result of the phosphorus content of the ore, the tap slag from Westhawk was phosphorus-rich (containing several weight percent) relative to slag from other bloomery smelting sites (Table 7.8). On the basis of the analyses in Table 7.7 the tap slag composition appears to have been consistent between the two workshops suggesting that the smelting conditions and raw materials were similar. The large, bowl-shaped furnace bottom slags formed in the base of the furnaces in a depression below the level of the tapping aperture. The furnace bottom slags had different compositions to the tap slag from the same workshops, containing higher proportions of iron oxide and less phosphorus oxide overall. The form of the tap and furnace slags suggests that slag was tapped through a hole 40 mm to 90 mm wide and up to 60 mm deep, slightly below the level of the furnace base.

The slag in the bloom fragments from Westhawk was enriched to varying degrees with phosphorus relative to the tap slag from the site and some phosphoric as well as ferritic iron was identified. The billet recovered from Westhawk contained an amount of phosphorus intermediate between the amounts in the two bloom fragments. Tylecote (1990, 174) states that 'two types of metal were used in Roman tools: moderate to high phosphorus iron, such as that from the Weald, and carburised iron such as that from the Forest of Dean'. Work-hardened phosphoric iron is considerably harder than ferritic iron (ibid., 145) and therefore suitable for applications where a hard metal is required.

Silica-rich clay was used to construct the furnaces. The furnace lining was subjected to high temperatures, and the inner lining reacted with ashes from the fuel and slag to form a vitrified surface. No intact blowing holes were found, although fragments of clay blocks were recovered that may have formed parts of blowing-hole plates. Wedge-shaped clay fragments with very flat, green-glazed edges, found amongst the ironworking waste, may have been used, in conjunction with another temperature resistant material such as stone, to form smithing hearth structures, although these fragments did not survive sufficiently well to investigate this further.

Smithing Slags

Hammerscale

A sample of hammerscale, a by-product of smithing, from the occupation deposit of structure R was examined. A magnet was used to separate the magnetic fraction, including the hammerscale, from the rest of the material in the sample. The magnetic fraction was found to contain small particles of slag and heavily-fired quartz-rich material (Fig. 7.12) in addition to hammerscale flakes and spheres. Examination of the magnetic fraction using an electron microscope showed charcoal fuel fragments and fired quartz-rich material frequently adhering to the hammerscale flakes. The presence of a thin reaction zone between the quartz-rich material and the hammerscale indicated that they had been in contact while at high temperatures and therefore that the hammerscale, slag and fired quartz-rich particles were all by-products of the smithing process.

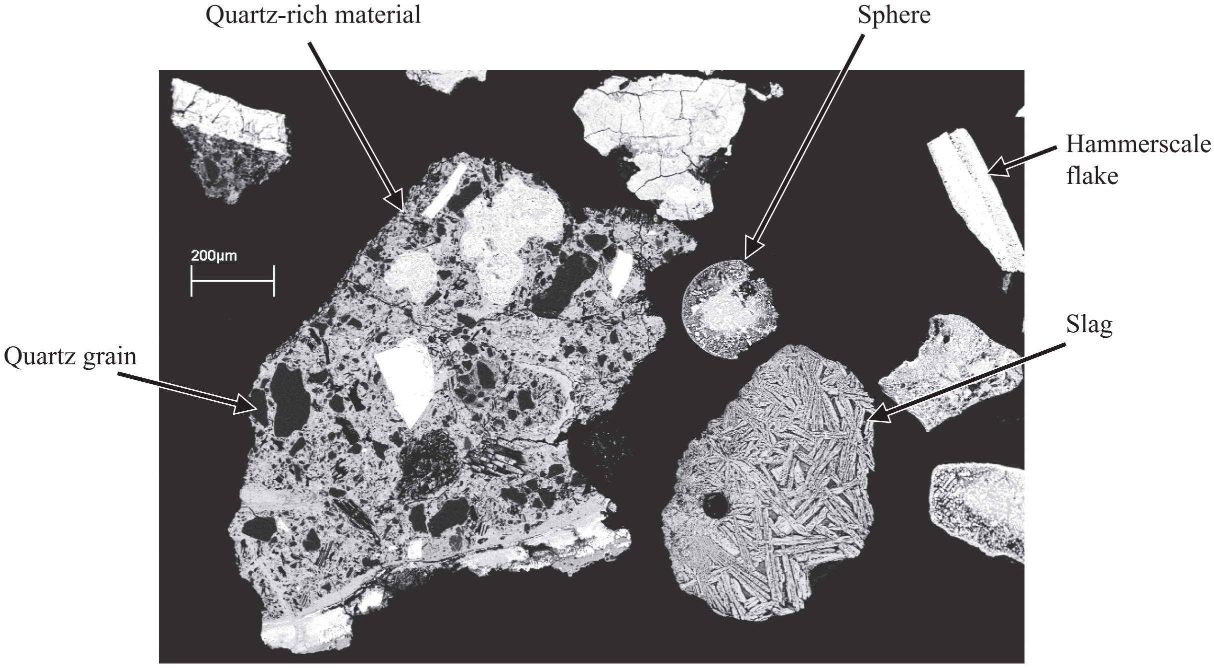

Figure 7.12   SEM back-scattered electron image of a hammerscale sample, which includes lumps of slag, spheres of hammerscale and hammerscale flakes with quartz-rich material adhering.

The quartz-rich particles consisted of angular quartz grains, the majority less than 130 µm in diameter, in an iron-rich matrix. Hammerscale flakes and spheres were analysed using XRD and found to consist predominantly of the iron oxides wustite (FeO) and magnetite (Fe_3O_4) (Fig. 7.13). The compositions of the different components of the magnetic fraction were also determined, using EDS analysis. The results are given in Table 7.21 and discussed further below.

It has already been suggested that the smithing hearths used for bloom refining were constructed, at least in part, from silica-rich clay (see 'Smithing hearth bottom slags' below, and also 'Clay' above), as were the smelting furnaces. The quartz grains in the material adhering to the hammerscale are similar

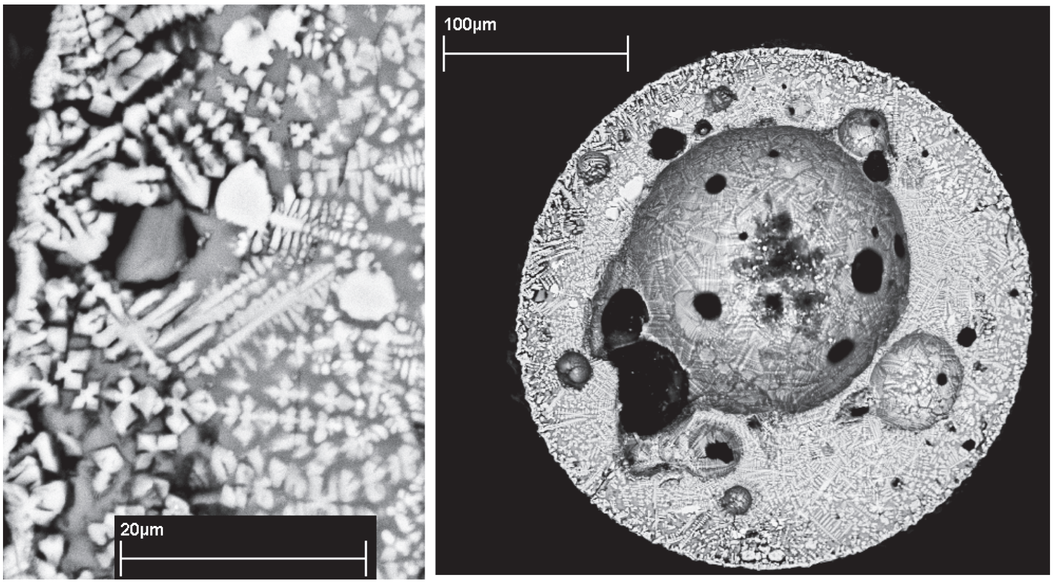

Figure 7.13   SEM back-scattered electron images of a hammerscale sphere, with the magnetite dendrites shown at high magnification on the left.

in size and angularity to the grains in the fragments of furnace lining from the site. Therefore the fired quartz-rich material amongst the hammerscale may be hearth lining that has been heavily fired and has partially reacted with slag. An alternative is that the smith may have used sand as a flux during smithing, which could result in the formation of fired, quartz-rich particles. Sand would react with the oxides on the surface of the iron to form molten slag that was easily removed to leave a clean metal surface (McDonnell 1991). However, the composition of some of the quartz-rich inclusions in the smithing hearth bottom slags, discussed in the next section of this report, suggests that the former hypothesis is more likely.

Mills and McDonnell (1992) have shown that there is a correlation between the amount of hammerscale in soil samples from smithing deposits and the weight of the magnetic fraction of the sample, even though other types of magnetic material are present. Therefore the inclusion of highly-fired, quartz-rich particles in the magnetic fraction of the Westhawk samples will not distort the hammerscale distribution plot (Fig. 7.16) as all samples are affected equally.

Smithing hearth bottom slags

The smithing slags recovered from Westhawk varied widely in form and size, from very small, low porosity slags (0.2 to 0.3 kg) to medium-sized slags (1 kg) to extremely large, unusually shaped slags (2 to 3 kg). Small, medium and large smithing slags were recovered from contexts 1257 and 1332 around structure R (Table 7.12). The large smithing hearth bottom slag from context 1332 is shown in cross-section in Figure 7.20. A medium-sized smithing slag from context 1225, near structure I, was also examined. All these slags were heterogeneous and are described in terms of a succession of layers, although a continuous gradation between the different regions was generally observed, rather than distinct boundaries. The average compositions of the smithing slags are given in Table 7.13. These are useful for comparison with other types of slag from Westhawk as well as with the average compositions of smithing slags from other sites. Only compositional data on bulk regions of the slags, rather than analyses of particular phases or inclusions, were used to generate the averages. Despite this the heterogeneity of this slag type is demonstrated by the large standard deviation of the results (Table 7.13) and therefore caution must be exercised when using the data. The full analytical data are given in Tables 7.22-7.26.

The top layer of each of the slags consisted of a corroded, iron-rich, amorphous matrix surrounding angular grains of quartz. The majority of the quartz grains were less than 150 μm in diameter although occasionally grains of up to 0.05 mm were observed. The grains were similar in size and shape to those in the quartz-rich material found in the magnetic fraction of the hammerscale samples and also to the quartz grains in samples of furnace lining (see above). Particles of entrained, quartz-rich material were observed in the upper halves of the medium-sized smithing slags from contexts 1225 and 1332. The particles nearer the middle of the slag were surrounded by reaction products, confirming that the particles were incorporated into the slag while it was forming, rather than being post-depositional material. These areas had compositions similar to the furnace lining samples discussed above. Charcoal fragments were also observed. Characteristically-shaped, iron-rich hammerscale particles, either spheres or parallel-sided flakes up to 0.4 mm in length, were occasionally observed in this top layer, and were particularly abundant in the small slag from context 1257 (Fig. 7.14).

The second layer of the smithing hearth slags sometimes contained a high proportion of charcoal. In this layer, and in the region immediately below, a large number of voids were consistently observed. The slag in these regions consisted of varying proportions of wustite dendrites and fayalite in a glassy matrix. The remainder of the slag also consisted largely of wustite dendrites and fayalite in a glassy matrix, although there were large variations in porosity and localised changes in composition led to variations in the relative proportions of the different phases and to the formation of other phases. For example an increased concentration of alumina led to the formation of very fine crystals of hercynite spinel and a pyroxene phase in the glass matrix surrounding the wustite and fayalite in some areas of the large smithing hearth bottom slag. A gradation to a coarser microstructure was quite frequently observed in the lower half of the slags suggesting that they had cooled more slowly. The base of the smithing slags was often found to contain a slightly lower proportion of wustite and have lower porosity. The medium-sized smithing hearth slag from context 1332 was particularly porous throughout with only small regions of crystalline slag having formed amongst the voids.

Table 7.13 Metalworking remains: Average compositions (and standard deviations) of smithing hearth bottom slags (SHB) (see Tables 7.22-7.26).

Ctx	SHB size	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
1257	small	0.3 ± 0.1	0.9 ± 0.5	3.6 ± 0.8	23.3 ± 4.4	1.2 ± 0.3	0.2 ± 0.2	1.4 ± 1.0	3.5 ± 2.2	0.2 ± 0.1	0.2 ± 0.2	65.0 ± 7.4
1332	large	0.2 ± 0.2	0.5 ± 0.1	6.3 ± 1.3	27.7 ± 3.0	1.3 ± 0.3	0.3 ± 0.2	1.0 ± 0.7	3.5 ± 1.9	0.3 ± 0.0	0.2 ± 0.1	58.8 ± 4.8
1332	medium	0.0 ± 0.1	0.4 ± 0.3	4.2 ± 2.6	17.4 ± 10.0	0.8 ± 0.5	0.2 ± 0.1	0.7 ± 0.6	2.1 ± 1.5	0.2 ± 0.1	0.2 ± 0.1	73.7 ± 15.1
1225	medium	0.0 ± 0.1	0.5 ± 0.1	8.2 ± 4.3	27.0 ± 12.0	2.0 ± 0.4	0.4 ± 0.6	0.4 ± 0.3	1.9 ± 0.5	0.4 ± 0.4	0.3 ± 0.1	59.0 ± 17.1

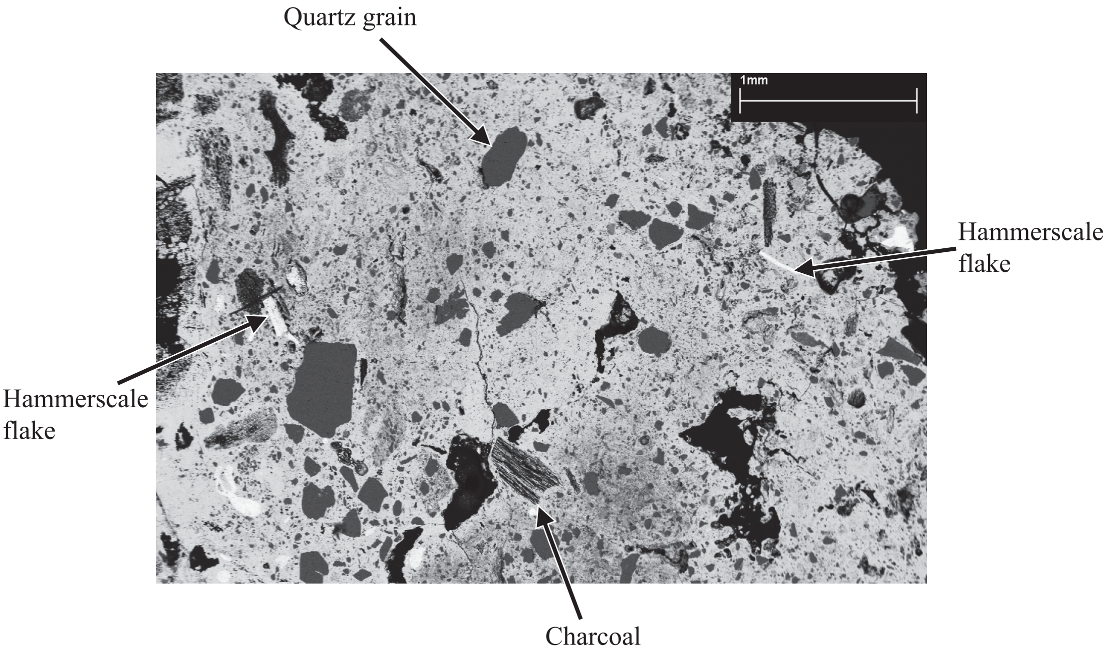

Figure 7.14 SEM back-scattered electron image of the top layer of a small smithing hearth slag from context 1257, consisting of an iron-rich matrix with fuel fragments surrounding angular quartz grains and hammerscale flakes and spheres (no spheres in this image).

A distinct boundary with a scalloped edge (Fig. 7.15) was observed in the large slag from context 1332 towards the base of the thicker end (to the right in Plate 7.4). The slag immediately beneath the boundary had a very low porosity and a coarser microstructure. The boundary may have formed when a smithing hearth bottom slag was displaced in the hearth, rather than being removed completely, and slag from a subsequent smithing operation was then deposited on top. The uneven shape and large size of this slag relative to others from the site also suggest that it may be the product of more than one smithing operation. The thicker end of this large slag was positioned near to the hearth wall as a thin layer of hearth lining adheres to it at this point. The hearth lining was analysed and found to be siliceous clay similar to that used in the furnace construction, containing approximately 75% silica by weight, 11% alumina and 7% iron oxide.

Figure 7.15 SEM back-scattered electron image of the microstructurural boundary in a large smithing slag, with a coarser fayalitic microstructure below the boundary.

Plate 7.4 Cross section of large smithing hearth slag.

Smithing slag summary

On average 0.2% manganese oxide by weight (up to 0.4%) and 1.3% phosphorus oxide (up to 3.3%) were detected in the Westhawk smithing slags. This compares with an average of 0.1wt% manganese oxide and 0.8wt% phosphorus oxide in smithing slags that have been studied from other sites (McDonnell 1986). The smithing slags at Westhawk Farm were found largely in contexts near workshops where waste from both smelting and smithing activity was found and is likely to be waste from primary smithing, during which the iron blooms produced by smelting were consolidated. The tap slag from Westhawk Farm contained high levels of phosphorus oxide and intermediate levels of manganese and the slag incorporated in some bloom fragments was particularly rich in phosphorus. The elevated levels of phosphorus and manganese oxides in the smithing slags from Westhawk Farm are likely to be the result of the incorporation of slag from the bloom and are consistent with the interpretation of these slags as by-products of primary smithing. Substantial inclusions of very fluid slag runs, resembling tap slag, were observed in the large smithing hearth slags examined. However, it should be noted that McDonnell (1986) found one or two secondary smithing slags with phosphorus oxide contents over 1wt% from an Anglo-Saxon smithy at Wharram Percy, Yorkshire, and in three analysed slags from a Roman smithy at Heybridge, Essex. The reasons for the compositional variation between smithing slags recovered from different sites are as yet poorly understood but these data demonstrate that elevated phosphorus (and manganese) contents in smithing slags do not necessarily indicate that the slags are by-products of primary smithing.

Although the smithing slags from Westhawk Farm were of different sizes, they were compositionally similar and this confirms that they are all by-products from smithing metal produced at the site. However, the different-sized slags may have been produced by different stages of a smithing process or hearth conditions, by multiple smithing operations or by different smiths using different techniques. For example, medium sized slags may be typical of one period of hearth use whereas larger slags may have been formed by multiple periods of hearth use. The smaller slags, which were less porous and more iron-rich, may have been formed in a shorter period of hearth use, for example when producing smaller objects or during the final stages of billet production.

The microstructure of the smithing slags suggests that they were formed through the accumulation and reaction of slag from the bloom, hammerscale, particles of fired quartz-rich material and charcoal fuel. All of these components were observed amongst the hammerscale samples examined. The quartz-rich material may derive from the hearth lining, which was, at least in part, siliceous clay. The lining would react with fuel ash and slag, becoming gradually vitrified during hearth use, until fragments were dislodged. Alternatively the quartz-rich material may derive from siliceous fluxes used by the smith. The hammerscale, slag, quartz-rich material and fuel ash reacted to form slags within which fuel fragments and gases became trapped. However, with increasing time in the hearth at high temperatures, the porosity was reduced and the fuel fragments burnt away except in the more recently formed, upper layers.

The microstructural changes observed through the thickness of each smithing slag may have resulted from variations in the smithing activity or hearth conditions during the period of hearth use. The less porous, coarser microstructure observed in the lower half of many of the slags is probably because this slag has been heated for longer, and because the lower regions of the hearth cooled more slowly once the fire was allowed to die down. The incomplete reaction of the components in the top layer of the smithing slags is consistent with the fairly rapid cooling of the slag after this final layer was deposited and the smithing operation completed. Compositional variations may similarly result from changes in the smithing activity or hearth conditions. For example, an iron-poor region might result from the deposition of vitrified hearth lining while the hearth was heated prior to smithing commencing. Iron-rich areas could result from large quantities of bloom slag being expelled or large amounts of hammerscale being dislodged.

The top layer of each smithing slag, comprised of quartz grains and hammerscale, contained slightly lower concentrations of phosphorus and manganese oxides relative to the rest of the slag. Manganese and phosphorus are likely to have been derived largely from the slag expelled from the bloom, the majority of which might be incorporated into the lower layers of the smithing slag during the early stages of smithing. Experimental replication of the primary smithing process and examination of the by-products it produces might help to explain these observations on the composition and structure of Roman slags.

The relative contributions of slag and hammerscale (from the bloom), quartz-rich material (from the hearth lining or flux) and ashes (from the charcoal) to the formation of the smithing hearth slags can be estimated from the compositions of each of these materials. For example if the slag from the bloom contributed the majority of the phosphorus and manganese detected in the smithing hearth bottom slag then approximately 70w% of each smithing hearth bottom by weight would derive from bloom slag, 10% from the hearth lining, about 20% from hammerscale and a small amount (around 2%) from the charcoal. (In this calculation it is assumed that the bloom slag contains approximately 2% phosphorus oxide and 24wt% silica.)

Secondary Smithing

The ferrous metalwork recovered from the site was largely in the form of nails (50% by number) and hobnails (24%) but the presence of 83 miscellaneous pieces of strip, rod and sheet suggests that some secondary smithing activity, producing objects other than billets, took place (see Scott, Chapter 5 above). As the ironwork is concentrated around structures R and I the same smith was probably responsible for both primary and secondary smithing. To determine whether any additional secondary smithing activity took place on site, the slag assemblage was examined to identify any contexts containing a particularly high proportion of smithing slag, relative to smelting slag and to see if these were concentrated in one area or assigned to a particular phase.

In Table 7.14, the contexts with more than 10% of smithing slag by weight (as a proportion of the total amount of slag recovered from that context) are listed. Nearly all of the contexts listed in Table 7.14 were near structure I and six (676, 739, 675, 720 and 707) were from one waterhole. However the vast majority of these contexts also contained some tap slag or furnace bottom slag. The remaining contexts contained only a small quantity of waste and so the proportion of smithing slag in the context was heavily weighted by the presence of one piece. Therefore the vast majority of the smithing slags from Westhawk Farm are likely to be by-products of primary, rather than secondary, smithing derived from workshops I and R. The chemical analyses of a small selection of the smithing slags, discussed previously, support this conclusion.

Other workshops

It appears that there was a break between the cessation of ironworking in structure I and the beginning of activity in structure R. However, the similarities between the layouts of the workshops, and the materials and technologies utilised in them, suggest that ironworking at the site was continuous until the settlement was largely abandoned in the mid 3rd century AD. There is a possibility that an earlier structure, possibly used for ironworking, was situated on the site of structure R (see above). Alternatively there

Table 7.14 Metalworking remains: Summary of iron-working waste from contexts containing a large proportion of smithing hearth bottom slags.

Context	Phase	Area	Tap (kg)	SHB (kg)	Furnace bottom (kg)	Slag-coated clay (kg)	Total (kg)	% SHB
565	3	I	0.0	2.3	0.0	0.4	2.7	83.7
8022	3	I	4.1	6.0	0.8	1.1	12.5	48.0
8569	3	I	0.0	1.6	0.0	0.0	1.6	98.9
1193	4	I	10.5	4.6	2.5	16.4	42.4	10.7
1460	4	I	1.4	2.7	0.0	2.7	8.1	32.9
707	5	I	0.0	0.3	0.0	0.0	0.3	92.3
720	5	I	0.0	0.8	0.8	0.2	2.0	41.4
725	5-6	I	0.0	1.0	0.0	0.0	1.0	100.0
275	6	I	0.7	0.5	0.0	1.9	3.4	14.5
675	6	I	0.4	0.5	0.0	0.3	3.5	13.2
676	6	I	0.5	3.3	1.1	1.0	5.9	55.9
739	6	I	0.8	1.3	0.0	1.4	4.4	29.2
1086	2	Nr P	0.0	0.3	0.0	0.0	0.3	100.0
1332	5	R	14.8	4.1	0.6	6.3	27.5	14.8
510	4	Nr R	0.4	0.4	0.9	0.0	1.7	23.5

may have been additional workshops in the unexcavated area of the site.

Ironworking hearths, furnaces and waste give rise to very strong responses in gradiometer surveys. While such responses can result from many different types of industrial activity as well as from features that are in no way related to industrial activity - and differentiation between these is not possible on the basis of the readings alone - at Westhawk Farm data interpretation is aided by the fact that the location of two iron smelting and smithing workshops is known. Both workshops gave rise to strong geophysical readings against which data from other areas of the settlement can be compared.

Geophysical Surveys of Bradford highlighted magnetically strong readings that might indicate regions of industrial activity in survey areas G (structure R), B (structure I), C, F, E, L (the slag deposits near structure P), M, Q and P (Fig. 7.16). The strong readings in areas P and E are not necessarily the result of industrial activity as the concentration of archaeological features suggests that these may be intensively occupied areas. The strong responses in areas F and Q appear to be slightly more scattered and/or less strong than those observed in the known workshop areas. The readings from Area M, and to a lesser extent Area C, appear to be the most similar to those from the ironworking workshops R and I. Areas M and C, like structures R and I, are also in the south-west half of settlement, with Area M on the same side of the road as structure R and Area C on the north-west side of the road near structure I. In Area C there appears to be an enclosure with quite strong, although slightly scattered, readings on both sides of the road. In Area M there is a large, dense cluster of very strong readings, the strongest of these forming a crescent shape, and a number of broad pit-type features were also identified. A high-resolution survey of these regions, particularly Area M, could be used to investigate the existence of additional workshops in the unexcavated area and to resolve features if a workshop is located.

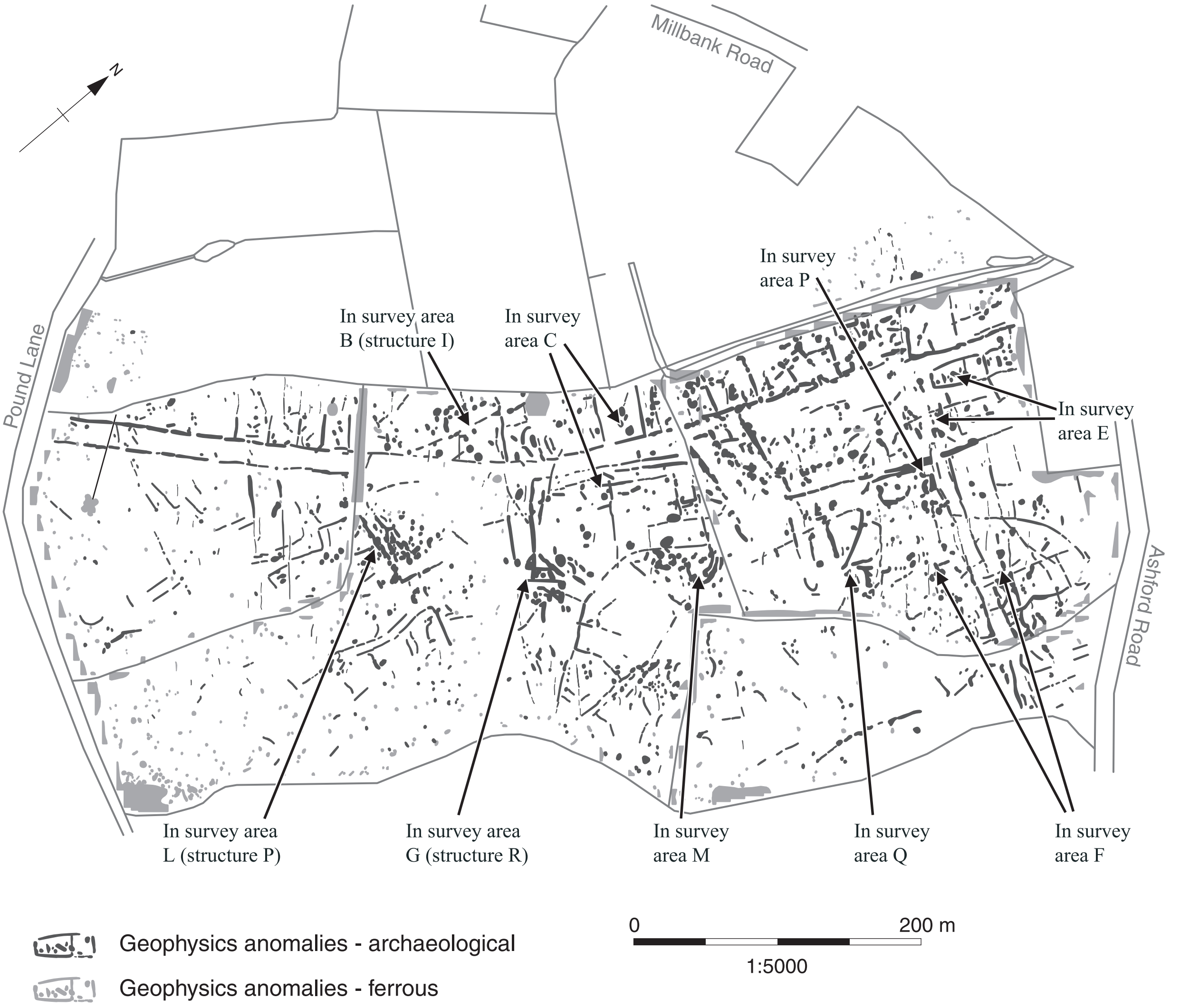

Figure 7.16 Geophysical survey areas where strong readings were detected, from the report by Geophysical Surveys of Bradford.

DISCUSSION

Scale of ironworking activity

Estimating the scale of the ironworking activity at Westhawk Farm involves many approximations as only a fraction of the ironworking waste was recovered and less than half of the site was excavated. The amount of slag in the excavated Areas B and C was estimated by extrapolating the amount of slag recovered from the volume of the feature sampled to approximate the amount in the feature as a whole. For example, since half of each pit was excavated, the ironworking waste recovered constitutes half of that likely to be present in the entire feature, and therefore the recorded figure was doubled to give an approximate value for the total ironworking debris in the pit. Similarly 10% of each linear feature was excavated, therefore the quantity of ironworking waste recovered from each linear feature was multiplied by 10 to give an estimate of the total present in the feature as a whole. However, this assumes an even concentration of waste along the length of the feature, which is unlikely. This process was completed for all of the contexts listed in Table 7.2, which gave an estimated total of ironworking debris in these features of 6300 kg, whereas 960 kg was actually recovered from the excavated sections. Across Areas B and C approximately 1650 kg (1.65 tonnes) of ironworking waste were recovered. Assuming a similar ratio of recovered waste to the total present for the whole assemblage, the amount of waste across Areas B and C can be estimated at (6300 / 960) by 1650 kg = 10830 kg.

Although the geophysical survey covered both the excavated and unexcavated areas of the site, it is not possible to differentiate between areas of high positive data caused by metalworking processes and those resulting from other types of activity or features, as mentioned previously. Therefore the amount of slag in Area A was estimated by assuming a similar density of debris across Area A (10 ha) as across Areas B and C (in total approximately 6 ha). Thus the quantity of ironworking waste in area A is assumed to be approximately (10 / 6) by 10830 kg = 18050 kg and the total quantity of slag across the whole site (areas A, B and C) is estimated at 18050 + 10830 kg = 28880 kg (about 29 tonnes).

This figure is likely to be an underestimate of the amount of ironworking waste produced over the lifetime of the site, since some of the slag has almost certainly been moved and reused. The road through the settlement (Margary's route 130) was metalled with slag and flint nodules within the site, although this only survived in small areas, and was also metalled with slag further west (Cleere and Crossley 1985). Some of this slag may have come from the Westhawk site since to date few other smelting sites of Roman date have been identified in the area. Hodgkinson (1999) estimates that 540 m^3 (roughly equivalent to 540 tonnes of slag) may have been used to metal each kilometre of a Roman road. If it were known that slag from Westhawk had been used to metal just one kilometre of road, the estimate of the site's slag output and hence iron production would increase by more than 30 times. Therefore in this discussion the estimate of the scale of the iron production at Westhawk is referred to as a minimum, since it is based on the quantity of slag recovered from the site and it is likely that some was removed in the past.

The Westhawk billet weighs approximately 4.5 kg. From experimental work Crew (1991) has estimated that about 50% of the bloom remains by weight after primary smithing, when the iron bloom is refined into a billet or bar. Assuming that the Westhawk billet was produced from one bloom, then the bloom in its unrefined state would have weighed about 9 kg. This estimate was compared to the weights of other blooms and billets of Roman date, although caution is required since the distinction between refined billets, or lumps of iron, and unrefined blooms is inconsistent in the literature. The Roman bloom recovered from Elms Farm, Heybridge weighed 12.2 kg (Dungworth 2001), another from Lower Slaughter, Gloucestershire weighed about 11 kg (O'Neil and Brown 1966) and one from Forewood Crowhurst, Sussex weighed 12.4 kg. A billet from Cranbrook, Kent weighed 7.1 kg and another from Strageath, Tayside weighed 5.7 kg (Tylecote 1990). Estimates of the size of refined blooms have also been obtained by examining large iron beams from Catterick and Corbridge, determining the number of refined iron masses that they contain, and calculating that each weighs approximately 7.5 kg (Bell 1912; Wright 1972; Starley 1997). Hooked billets of the period range in weight from 1.1 kg to 2.9 kg (Salter 1997, 96). These data raise the possibility that the unrefined blooms produced at Westhawk Farm may have been larger than 9 kg on average and that the production of the large (4.5 kg) billet may not have required the use of a complete bloom. However, for the purposes of these calculations, it has been assumed that a 9 kg unrefined bloom was produced in each smelt at the site.

Investigation has shown that the ore utilised by smelters at Westhawk Farm had a variable iron content. However, the three tap slag samples analysed had similar compositions suggesting that the ore batch may have varied very little between smelts. For the purposes of these calculations, a value of 70% of iron oxide (Fe_2O_3) by weight in the roasted ore has been used, which is an appropriate value if a mixture of ferruginous sandstone and more iron-rich concretionary ironstone were smelted together in each batch. The results of experimental smelting in bloomery furnaces have indicated that approximately 40% of the iron (as Fe) available in the ore will form the bloom whereas the rest is lost as slag (Crew 1991, 29). The quantity of ore required in each smelt, to produce a 9 kg bloom, can be approximated as follows (atomic weight iron Fe = 55.85; molecular weight FeO = 71.9; molecular weight Fe_2O_3 = 159.7):

The amount of iron (Fe) in the ore = 9000 / 0.4 = 22500 g Fe

Moles of iron (Fe) in the ore = 22500 / 55.85 = 402.9

In the roasted ore, the iron is in the form of Fe_2O_3, therefore the amount of roasted ore per smelt = 402.9 by 159.7 = 64.3 kg

Approximately 60% of the iron (Fe) available in the ore will form the waste slag = 0.6 by 22500 = 13500 g

Moles of iron in slag = 13500 / 55.85 = 241.7

Amount of iron oxide (FeO) in slag = 241.7 by 71.9 = 17378 g

The slag produced contains approximately 60wt% of iron oxide (FeO). Therefore the approximate quantity of slag produced per smelt = 17378 / 0.60 = 29 kg

From experimental work it has been estimated that approximately 100 kg of charcoal are required per 100 kg of ore (Crew 1991, 27). Therefore 64 kg charcoal are likely to have been required for each smelt and approximately 416 kg of wood might be required to produce this amount (Kelley 1986). Additional charcoal would be used for smithing the bloom, which has not been taken into account here:

Ore (64 kg) + Charcoal (64 kg) → Iron bloom (9 kg) + Smelting slag (29 kg)

The total estimated quantity of ironworking waste on the site is 29 tonnes. About 60% of the waste from Westhawk Farm by weight is tap slag, furnace bottom slag and undiagnostic slag (likely to derive from smelting). Therefore, assuming that 29 kg of slag were generated per smelt, the number of smelts at the site can be approximated at a minimum (as some slag may have been removed from the site) of 29000 by 0.6 / 29 = 600. The amount of refined iron produced can be estimated at a minimum of 600 by 4.5 = 2.7 tonnes (equivalent to 600 billets of 4.5 kg each). A minimum of approximately 38.4 tonnes of ore would have been consumed with a minimum of 250 tonnes of wood (38.4 tonnes of charcoal).

The duration of occupation of structures I and R has been estimated at 100 years in total, although it is possible that smelting activity also took place elsewhere on the site, particularly during the period between the ironworking ceasing in structure I and starting in structure R. However, if the smelting activity were spread evenly over the estimated period of occupation of structures I and R, it would equate to a minimum of six smelts a year. As some of the waste slag is likely to be unaccounted for (for example, if slag was removed for road metalling) six smelts a year is an underestimate.

Although the ironworking waste was fairly equally divided between Structures R and I, the geophysical survey suggests that there may be large deposits of ironworking waste associated with structure R that were not excavated. However survival of features in and around structure I was poorer than at structure R. Therefore it is difficult to draw any meaningful conclusions about the relative intensity of ironworking activity between the two structures. However, assuming that smelting activity was comparable in structures R and I, then a minimum of 300 smelts would have been completed in structure R during its occupation. From observations on furnace re-use from experimental smelting (Crew 1991, 22) it is likely that at least 40 smelts could be completed before furnace reconstruction was necessary. As the basal remains of seven furnace structures were identified in structure R, this would equate to at least 280 smelts over the period of occupation. In addition, since only very shallow remains of these furnaces survived, it is probable that additional furnaces were constructed and used but the evidence of these has not survived. If the scale of ironworking activity in Structures R and I was similar, then a similar number of furnaces would have operated in Structure I, although only two survive in this workshop.

Impact of ironworking activity on the settlement

The assemblage of ironwork at Westhawk has been described as 'remarkable only because of the limited number and range of objects found' (Scott, Chapter 5 above). As it has been estimated that in excess of 27 kg of refined iron was produced at the site each year, the vast majority was probably traded, perhaps in the form of billets like the one recovered from the site. The situation of the site, at the intersection of two roads leading to ports and major towns, would facilitate transport of the iron produced. Cleere has attempted to calculate the consumption of the military and civilian populations of Roman Britain and concluded that a considerable proportion was probably traded outside Britain. Gaul and the army of the Rhine have been suggested as possible markets. The abandonment of the Westhawk settlement, and many others in the Weald, coincides with the upheaval in Gaul in the second half of the 3rd century AD and the disappearance of the Roman fleet in Britain, the *Classis Britannica,* from the record (Cleere and Crossley 1985; Salway, 1981 639).

Iron was a valuable commodity and the ironworking at Westhawk Farm is likely to have contributed to the prosperity of the settlement and that of the area as a whole (Cleere and Crossley 1985, 79-84). Previous research has suggested that the *Classis Britannica* supported the iron industry in the south of Britain and this is further evidence of the strategic importance of the Wealden iron industry (Cleere and Crossley 1985; Salway 1981, 637). However, although large quantities of iron were produced in the Weald, the ironworking activity would not necessarily have involved a large number of people or have occupied all of their time.

Examination of the slag heaps at Beauport Park, Holbeanwood and Bardown in the Weald has suggested that ore collection, timber felling, charcoal production, smelting, forging and furnace reconstruction, may have been performed consecutively on an annual cycle (Cleere and Crossley 1985, 50-51). Ethnographic studies of ironworking have also observed seasonality in the operations associated with iron smelting (Schmidt 1996, 64). This may be particularly true of sites with a smaller smelting operation and greater dependence on other activities, for example agriculture, where ironworkers have been observed to work the fields during part of the year, smelt in the dry season and smith intermittently (Childs and Killick 1993, 329). It has been estimated from ethnographic studies and smelting experiments that three individuals can comfortably operate a furnace and smithing hearth. If the gathering of raw materials, smelting and smithing took place seasonally, spanning a long period, and if only one or two furnaces were operated at a time, then a small number of individuals could have undertaken the entire process.

Ironworking in the Weald

Westhawk Farm is at the north-east edge of the Weald and examination of the chronological patterns of iron production in the area (Cleere and Crossley 1985) has suggested that there was a shift towards more northern sites, in the High Weald, around AD 120-140. Where sites were already established in the High Weald it appears that satellite sites developed in their vicinity. However, there appears to have been a cessation of smelting activity across the Weald around the mid 3rd century AD, save at some of the larger sites. Therefore the estimated duration of smelting activity at Westhawk is entirely consistent with evidence from other sites in the region.

Some of the Wealden Roman sites are estimated to have produced iron on a vast scale (Hodgkinson 1999). For example, there is estimated to have been 30,000 tonnes of ironworking waste of Roman date at Beauport Park (~AD 120-250). The ironworking at Westhawk Farm, on the basis of the quantity of slag remaining, was on a much smaller scale. However, it is probable that some slag was removed from the site and that the scale of iron production has therefore been underestimated.

CONCLUSIONS

Approximately 1.65 tonnes of ironworking waste was recovered during the excavation. Two structures, R and I, where ironworking took place, were located within the excavated area. The waste, more than half of which was diagnostically iron-smelting waste, was concentrated around these two structures. A small proportion of smithing slag was identified and a deposit of hammerscale was found in a workshop context indicating that some primary smithing also took place at the site. No conclusive evidence of secondary smithing activity was found, although the recovery of a number of fragments of bar and sheet from around the workshops suggests that some secondary smithing may have taken place there. Ironworking activity in structure I (~AD 110-160) preceded that in structure R (~AD 200-250). There were strong similarities between the organisation of the workshops and the technologies and materials used in each, suggesting that ironworking continued uninterrupted from the early 2nd to the mid 3rd centuries. If this is so, at least one additional workshop must be located in the preserved region of the settlement. The duration of smelting activity is consistent with the overall pattern observed for the Weald during this period, with activity ceasing in the mid 3rd century.

Smelting and smithing both took place in the same ironworking enclosures at Westhawk Farm, although the areas for each activity were distinct. Groups of bloomery-tapping furnaces were arranged at the edge of the workshop structure in each enclosure. They were round in plan, constructed from quartz-rich clay (in excess of 80% silica by weight), with an internal diameter of about 0.26 m and a wall thickness of about 0.17 m. The tapping apertures of the furnaces probably faced away from the workshops and downhill, although no evidence of tapping apertures or tapping pits survived. The shape of some of the tap slag flows indicates that the tapping aperture was probably up to 90 mm wide and up to 60 mm deep. The furnaces are likely to have been operated one at a time or in pairs. No surviving examples of blowing-holes (or tuyères) were found, although fragments of slag-coated clay blocks were recovered, which may have been parts of blowing-hole plates or repairs. The workshops may have been open along one or more sides, but the roofs are likely to have extended over the furnaces to provide overhead cover for bellows operators, the people charging the furnaces and the furnaces themselves.

Primary smithing took place in another area of each workshop. A ground level, sub-rectangular hearth, 0.6 m in diameter, appears to have been used in workshop R, although the entire hearth construction may have been larger than the fired area that survives. The hearth was probably constructed from blocks of siliceous clay, and possibly another material such as sandstone or tile. A large, consolidated hammerscale deposit covered the floor in workshop R. The distribution of the hammerscale indicates that the hearth and anvil are likely to have been situated near to each other and to a large, sunken ceramic vessel; examples of the latter were found in both workshops. No trace of the anvil remains.

The ore used was probably concretionary ironstone containing varying amounts of quartz, ranging from very iron-rich stone to more silica-rich ferruginous sandstone. The majority of the ore was obtained locally from the Lenham Beds or the 'Sand in Clay-with-flints', less than 10 miles from Ashford. The ore was roasted before smelting, possibly in the shallow, rounded features near the furnaces at the perimeters of the workshops. Charcoal, predominantly oak, was used as a fuel. The waste produced was largely tap slag with some furnace slag, including fuel-rich lumps and large, bowl-shaped furnace bottom slags. The ore contained variable, but significant quantities of phosphorus, which led to the production of smelting slag with a characteristically high phosphorus content. The products of smelting were probably blooms of iron containing varying amounts of phosphorus, from ferritic (low-phosphorus) to phosphoric iron (high-phosphorus). The potentially greater hardness of the latter meant that it was selectively utilised for certain objects, such as tools, in this period, in much the same way as steel was used.

The blooms of iron produced were probably smithed into large billets for trade, since a billet of 4.5 kg was found at the site. Very few iron objects were recovered, other than nails. The by-products of the smithing operation were hammerscale and smithing hearth bottom slags. Quartz-rich material, likely to be vitrified, siliceous hearth lining, adhered to many of the hammerscale flakes and spheres, although another possibility is that this quartz-rich material is a siliceous flux that was used by the smith. Fuel fragments and larger droplets of fayalitic slag were also observed amongst the hammerscale. The smithing hearth bottom slags probably formed from the reaction of these components: hammerscale, quartz-rich material, fuel ash and slag. They had slightly higher phosphorus and manganese contents than most smithing slags from other sites for which data was available. This is consistent with the conclusion that the Westhawk smithing slags were by-products of primary smithing and therefore contained a proportion of slag from the bloom, containing elevated levels of phosphorus and manganese. The size of the smithing hearth bottom slags varied greatly, even when comparing material from one workshop, from 0.2 kg up to 4 kg. The different sizes and shapes may have resulted from different stages and types of smithing operation and possibly multiple periods of hearth use.

The total quantity of ironworking waste on the site was estimated at 29 tonnes. The amount of refined iron produced over the lifetime of the site was estimated as a minimum of 2.7 tonnes (equivalent to 600 billets of 4.5 kg each). A minimum of approximately 38 tonnes of ore would have been consumed with a minimum of 250 tonnes of wood (38 tonnes of charcoal). These figures are likely to be underestimates as some slag was probably removed from the site in the past for reuse, for example for road metalling, and the efficiency of the smelting and smithing processes, based on the results of experimental archaeology, may have been underestimated.

Unlike other types of metal ore, which are found only in certain regions, sources of iron ore can be found across the country. However, the intensity of iron production in the Weald, with a large number of smelting sites, some of them operating on a vast scale, is unparalleled elsewhere in Britain during this period. Cleere concludes that the scale of the Wealden iron production in this period exceeded the iron consumption of the military and civilian markets in Britain and suggests that a considerable proportion of the iron produced was traded outside Britain, for example to Gaul and the army of the Rhine (Cleere and Crossley 1985). Iron was traded widely both within the province of Britannia and in adjacent provinces of the Roman Empire. Therefore the proximity of the Wealden smelting sites to ports and the proposed involvement of the *Classis Britannica*, in facilitating transport of the iron produced, may have been very important to the development of the Wealden iron industry.

FUTURE WORK

Despite the Weald being a major producer of iron in this country in the Roman period, virtually no analyses of bloomery smelting slag from the region could be found in the literature. Siderite, a carbonate of iron, was not smelted at Westhawk Farm, but it is likely to have been smelted at sites across much of the region and some compositional data on this ore were available. These data indicated that the roasted ore generally contains significant levels of lime, phosphorus oxide and some magnesia and may therefore have resulted in slag by-products with characteristic compositions also rich in lime, phosphorus oxide and magnesia. To date, the author has analysed bloomery slag samples, thought to be Roman, from only two additional locations in the Weald; a smelting site at Far Blacklands (TQ45153810) and a road at Holtye (TQ46253884), both near East Grinstead, Sussex. The slag from the former site contained about 6% lime by weight, 2.5% magnesia and 0.9% phosphorus oxide, suggesting that siderite was smelted at Far Blacklands. The slag samples from the road at Holtye contained about 1% magnesia, 1.2% lime and 1.1% phosphorus oxide, which suggests that an alternative ore to siderite may have been smelted to produce this slag. A programme of analyses of bloomery slag from smelting sites across the Weald would enable regional variations in slag compositions to be established and potentially liked to the local geology and ore sources.

TABLES OF RESULTS OF ANALYSES

Table 7.15 Composition of furnace linings, measured by EDS, normalised (see also Fig. 7.3 above).

Context	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
1332	0.00	0.28	8.54	83.07	0.94	0.11	1.35	0.53	0.89	0.04	4.03
	0.16	0.65	11.35	80.65	0.77	0.06	1.52	0.44	0.77	0.03	3.31
	0.00	0.33	7.14	86.13	0.64	0.12	1.16	0.52	0.74	0.01	2.95
1225	0.00	0.55	10.74	82.39	0.25	0.22	1.09	0.27	0.95	0.07	3.43
	0.00	0.48	9.89	83.14	0.13	0.14	1.12	0.34	0.93	0.03	3.51
	0.00	0.58	9.36	83.49	0.22	0.30	1.16	0.34	0.92	0.03	3.36

Table 7.16 Composition of ore samples, measured by XRF, normalised (see also Fig. 7.6 above).

Context	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
1332	7.98	32.83	0.41	0.36	0.28	0.16	0.28	0.55	57.16
	3.69	62.37	0.28	0.24	0.06	0.09	0.10	0.22	32.94
	18.24	6.10	3.43	0.36	0.20	0.45	0.27	1.77	69.18
	7.76	43.06	0.44	0.24	0.49	0.13	1.37	0.24	46.25
	8.49	31.62	1.46	0.24	0.26	0.24	0.32	.45	56.92
	6.78	21.38	0.63	0.60	0.10	0.17	0.28	0.64	69.40
	2.41	29.49	0.49	0.00	0.00	0.12	0.00	0.27	67.22
	2.26	28.54	0.51	0.00	0.00	0.10	0.00	0.32	68.27
	2.03	47.37	0.33	0.00	0.00	0.07	0.00	0.40	49.79
841	3.47	7.81	1.67	0.00	0.00	0.20	0.00	0.29	86.56
17	5.35	24.66	0.22	0.00	0.11	0.22	0.00	0.33	69.13
502	2.50	45.35	1.00	0.00	0.00	0.26	0.00	2.68	48.20
1460	13.03	22.69	0.50	0.00	0.00	0.59	0.00	3.15	60.04
198	2.15	32.46	0.28	0.00	0.00	0.05	0.00	0.27	64.78
802	2.44	5.17	0.43	0.00	0.00	0.13	0.00	0.49	91.34
1548	1.58	2.19	0.91	0.33	0.01	0.20	0.00	0.57	94.21
	6.63	14.23	0.26	0.30	0.23	0.15	0.00	0.46	77.73
	2.04	3.72	0.75	0.00	0.00	0.24	0.19	0.83	92.24
	1.94	3.32	0.94	0.00	0.00	0.17	0.20	0.49	92.94
1356	1.33	2.85	0.17	0.44	0.03	0.10	0.00	0.26	94.82
	0.47	0.86	0.80	0.30	0.00	0.21	0.00	0.74	96.61
1265	4.35	34.01	0.97	0.00	0.11	0.30	0.29	0.53	59.44

Table 7.17 Composition of tap slags, measured by EDS, normalised (see also Fig. 7.7 above).

Context	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
1332	0.90	0.47	5.95	25.65	1.72	0.00	0.31	2.83	0.08	0.58	61.22
	0.56	0.39	6.15	25.31	2.18	0.19	0.48	2.53	0.38	0.54	61.20
	0.46	0.47	6.80	26.15	1.87	0.15	0.33	2.37	0.38	0.73	60.29
	0.19	0.22	7.23	27.23	2.07	0.00	1.37	2.78	0.39	0.57	57.66
	0.72	0.45	6.74	27.97	1.84	0.12	1.14	2.59	0.42	0.50	56.94
319	0.00	0.42	5.62	23.92	1.34	0.07	0.68	1.49	0.34	0.52	65.60
	0.85	0.02	13.76	28.51	6.05	0.55	6.05	8.94	0.41	0.16	34.69
	0.13	0.48	7.41	24.73	1.69	0.14	1.20	2.25	0.23	0.43	61.31
	0.00	0.49	7.21	24.61	1.83	0.06	1.35	2.36	0.22	0.52	61.35
	0.33	0.43	7.12	24.98	1.77	0.17	0.18	2.27	0.28	0.45	62.02
	0.00	0.55	6.36	25.33	1.51	0.08	0.97	1.93	0.31	0.47	62.48
480	0.24	0.33	5.35	24.64	2.73	0.12	0.15	2.70	0.30	0.31	63.12
	0.15	0.33	5.98	23.53	3.10	0.29	0.38	2.79	0.19	0.27	63.00
	0.00	0.41	5.64	22.25	1.59	0.34	0.41	1.51	0.08	0.35	67.43
	0.09	0.52	5.53	19.93	1.04	0.02	0.08	0.97	0.20	0.36	71.26
	0.00	0.35	9.32	19.88	1.90	0.15	0.83	1.97	0.15	0.34	65.11
	0.00	0.39	5.75	20.62	1.39	0.10	0.49	1.45	0.12	0.38	69.31

Table 7.18 Composition of furnace bottom slags, measured by EDS, normalised (see also Fig. 7.9 above).

Context	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
1225	0.08	0.25	4.03	21.79	0.61	0.06	0.73	1.54	0.24	0.23	70.42
	0.34	0.15	5.21	23.59	1.07	0.00	1.09	1.93	0.29	0.24	65.74
	0.05	0.13	4.16	23.02	0.76	0.00	0.80	1.57	0.19	0.16	68.91
	0.25	0.00	3.70	22.67	0.82	0.14	0.82	1.72	0.23	0.14	69.25
	0.00	0.26	4.95	27.22	0.74	0.05	0.66	1.55	0.17	0.20	63.85
1510	0.30	0.28	5.34	27.13	0.91	0.21	0.93	2.04	0.29	0.10	62.14
	0.11	0.40	4.17	20.19	1.05	0.15	0.81	1.99	0.28	0.12	70.38
	0.23	0.25	4.71	18.23	1.17	0.34	0.78	2.15	0.29	0.11	71.66
	0.05	0.40	3.73	19.61	0.91	0.18	0.32	1.02	0.05	0.03	73.55
	0.00	0.47	2.84	17.14	0.90	0.21	0.44	1.22	0.06	0.01	76.33
	0.06	0.58	2.74	18.95	0.68	0.00	0.27	1.15	0.10	0.04	75.12
	0.17	0.53	3.38	20.93	0.73	0.29	0.46	1.41	0.13	0.14	71.46

Table 7.19 Composition of slags within the bloom fragment from context 1333, measured by EDS, normalised (see also Fig. 7.10 above).

Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
0.24	0.42	2.11	11.71	3.53	0.17	0.86	1.29	0.05	0.24	79.38
0.20	0.49	1.82	7.01	7.25	0.45	0.52	1.20	0.09	0.25	80.72
0.00	0.30	1.40	6.61	5.02	0.27	0.12	0.86	0.13	0.28	85.02
0.00	0.79	1.79	20.99	10.44	0.25	1.19	1.60	0.04	0.49	62.41
0.00	0.51	2.72	15.01	8.62	0.45	0.85	1.88	0.12	0.42	69.40
0.11	0.54	2.68	15.72	9.08	0.66	1.09	1.90	0.11	0.42	67.68

Table 7.20 Compositions of slag inclusions sampled from billet (SF905, context 7009), measured by EDS and normalised (see also Fig. 7.12 above).

Area (μm^2)	Type	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
22494	Fayalite and glass	0.32	1.07	4.07	0.16	0.06	0.12	0.46	0.08	0.25	93.41
14276		0.31	1.50	6.69	0.31	0.06	0.25	0.74	0.11	0.30	89.74
28500		0.42	2.56	14.60	0.67	0.20	0.56	1.53	0.14	0.31	79.00
1666	Wustite, fayalite and glass	0.82	4.59	25.73	1.39	0.63	1.22	3.53	0.34	0.99	60.77
1980		0.77	4.83	26.61	1.32	0.67	1.35	3.69	0.20	1.00	59.55
7548		0.66	3.86	19.96	0.50	0.21	1.01	2.78	0.33	0.81	69.88
1360		0.69	4.31	21.46	1.43	0.81	0.75	2.72	0.29	0.80	66.73
1218		0.73	4.86	26.28	1.06	0.47	1.25	3.68	0.25	0.97	60.46
68400	Glass only	0.84	5.30	30.13	0.70	0.32	1.44	4.12	0.46	1.23	55.46
31740		0.89	5.34	30.50	0.87	0.48	1.49	4.25	0.47	1.26	54.45
15755		0.92	5.26	31.14	0.84	0.45	1.50	4.30	0.43	1.28	53.88

Table 7.21 Composition of various components of the hammerscale deposit from structure R, measured by EDS, normalised.

Area	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
Flake plus adhered quartz-rich region	0.3	4.7	24.6	2.0	0.3	0.4	1.5	0.1	0.0	66.0
Flake (bulk)	0.1	0.6	1.2	0.1	0.0	0.0	0.1	0.1	0.0	97.8
Flake matrix (point analysis)	0.3	2.5	6.0	2.6	0.3	0.2	0.5	0.0	0.0	87.6
Sphere (bulk)	0.3	2.0	11.4	2.7	0.2	0.4	1.0	0.1	0.1	81.8
Adhered quartz-rich region (bulk)	0.3	3.9	32.1	2.4	0.6	0.3	1.3	0.3	0.2	58.6
	0.2	2.8	41.8	3.3	0.3	0.3	1.5	0.2	0.2	49.3

Table 7.22 Composition of various areas of the small smithing hearth slag from context 1257, measured by EDS, normalised (see also Fig. 7.13 above).

Mini SHB	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
Top layer (bulk)	0.22	0.22	3.21	25.39	1.02	0.45	0.31	0.76	0.10	0.00	67.89
Top layer matrix (spot analysis)	0.39	0.35	4.14	11.66	0.24	0.44	0.26	0.47	0.09	0.29	79.86
3rd layer – high wustite (bulk)	0.17	1.03	2.56	16.64	0.95	0.00	0.77	2.71	0.27	0.36	74.13
4th layer (bulk)	0.37	1.29	4.23	25.53	1.56	0.15	2.29	5.43	0.24	0.32	58.41
	0.36	1.14	4.33	25.62	1.14	0.00	2.17	5.16	0.30	0.27	59.40

Table 7.23 Composition of different regions of the thicker end of the large smithing hearth bottom slag from context 1332, measured by EDS, normalised (see also Fig. 7.13 above).

1332 Large SHB	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	FeO
Top layer	0.00	0.51	7.31	28.70	1.19	0.33	0.00	2.72	0.24	59.01
Porous 2nd layer	0.23	0.49	7.02	24.54	1.46	0.29	1.32	4.41	0.36	59.78
Different areas above boundary	0.00	0.40	6.11	23.84	1.09	0.67	1.07	2.57	0.27	63.72
	0.29	0.61	7.02	28.94	1.72	0.13	1.65	6.51	0.35	52.34
	0.00	0.00	15.28	34.65	3.34	0.13	12.03	4.17	0.46	29.43
Below boundary	0.34	0.41	7.30	30.08	1.64	0.16	1.84	4.78	0.37	53.09
Base	0.52	0.85	3.91	29.74	0.92	0.16	1.14	2.84	0.33	59.56

Table 7.24 Composition of different regions of the thinner end of the large smithing hearth bottom slag from context 1332, measured by EDS, normalised (see also Fig. 7.13 above).

1332 Large SHB	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
Top layer	0.22	0.48	5.12	32.66	0.93	0.12	0.72	0.66	0.29	0.11	58.62
Upper half	0.23	0.51	7.68	26.48	1.41	0.06	1.86	6.08	0.28	0.20	55.10
Lower half	0.04	0.49	6.88	28.35	1.33	0.52	0.69	2.99	0.38	0.06	58.24
Base	0.15	0.38	4.59	23.39	0.87	0.37	0.02	1.22	0.34	0.27	68.24

Table 7.25 Composition of different regions of medium-sized smithing hearth bottom slag from context 1225, analysed by EDS, normalised (see also Fig. 7.13 above).

1225 SHB	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
Top quartz-rich layer	0.00	0.43	15.94	50.56	1.44	1.64	0.26	2.46	1.25	0.04	25.98
2nd layer	0.22	0.48	6.81	24.52	2.20	0.16	0.88	2.40	0.16	0.33	61.83
2nd layer	0.01	0.50	7.29	23.63	2.17	0.28	0.50	2.06	0.13	0.30	63.13
2nd layer	0.00	0.33	9.76	26.61	2.59	0.20	0.00	1.27	0.25	0.29	58.69
Quartz-rich area	0.00	0.27	7.42	77.60	0.91	0.32	1.17	0.47	0.47	0.02	11.34
3rd layer	0.00	0.48	4.18	17.85	1.52	0.07	0.28	1.37	0.13	0.40	73.73
Final layer	0.01	0.50	4.97	18.85	1.91	0.12	0.60	1.97	0.21	0.29	70.58

Table 7.26 Composition of different regions of medium-sized smithing hearth bottom slag from context 1332, analysed by EDS, normalised (see also Fig. 7.13 above).

1332 SHB	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	FeO
Quartz-rich top layer	0.00	0.36	3.93	22.08	0.78	0.29	0.46	0.81	0.22	0.10	70.97
2nd layer fayalitic region	0.00	0.78	5.97	24.20	1.13	0.09	0.81	2.90	0.33	0.29	63.50
2nd layer porous region	0.00	0.19	0.61	2.95	0.24	0.27	0.05	0.56	0.05	0.02	95.05
3rd layer quartz-rich clay	0.01	0.53	7.02	52.14	0.13	0.61	0.94	0.45	2.39	0.00	35.78
3rd layer fayalitic region	0.23	0.74	6.04	24.47	1.11	0.09	1.52	3.78	0.32	0.21	61.47
4th layer porous	0.00	0.11	1.73	6.48	0.24	0.43	0.06	0.82	0.04	0.09	90.00
Base bulk fayalitic	0.00	0.47	6.86	24.47	1.42	0.17	1.18	3.57	0.35	0.22	61.31