EXCAVATION OF A ROMAN BLOOMERY FURNACE AND TAPPING PIT AT BRADENHAM

GARY MARSHALL, WITH CONTRIBUTIONS
FROM PAUL BOOTH, STEVEN CRABB & PAUL GREEN

Aerial survey, followed by geophysical survey, has led to the discovery of an important iron-smelting furnace and tapping pit in an arable field at Bradenham. Excavation has confirmed the sunken shaft furnace to be in an unusually good state of preservation, with the structure surviving to a height of 0.7m. Significant amounts of slag totalling 163.75kg were recovered by half-sectioning of the tapping pit. Evidence from radio-carbon dating and from a handful of pottery sherds recovered from the fill of the tapping pit suggests a late Iron Age or early Roman date for the operation of the furnace, which is probably the most complete example to have been located in the Chilterns. Analysis of slag samples suggests this to have been an efficient furnace, operating at high temperatures, and capable of extracting a significant amount of iron oxide from the ore.

Introduction

Attention had first been brought to this particular arable field on the National Trust's estate in Bradenham parish following an aerial photographic survey carried out by members of the Risborough Countryside Group (RCG). Cropmarks in a field immediately north of the A4010 were thought to warrant further investigation by means of geophysical surveys. Whilst these proved to be of limited assistance in further interpreting the cropmarks, an informal walkover did identify a dense concentration of iron slag towards the centre of the field (grid ref. SU 8198 9782). A magnetic gradiometer survey of an area measuring 40 x 40m was undertaken by the National Trust (April 2014), assisted by RCG members. A strong anomaly discovered at the centre of the survey hinted at a possible source for the slag and in the autumn of 2015 members of the RCG's Archaeology Team were invited by the Trust to open an evaluation trench over the anomaly. The site is cultivated annually, posing real threats to potential in-situ archaeological remains. The site was hand-excavated and all of the spoil was sieved through a 1cm^2 sieve.

Subsequent analysis of slag samples recovered from the site was undertaken by Steven Crabb of Hertford College, Oxford University, as part of his thesis into the production of iron in the Iron Age and Roman periods of Southern Britain. The author is grateful for the contribution the analysis has made to understanding the technology of the Bradenham furnace. A copy of his report is included in this article.

Topography and archaeological background

The excavated site lies in the centre of an arable field, 180m north of the A4010 and 400m south-east of the Clare Charity Centre. The field occupies a gentle south-facing slope and the excavation lies on a slight plateau running east-west across the slope (Fig. 1). About 900m to the north lies Park Wood, incorporating the site of Bradenham's Tudor deer park. Earthwork remains of the park pale survive. The National Trust's archaeological survey of the Bradenham estate (Matthews & Wainwright 1990) identified several surface concentrations of iron slag overlying earlier plough lynchets within the woods at Bradenham (SU 8300 9790 and SU 8340 9735), suggesting smelting may have taken place on the slopes immediately north of the current excavation. Several large trees growing in close proximity to these concentrations were toppled by the 1991 gales and late Iron Age and Romano-British pottery was recovered from the root plates, suggesting a possible date for the smelting. Production of iron in these woods may well have continued into the medieval period, as iron slag has also been recovered from earthworks in Park Wood, forming the so-called 'Homestead' site (SU 8264 9815). This scheduled site has been roughly dated to the 13th/14th century by the recovery of pottery (Cookson 1973).

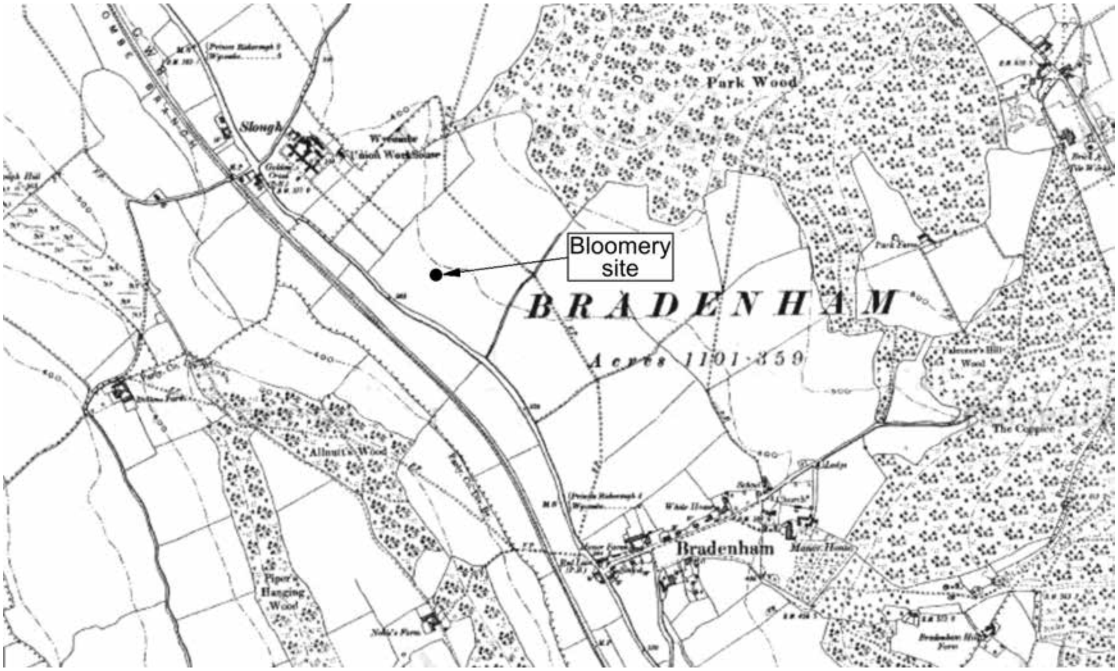

FIGURE 1 Site location

METHODOLOGY

In order to evaluate the magnetic anomaly identified from the geophysical survey a 2m square trench was initially laid out over its centre. Removal of plough soil to a depth of 0.25m led to the discovery of the top of the furnace shaft and the outlines of the associated tapping pit (Fig. 2). Subsequent enlargement of the trench confirmed the full outline of the pit, measuring 2.55m at its maximum length (north-east to south-west) and 2.15m at its maximum width (south-east to north-west). The fill of the furnace shaft was fully excavated using a small modelling tool working to arm's length, at which point the base was thereafter exposed by exploiting an existing entry point from the floor of the tapping pit. The tapping pit was half-sectioned, the western half of the fill of the pit being left in-situ. After excavation the pit and shaft were backfilled to preserve both features for possible future examination.

Excavation of the furnace

The furnace survived in an excellent state of preservation below the plough zone, comprising several concentric zones of fired clay forming the lining to an oval cut (1002) in the natural reddish-orange clay measuring 0.8 x 0.65m. This natural clay (1004) was noted to be strongly heat-affected adjacent to the furnace and hence coloured to a darker reddish colour. The clay linings (Figs 3 & 6) exhibited variations of width and gradations colour, reflecting the intensity and phases of heating within the furnace. 1005 formed the outermost lining, measuring between 70 and 100mm in width, fired to a creamy yellow/brown colour. This encircled 1006, fired to an orangey terracotta colour and measuring between 20 and 50mm in width. 1006 in turn encircled the two innermost clay linings, each up to 25mm in width (1010 and 1011) and grading in colour from mid orange (outermost) to light buff, deep red and light grey (innermost). A slight dark line between 1010 and 1011 suggested the division between these two phases of lining. The exposed internal surface of 1011 was noted to have a glassy vesicular texture, resulting from the final firing of the furnace.

The clay lining extended to a depth of 0.7m, measured from the truncated upper surface to the interior of the rounded base (Fig. 4). The interior had a D-shaped plan at its mid-point (Fig. 3), but in cross section was slightly narrower at its top where it measured 320 x 190mm before bellying out at

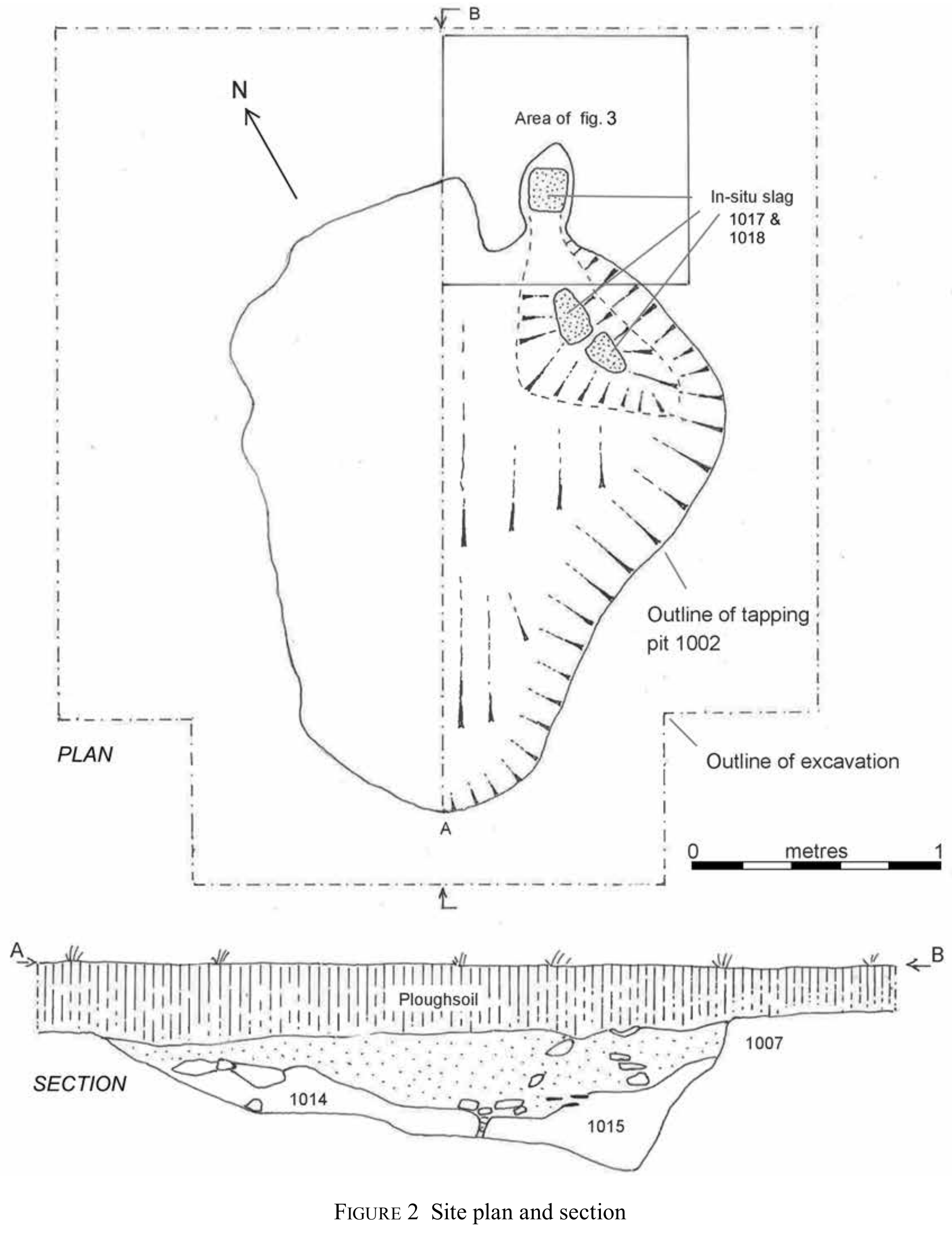

FIGURE 2 Site plan and section

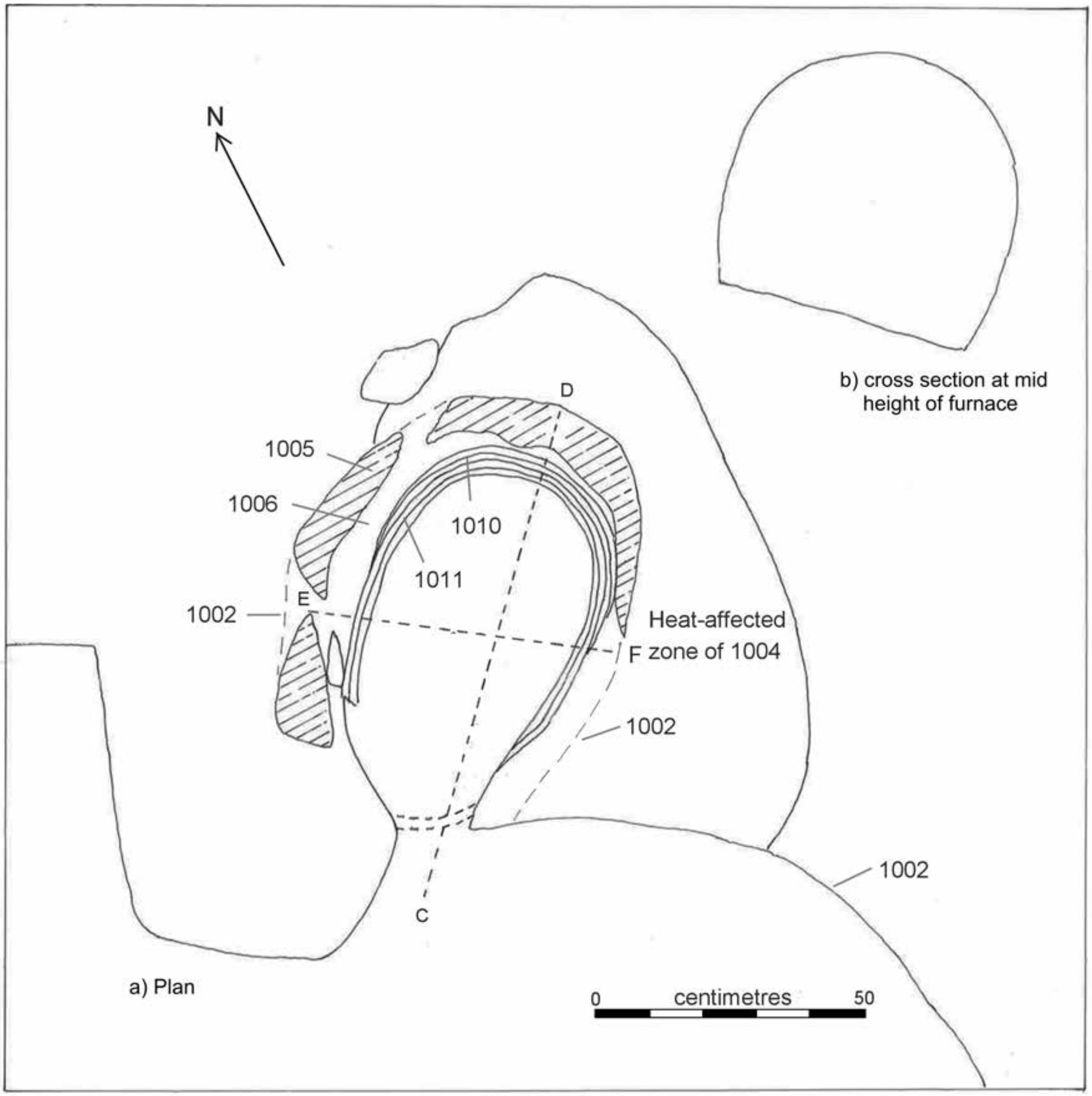

FIGURE 3 a) plan of bloomer; b) mid-height cross-section of furnace

its mid-point to 250 x 265mm. The base of the shaft narrowed to form a shallow, rounded bowl. The shaft tapered across both axis but displayed a slightly shallower angle to the back wall, with a slight step at its mid-point (Fig. 4). Very little of the front wall survived as it had been knocked through at the base to extract the last iron bloom. Unfortunately this removed the 'tuyère' or opening where the bellows would have passed through the front wall to provide the blast. Below the tuyère a tapping arch would have provided the means of draining out the waste molten slag during smelting. However, this was also removed when the furnace was knocked through to extract the iron bloom.

After its final use the furnace shaft was backfilled, consistent with the deposits used as backfill in the adjacent tapping pit. The uppermost deposit (1009) was a 0.1m thick mid reddish-brown heat-affected clay containing occasional small flints and a small amount of slag. It was found to

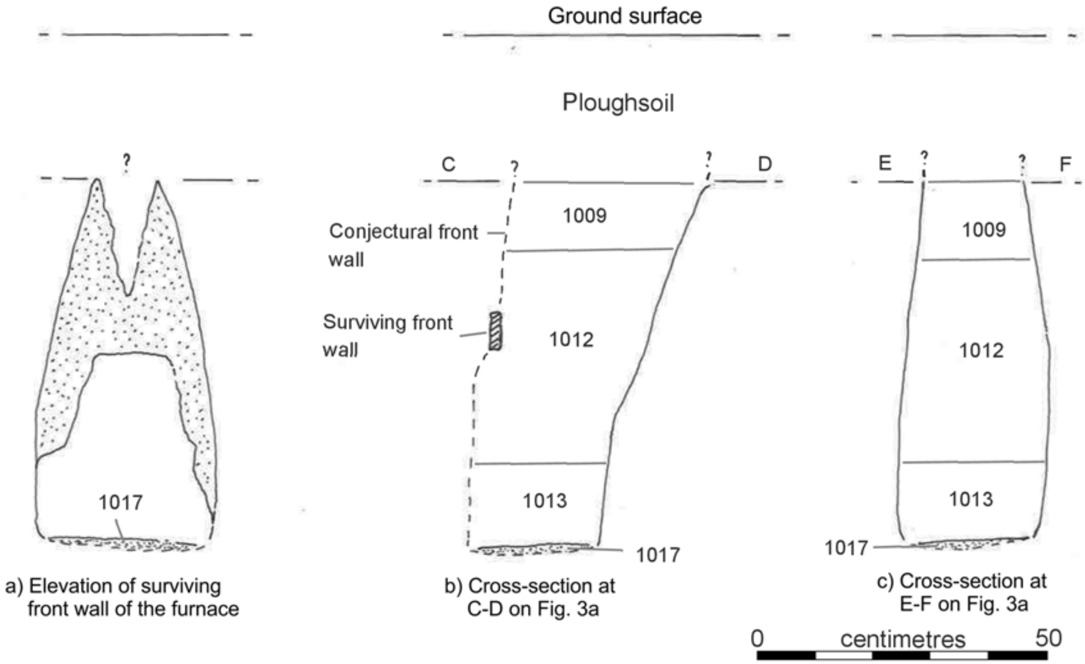

FIGURE 4 Elevation and cross-sections of furnace

equate with the upper backfill of the tapping pit, (1007). Beneath this was a second 0.32m-thick layer of red heat-affected sandy clay (1012), with inclusions of fragmented furnace lining. Beneath this was a 0.2m-thick compacted dark red clay (1013) with a lumpy consistency, containing pieces of slag up to 0.06 x 0.08m in diameter. At the bottom of the furnace shaft, (1017) comprised a thin black layer of charcoal and slag overlying a 'plug' of congealed slag. This appears to be the residue from the last operation of the furnace and was sampled and retained for radiocarbon dating. The bottom of the shaft was formed by the natural reddish-orange clay (1004).

Excavation of the tapping pit

The pear-shaped 'tapping pit' (1002) became apparent after the removal of the plough soil revealed a grey silty clay (1007) filling the outline of the top of the pit (Figs 2 & 5). It formed a south-westerly extension of the cut into the natural clay for the furnace shaft, measuring 2.55m in length and 2.15m in width at its widest point, narrowing to 1.2m in width before eventually tapering at its southern end. The pit was shallowest at its tapered southern end, measuring 0.07m in depth, but increasing to 0.65m close to the front wall of the furnace shaft. Subsequent ploughing had removed the upper part of the pit, so its original depth would have been slightly greater than that recorded. It was probably first excavated to obtain clay for lining the furnace before being extended in depth at its north-east end to accommodate the furnace. An irregular-shaped scoop cut into the base of the pit in front of the furnace allowed for the accumulation of tapped slag. This is shown by the dotted line on Figure 2. The pit appeared to have been lined throughout with clean clay, 0.02-0.03m thick (1019).

After the furnace had ceased operating the pit also seems to have been deliberately backfilled. Context 1007 comprised a layer of decayed clay derived from the furnace structure, containing large amounts of slag (130kg recovered from the excavated half of the pit), charcoal, large flint nodules and bone. Also present were broken pieces of furnace wall lining (20.5kg recovered from the half-section). Five sherds of pottery were found in this context. Beneath this, context 1014 occupied the base of the southern half of the

FIGURE 5 Furnace, looking north

pit, comprising a greyish–brown clay containing more charcoal than 1007, thus giving the context a darker colour. It was probably directly associated with the operation of the furnace, rather than constituting backfill. It also contained flint, bone, slag (5.5kg), and a single sherd of pottery. At the northern end of the pit, beneath 1007, lay several layers of heat-affected sandy clay 0.35m thick, clearly originating from the operation of the furnace. Extending into the recorded section, 1015 comprised a reddish-orange clay. This abutted 1016, a yellowish-orange coloured clay, silkier in texture than 1015, occupying the eastern half of the northern end of the pit. Both contained inclusions of small pebbles, rounded flint nodules, charcoal and 5.25kg of slag. Beneath this and in front of the furnace in the shallow scoop of the pit was a black deposit (1018) of charcoal and slag. This was clearly the remains of the very last firing: it included a solidified run of molten slag from the base of the furnace (Fig. 2).

THE POTTERY

by Paul Booth (Oxford Archaeology)

Six small Roman sherds, with a total weight of 30g, were examined, from two contexts (1007 and 1014). Broad fabric codes in the Oxford Archaeology recording system were assigned. The fabrics thus identified were:

O10. Fine oxidised ware. 1 sherd, 3g. A small out-sloping rim, probably from a bowl with an upright neck (but possibly a jar).

R20. Fairly coarse sand-tempered reduced ware. 2 sherds, 6g. One out-curving thickened rim, probably from a small jar.

R30. Medium, densely sandy reduced ware. 2 sherds, 17g. One (13g) is a rim sherd from a beaker with an angled everted rim, possibly a form derived from a butt-beaker.

R90. Coarse grog-tempered ware. 1 sherd, 4g.

FIGURE 6 Detail of furnace

None of the fabrics can be assigned with confidence to a known source. The nearest known production sites in the region appear to be those of the Fulmer-Hedgerley complex, located roughly 18km to the south-east, while a further possible kiln site was at Nettlebed, c.16km to the south-west. Both sites produced sandy reduced coarse wares, but it is not certain that these were matched in the present material, none of which is very diagnostic. In broad terms a later 1st to 2nd-century date seems likely, but only the rim sherd in fabric R30 can be confidently assigned to this date range.

All the sherds except the rim fragment in fabric R20 were from context 1007. There is insufficient material to allow identification of any possible difference in date between the two contexts.

Slag Analysis
by Steven Crabb

A sample of the slag recovered from this site was taken for scientific analysis at the University of Oxford as part of a wider PhD thesis into the transition in the production of iron from the Iron Age into the Roman period. The slag was analysed using a series of complementary analytical methods. The combination of macromorphological, micromorphological and chemical analysis with the archaeological evidence makes it possible to reconstruct the smelting activity that was carried out on this site.

Macromorphological analysis records the form of the slag as it solidified and therefore provides a snapshot of how the furnace was operating. There are two main types of slag, that which was removed from and that retained within the furnace. Slag retained within the furnace can have imprints of the shape and size of the furnace structure. Slag removed from the furnace is often (but not always) smaller than that retained within. The main type of slag which was removed from the furnace is tapped slag which was fluid enough to drain from the furnace.

The micromorphology of the slag is typical of bloomery smelting slag. It is dominated by three main phases; fayalite, wüstite and an interstitial glassy phase. Fayalite is an iron silicate mineral of the olivine group with the composition $2FeSiO_4$. Its form changes depending on the thermal gradient which in the smelting process can be interpreted as the cooling rate of the slag. When cooled rapidly a steep thermal gradient from high to low, the fayalite forms thin needle-like crystals. When cooled slowly with a shallow thermal gradient or where the melt is held at a high temperature the fayalite forms larger, more blocky crystals. Wüstite is the dominant type of iron oxide from these samples with the composition FeO. It takes a dendritic or tree-like form which can also indicate the cooling rate of the slag. A fine skeletal form of wüstite is an indicator of a fast cooling rate as the dendrites rapidly form a thin simple form. The amount of iron oxide present in the slag reflects how efficient the furnace was at reducing the ore to metallic iron. More wüstite present in the slag means less available for the production of iron. The interstitial glass is the remaining matrix which solidifies last and between and around the fayalite and wüstite.

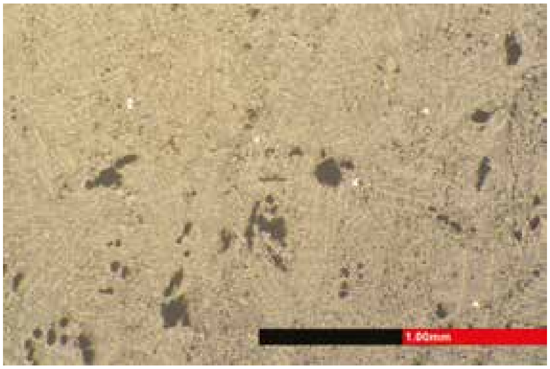

FIGURE 7 BRAD 1007 3, moderate fine wüstite dendrites and metallic prills

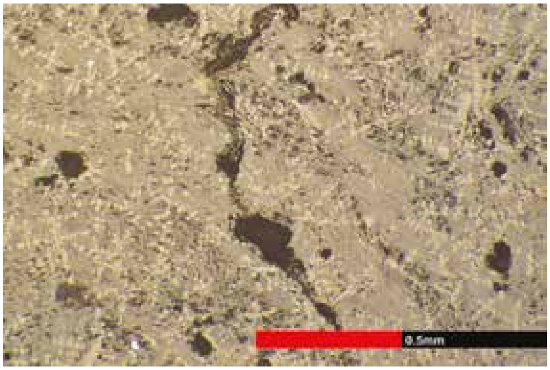

FIGURE 8 BRAD 1007 6, blocky fayalite laths

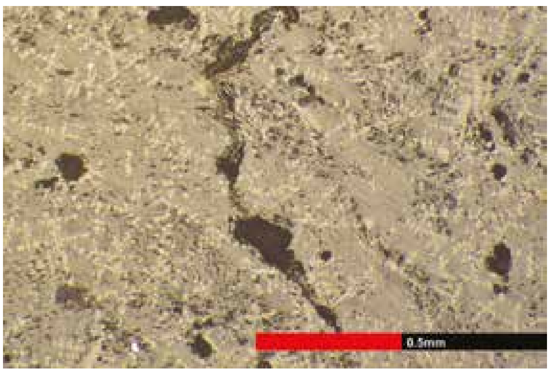

FIGURE 9 BRAD 1018 3, low wüstite levels

The chemical composition of the slag is the result of the inputs to the smelt, the different elements are partitioned into the slag, the metal or burnt off as volatile elements or a combination of these. (Table from Charlton *et al* 2010)

As well as indicating the raw materials which went into the smelt, the composition can also be used to estimate the melting temperatures and viscosity, both of which are very useful for understanding the smelting process. Pure iron can be reduced from its ore to metallic iron at a temperature of c.900°C while it becomes liquid at a temperature in excess of 1500°C. Therefore to separate the metal from the slag it is necessary to have a slag which is fully liquid. The melting temperature is calculated by plotting each sample onto a FeO-Al_2O_3-SiO_2 ternary phase diagram (Fig. 10) with two areas which have an optimum composition plotted (Rehren *et al* 2007). The viscosity of the slag is important for the same reason as a slag which is more liquid will separate more easily from the iron. In a slag tapping furnace then the slag has to be fluid enough to be tapped from the furnace and travel away from the furnace before solidifying. The viscosity of the slag was calculated using the Algoness slag calculator (Algoness.co.za). As well as the melting temperatures and viscosities of the slag (Fig. 11) the amount of reducible iron which remains in the slag will also be calculated using Charlton's reducible iron index (RII) method (Charlton 2007). When the RII is above 1, then the furnace was less reducing leading to more iron oxide remaining in the slag: below 1, more of the iron was removed from the slag indicating it was more reducing.

The slag for this study was selected from the representative assemblage retained post-excavation. The assemblage was characterised to give a wide view of the smelting process. The samples were cleaned and the macromorphological characteristics were recorded.

The macromorphological analysis of the slag from this site shows that it was a slag-tapping furnace where the slag was drained from the furnace in a liquid state during the smelt to stop the build-up of slag blocking the air flow into the furnace. This slag is identifiable by evidence of liquidity and flowing on the surface of the slag. Often this takes the form of a ropey surface, but it can also take the form of a smooth flat surface where the slag is very liquid. The underside of this type of slag takes an impression from what it has flowed. In rare occasions tap slag can be found in-situ at the front of the furnace in the channel

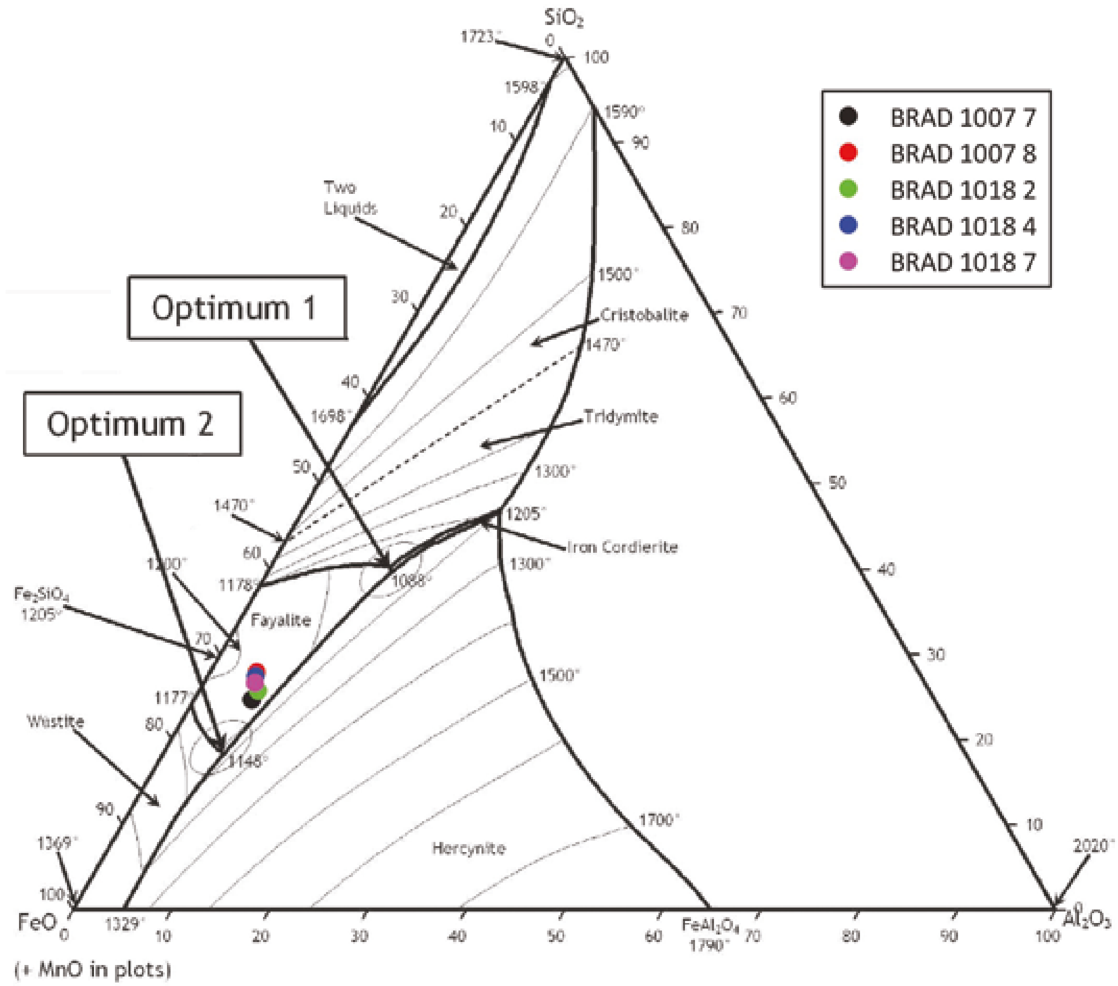

FIGURE 10 BRAD samples, plot of iron, aluminium and silica oxides ($FeO-Al_2O_3-SiO_2$)

where it was tapped from the furnace. This is the case at this site, and while this mass was left in-situ when the site was backfilled an essentially identical mass was identified from the deposit of discarded slag.

The macromorphology showed that this furnace was using slag-tapping technology to produce slag on a small scale, but at least two separate smelting events took place at this site.

The microstructure of the slag from this site is dominated by fayalite in lath and blocky lath form: most of the samples have a low level of wüstite with a small number having moderate levels. The lath fayalite indicates that the slag cooled rapidly over a short thermal gradient. As the wüstite dendrites are fine and skeletal in most cases this supports the evidence of rapid cooling from the fayalite. This rapid cooling confirms the macromorphology that the slag was removed from the furnace. The relatively low levels of iron oxide suggest a process which was quite efficient at reducing the ore to metallic iron. The high levels of reducing gases would have had the potential effect of increasing the carbon content of the iron. The removal of the iron oxide from the slag to form more metal increases the viscosity of the slag which would then need to be heated beyond its liquidus to be able to flow from the furnace.

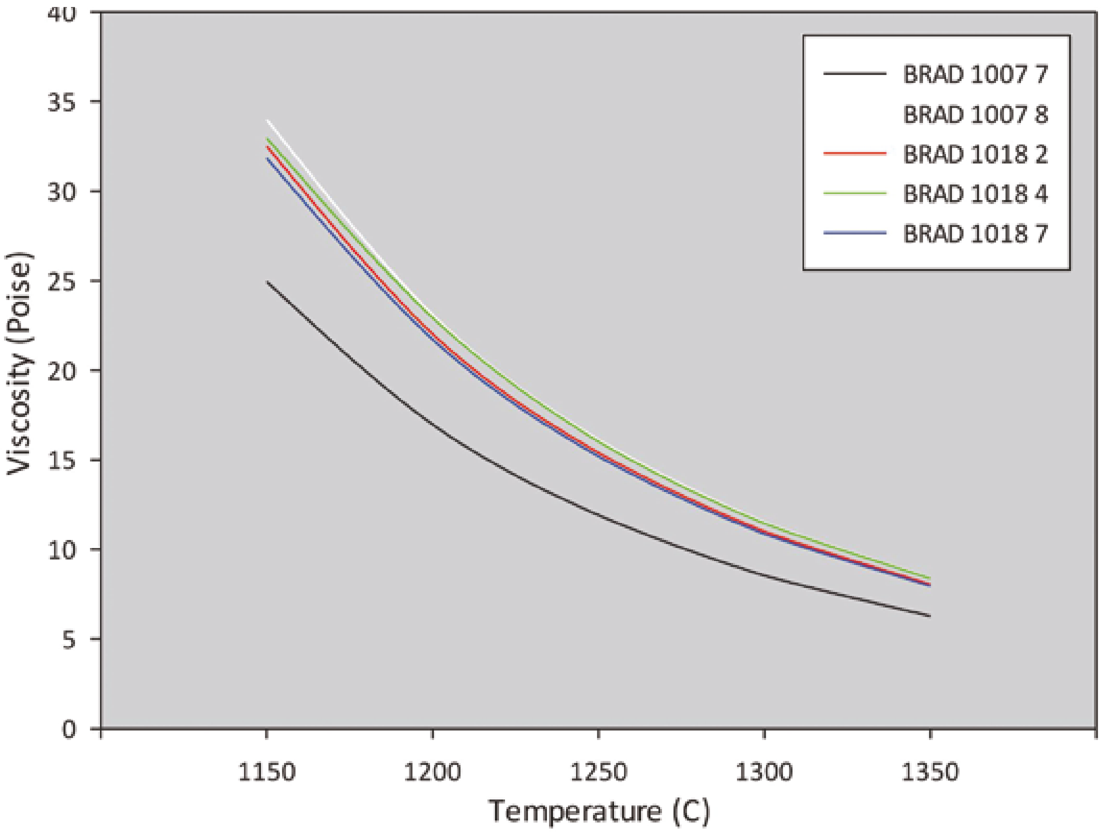

FIGURE 11 BRAD samples, viscosity (Poise) vs Temperature (°C)

Chemical Composition

The samples from this site are very consistent, the largest variation in any one element being only 2%. This suggests a very controlled process both in terms of technique and inputs. The iron level is consistently high around 66%. The phosphorus and calcium levels are both low while the alumina level is elevated suggesting inputs from the furnace lining.

The liquidus temperature of the slag has been estimated to be 1175°C and plotting very closely together. The slag would have become free flowing around 1200°C; sample BRAD 1007 7 would have been free flowing at a lower temperature but this is not due to differences in any one element but minor variations across several. The RII of the slag from this site shows that the smelt had slightly depleted reducing conditions but still was producing a reasonable amount of metal from the ore.

Analysis of the slag from this site indicates that the slag was produced using a slag-tapping furnace. The same furnace was used for at least two smelting events, but the composition and microstructure of the slag indicate that these were almost identical. The samples from different points of the smelt also have very consistent compositions (Table 1), showing that the optimal conditions for the production of iron from this furnace were reached early in the smelt and maintained throughout. This would indicate that the furnace was preheated before the first ore was charged into the furnace and that there was minimal ore and fuel wasted at the start of the smelt. The consistency of composition is shown as the liquidus temperature closely clusters around 1175°C and the viscosity (Table 2) is very similar for all but one of the samples (BRAD 1007 7) which appears to be higher because of the elevated calcium content. All of the samples apart from BRAD 1007 7 would be free-flowing at a temperature of approximately

1250°C. The level of iron oxide present in these samples suggests that a mixed composition bloom was likely produced with some areas being more steely and some more pure. There is some phosphorus within the slag, but it is quite a low level and is unlikely to have affected the metallic product. This site is an isolated smelting site which has remarkable preservation of the furnace remains. The furnace was excavated into the side of a pit, which means that the shaft of the furnace has remained intact. As well as the remarkable preservation of the furnace remains, the pit containing the furnace also contained the slag produced from the smelt, preserving a representative assemblage. The base of the furnace contained an in-situ mass of slag from the last smelt that took place at this site: the form of this mass shows that the slag was being actively tapped through to the end of the smelt. It also reveals that the slag was raked away from the entrance of the furnace once it had solidified. The smelting on this site was consistently less reducing (Table 3), suggesting that the production of a suitably fluid slag was more important than the reduction of a high proportion of the iron from the ore. This site is located in the chalk valleys of the Chilterns, an area which does not have exploitable deposits of iron ore. The nearest possible local source is approximately 10km away in the ridge of Greensand to the north-west (Morris 2009, 2). It is not possible to derive a more focussed location for this ore source from the chemical composition. Therefore this site would have been located for the presence of woodland for fuel and for the superficial clay deposits for the production of the furnace shaft. The scale of production at this site would have been quite small as shown by the size of the

TABLE 1 BRAD compositions

	Na_2O_3	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO	Total
Brad 1007 7	b.d	0.4	5.5	23.3	0.7	1.1	1.7	0.3	0.3	67.4	100.7
Brad 1007 8	b.d	0.4	4.5	26.8	0.6	0.5	0.9	b.d	0.6	66.1	100.3
Brad 1018 2	0.4	0.4	5.6	24.4	0.8	1.0	1.5	0.3	0.8	65.7	100.9
Brad 1018 4	b.d	0.4	4.6	26.4	0.6	0.5	0.9	b.d	0.5	66.4	100.3
Brad 1018 7	0.5	0.4	4.9	25.5	0.7	0.7	1.1	b.d	0.6	66.5	100.7

TABLE 2 BRAD viscosity (poise)

	1150°C	1200°C	1250°C	1300°C	1350°C
BRAD 1007 7	24.95	16.96	11.9	8.54	6.27
BRAD 1007 8	33.99	23.09	16.11	11.51	8.4
BRAD 1018 2	32.51	22.02	15.38	11	8.04
BRAD 1018 4	32.96	22.93	16.01	11.45	8.37
BRAD 1018 7	31.84	21.72	15.18	10.86	7.95

TABLE 3 BRAD RII (all less reducing)

	RII
BRAD 1007 7	0.82
BRAD 1007 8	0.96
BRAD 1018 2	0.87
BRAD 1018 4	0.94
BRAD 1018 7	0.91

furnace and the amount of slag which was recovered. It would likely be in the tens of kilograms, which is a figure which would fit with small-scale local consumption of iron rather than a larger scale production aimed towards trade.

Discussion

The unearthing of such an exceptionally well-preserved sunken shaft furnace at Bradenham sheds light on an important aspect of Chilterns' archaeology which has so far received relatively little attention. Surface scatters of iron slag are widely reported, usually from wooded areas where the absence of ploughing and disturbance has allowed for their survival. These woodland sites usually occupy hilltop locations where the acidic clay and flint is unsuited to cultivation. In addition to the sites mentioned in the introduction, several clusters of slag have been identified on the National Trust's Ashridge estate, where they appear to be associated with late Iron Age and Roman pottery (Wainwright, Marshall & Salkeld 2010). Several dense concentrations of iron slag have been recorded at Pigott's Wood in the Hughenden Valley (Morris 2009). Morris' research has identified 35 iron slag sites in Bucks, mainly to the north and east of High Wycombe (analysis of samples taken from Newsets Wood, Hertfordshire, and Piggotts Wood and Cindry Bottom Wood, Buckinghamshire, appears in Mahoney & Fregni 2009). These are mostly in woodland and often linked to enclosures in the Wye and Misbourne valleys. The association with enclosures appears to be a common theme. Fragments of furnace found by the Chess Valley Archaeological Society within an old enclosure at Common Wood near Penn are likely to have an early origin, as excavations of the enclosure ditch unearthed pottery dating from the late first century to early third century (Zeepvat & Radford 2010). Chance finds of slag and pottery have been recovered from the roots of an upended tree within a suspected Iron Age enclosure on Naphill Common at grid ref. SU 8375 9685 (pers. comm. Trevor Hussey). Excavations by the Berkhamsted & District Archaeological Society at the Cow Roast site between 1972 and 1993 produced in excess of 2 tonnes of iron slag (Zeepvat 1997). Two 'bowl furnaces' were excavated on the Fendley House Orchard site at Cow Roast and dated to the late 2nd to early 3rd century AD (Thompson 2002), and several features were found to contain ash or other burnt deposits which may have originated from smelting or metalworking (Wilson 1975).

Examples of excavated furnaces in the Chilterns are much rarer. There is direct comparative evidence from excavations at Duckmore Lane during the construction of the Tring bypass in 1974, where the bases of two shaft furnaces with tapping pits were revealed (Herts HER 6069). The shafts were lined with red/orange burnt clay 3-4½" thick (0.07-0.12m) and had an internal diameter of 14-16 inches (0.35-0.4m). The Herts HER also records four shaft furnaces found at the Bridgewater School site at Dellfield, Berkhamsted, between 1971 and 1972 (HER 4904). Excavations at Cholesbury hillfort in the 1930s recovered evidence of three similar-sized hearths with fayalite-magnetite slag, probably dating from the 1st century AD (Kimball 1933). A later watching brief (1997) associated with building a stable in the fort recovered over a kilo of slag, plus evidence of two possible hearths adjacent to the area where Kimball had excavated in the 1930s (Bucks County Museum Archaeology Service 1997). In 2013, evidence of a partially surviving furnace was discovered at Coleman's Close, Holmer Green. These excavations revealed the circular base of a furnace shaft consisting of fired clay and flint, c.0.95m in diameter. The base retained the outlines of an in-situ south-west-facing arch, 0.2m in width and 0.1m in height, which would have facilitated the removal of slag (King 2013). Unfortunately it remains undated, the pottery recovered from the locality implying it could be anything from Roman to late medieval.

Also in the Chilterns, excavation of the Romano-British villa estate at Mantles Green, Amersham, in 1983–84, produced 187kg of tap slag resulting from smelting (Yeoman & Stewart 1992). No firm evidence of a furnace was identified, though a roughly circular area of burnt clay and flint produced 13kg of furnace lining, as well as tap slag. The main period of smelting here appears to date to c.AD 160–175, associated with the establishment of the settlement. Smithing activity on the site was evidenced by 140kg of smithing slag. Two types of hearth and furnace lining totalling 63kg were recovered, a high quality refractory lining incorporating a substantial proportion of sand in the clay, and a clay lining containing little refractory material which produced a low density, vesicular structure after vitrification. The former was probably associated with smelting, the latter with smithing.

Beyond the Chilterns but still within Buckinghamshire, large quantities of ex-situ iron slag were found in the fills of ditches during excavations for a gas pipe at Grendon Underwood. According to the authors of the report (Cambridgeshire Archaeology 2006) the ditches may have formed enclosures around the iron-smelting activity. Pieces of furnace lining were also found, including part of the aperture which the authors estimated measured 0.17m in diameter. Evidence for Roman iron-smelting in the form of a tapering gully 33' (10m) in length, leading to an oval pit 7'6" (2.3m) long was found at Salden Wood, Newton Longville, whilst bulldozing topsoil to fill a former gravel quarry used as a municipal tip. The presence of tap slag suggested iron smelting and a 1st to mid-3rd century date was suggested, based on pottery finds (Griffiths & Southernwood 1973). Excavations at the *Magiovinium* site on the edge of Milton Keynes produced 59kg of slag and evidence of several furnaces, though the author considered this as more likely to be associated with smithing rather than smelting (Neal 1987). Comparative evidence of tapping pits comes from excavations at Woburn Golf Club in 2012, where two late Iron Age furnaces were excavated with associated pits. The larger pit measured 3m x 1.5m by 0.7m in depth and was associated with a furnace 0.5m in diameter and 0.52m in depth. The smaller pit measured 1.35m x 1.1m by 0.6m in depth and was associated with a furnace measuring 0.46m in diameter and 0.5m in depth. Clay linings to these two furnaces measured 0.1m and 0.05m respectively (Headland Archaeology 2014).

A note in *Records* (1969) briefly mentions a probable Iron Age furnace pit for smelting iron found at Dundridge in Aston Clinton. The Bucks HER notes this pit was c.0.9m deep and found in a brick-earth pit in 1946. It contained iron slag and ironstone (ore?). The site overlooks the valley called 'Cindrey Bottom' and the note ends by saying 'Quantities of slag are still to be found there and Mr Brackley is having some samples analysed' (the outcome of the analysis remains unknown!).

With the lack of a known local source of iron ore, the obvious question is why was the furnace located here at Bradenham? Three main components are required for the smelting of iron: ore, charcoal, and clay to line the furnace. Two of these components are available at this location. The natural deposit of smooth fine clay used to build the furnace shaft forms an extremely localised post-glacial deposit situated on the crest of the slope running across the field. The large amounts of charcoal required to heat the ore are also likely to have been readily available. Estimates suggest up to 40 tons of wood would have been needed to produce a single ton of iron (Mahoney & Fregni 2009). Charcoal burns at a temperature of 900°C, but with the use of an air blast can reach temperatures of 1600°C. Silica impurities will form liquid slag at 1135°C, but a temperature of 1200°C needs to be achieved for the iron content of the ore to achieve the semi-liquid state at which the bloom will start to concentrate in the belly of the furnace (Sim 2002). Small lumps of charcoal are required to reach the necessary temperatures and it is unlikely that the charcoal was transported over large distances due to its bulk and fragile nature.

This leaves a question over the source of the ore? Buckinghamshire is listed by Tylecote (1963) as one of the English counties without a major ore source. Analysis of the slag from the Mantles Green site showed that it contained up to 10% manganese oxide, indicating a manganese-bearing ore was used. Occasional nodules of iron sulphide can be found on the surface of ploughed fields throughout the Chilterns. These are primary concretions occurring within the chalk due to bacterial action and other processes over geological time. They can be oxidized naturally in the soil once exposed by erosion, or artificially by roasting to reduce sulphur content to the point that it may not be a problem during iron smelting. However, the use of iron sulphide derived ores for ancient iron smelting is not proven. (The author is grateful to Dr Chris Salter of Oxford University for the above and for following guidance on the type of ores suitable for smelting). A more likely source is 'bog ore', hard pan, or podsols which form under similar conditions. These have a high iron content but usually do not have a high enough sulphur content to cause problems for smelting. They develop where iron in solution, from higher in the water table, percolates down to a point where the Eh-pH conditions change, forcing the deposition of the iron oxides and hydroxides, usually where there is more oxygen available. The original source of the iron may be iron sulphide nodules in the chalk, but very often the greensand underlying the chalk.

The underlying geology at Bradenham comprises the Lewes formation of nodular chalk, with overlying clay and flint on the upper parts of the valley slopes. It does not provide an obvious source of ore, though anecdotal evidence suggests nodules of ironstone were found when brick clay was dug nearby in the 1920s at both Brown's and Bristow's brickyards at Walters Ash (pers. comm. Trevor Hussey). A pipeline trench at Haddenham dug in 1980 revealed a pit cut into a surface exposure of ironstone containing Roman pottery (Bucks. HER 04743), suggesting the ironstone forming part of the Lower Cretaceous Whitchurch Sand formation may have been exploited as an ore source. Haddenham lies about 7 miles north of the Bradenham site, making it feasible that the ore could have been carried this distance, either by packhorse or by horse and cart. The ironstones of the Jurassic ridge lie further to the north (Northampton to Banbury and Wroxton) and are probably too distant to have provided a source for the Bradenham furnace. Estimates suggest that in the region of 17 tons of ore were required to produce a ton of iron (Sim 2002). As ore was not recovered from the excavations this might indicate it was roasted at source. Roasting was necessary to dry the ore, to remove impurities and increase the iron content but it would leave the ore brittle, porous and crushable during transport. Possibly the ore was transported to the Bradenham site in its raw state then roasted in a separate ore preparation area. The ore would be too valuable to be wasted and its absence at Bradenham implies it was fully utilised during smelting. No evidence was found for an ore roasting pit, implying this initial part of the process was carried out at source.

Clearly the relationship between ore sources and the location of smelting in the late Iron Age and Romano-British periods needs further study. A review of the evidence relating to the Cow Roast site at Northchurch (Thompson 2015) suggests that Akeman Street could have been used to carry ore from the site as far as Colchester. Catt *et al* (2010) are uncertain whether local deposits would be sufficient, considering that a 'more likely' source would be the ironstones of the Woburn Sand Formation of south Bedfordshire, 30km north and north-west of *Verulamium*. Quite possibly, ore was obtained from a variety of sources, near and far, for distribution to the major late Iron Age centres within a much larger network. Haselgrove (2011) even suggests that one of Verulamium's sources lay in the 'ironstone deposits on the plateau flanking the Welland valley in the Corby area'.

The Bradenham furnace belongs to a type known as a shaft furnace. This was a common technology in the Roman period, in widespread use across the east Midlands zone of Iron Age and Roman iron-working. The alternative was the bowl furnace, a clay-lined depression in the ground covered by a circular dome, like the Berkhamsted furnaces previously described. In this case the slag would collect within the depression, whereas with the shaft furnace the slag was directed to an external pit, as at Bradenham. In either example, part of the shaft or dome would have to be broken away to extract the final iron bloom. The original height of the Bradenham shaft is likely to have been about 1m, so up to 0.3m is likely to have projected above the ground surface. The method of production involves heating the ore in an oxygen-starved atmosphere of carbon monoxide, provided by the burning charcoal. The carbon monoxide has a strong affinity for oxygen, allowing it to form carbon dioxide, thus reducing the iron ore to leave the iron in the form of a spongey lump known as a 'bloom'. During the process impurities such as silica and alumina separate out to form the waste slag. Air provided by leather bellows would be introduced into the furnace via a circular or rectilinear clay pipe passing through the base of the furnace wall. Unfortunately, evidence of the pipe or 'tuyere' was not recovered. Eventually the bloom becomes so large that it blocks the air flow and obstructs the smelting process. It would then be extracted by breaking through the furnace wall. The bloom was then re-heated hammered in a process known as 'smithing' to consolidate the bloom and remove more waste.

That only one furnace was found associated with a pit of this size is of note compared to other sites. The total amount of slag (163.75kg from the half-sectioned tapping pit) indicates a successful furnace. Having said this, the shaft showed signs of relining and reuse, therefore it is almost certain the large volume of slag originated from more than one firing. This assumption is supported by the recovery of a second 'plug' of slag originating from the base of the furnace but found within dump layer 1007.

With regards to dating the furnace it is fortunate that the Bradenham excavations provided useful samples of charcoal suitable for radiocarbon analysis (from context 1017). Assessment of the charcoal by Oxford Archaeology has confirmed that the small quantities of recovered charcoal are either oak or beech wood. The two samples provided calibrated date ranges as follows:

Sample 1, 18 cal BC to 130 cal AD (95% confidence; SUERC-66758; 1937+/–30)
Sample 2, 37 cal BC to 124 cal AD (95% confidence; SUERC-66759; 1953+/–30)

These correspond neatly with the 1^{st}-2^{nd} century AD date-range suggested by the pottery from the tapping pit. They also tie in with Matthews and Wainwright's observations on the pottery associated with slag heaps in the adjacent woodland. The exact relationship of the slag to the surviving plough lynchets in the woods at Bradenham remains unclear, but it seems likely the fields had previously gone out of use before smelting commenced. It is possible that after their abandonment the woodland developed and this then provided a source for the charcoal. An expansion of the east Midlands iron industry followed on from the arrival of the Roman army in the first century AD and as Schrüfer-Kolb (2007) points out, the Romans may have brought new technological advances to an existing tradition of iron-making. During this period there is likely to have been a hierarchy of manufacture ranging from household production to productive industrial units. Three possible models of production have been suggested by Morris and Wainwright (1995) associated with extensive evidence of Iron Age and Romano-British iron-working in the Bulbourne Valley: controlled production by an elite authority, market production by 'free market' craftsmen and subsidiary production as an incidental seasonal activity within a predominantly agriculturally-based local economy. The isolated nature of the Bradenham site suggests it conforms to the seasonally productive model, possibly associated with nucleated settlement in the Saunderton Valley, perhaps operated by a family unit. Where this settlement was located is not clear; the nearest recorded Roman settlement is the unexcavated villa at Saunderton Lee, c.2.4km west of the furnace site (Hepple & Doggett 1999). Further north, but still within the parish of Bledlow-cum-Saunderton, lies the villa at Hemley Hill, excavated in 1938 (Ashcroft 1939) and reassessed in 1969 (Branigan 1969). The author has reported elsewhere (Marshall 2008) on extensive Roman evidence found in the environs of West Wycombe Park, suggesting the presence of either a villa or settlement centred on West Wycombe Village. This suggestion was enhanced by the discovery of four Roman graves on Church Lane in the centre of the village in 2010 (Carlyle 2012). Though no direct connection can be made, it is nevertheless likely that these settlements would have provided an indirect market for the output of the furnace, though if this were the case the iron would first require further refining through the smithing process and subsequent conversion to usable implements.

References

Ashcroft D 1939 Report on the excavation of a Romano-British Villa at Saunderton, Buckinghamshire, *Recs Bucks* **13**, 398–426

Branigan K 1969 The Romano-British Villa at Saunderton reconsidered' *Recs Bucks* **18**, 261–76

Bucks County Museum Archaeology Service 1997 *A Watching Brief at Overburnts, Cholesbury Hillfort*

Cambridgeshire Archaeology 2006 *Roman Settlement at Grendon Underwood, The Hardwick to Marsh Gibbon Pipeline: Archaeological Evaluation*, 30–31

Carlyle S 2012 Roman Burial at 40 Church Lane, West Wycombe, *Recs Bucks* **52**, 83–94

Catt J, Perry B, Thompson I & Bryant S 2010 Prehistoric archaeology and human occupation of Hertfordshire, *in* J Catt (ed.) *Hertfordshire Geology & Landscape*, 226–55. Herts Natural History Society

Charlton M 2007 *Ironworking in northwest Wales: an Evolutionary Analysis.* Doctoral thesis, Univ of London

Charlton M, Crew P, Rehren T, Shennan SJ 2010 Explaining the evolution of Ironmaking Recipes – an Example from North-West Wales. *J Anthropological Archaeol* **29**, 352–367

Cookson A 1973 A Medieval Homestead at Park Wood, Bradenham, Bucks, *Recs Bucks* **21**, 98–115

Griffiths R & Southernwood J 1973 Archaeological Notes from Newton Longville, 1964–72, *Recs Bucks* **19**, 317–328

Haselgrove CC 2011 Beyond Hallaton: rewriting the early history of central Britain, *in* V Score *Hoards, Hounds and Helmets: a Conquest-period Ritual Site at Hallaton, Leicestershire*, 165–74. Leicester Archaeology Monograph **21**

Headland Archaeology 2014 *Archaeological Investigation, Recording, Analysis, and Publication at Woburn Golf and Country Club* (unpublished)

Hepple LW & Doggett AM 1999 *The Chilterns.* Phillimore

Kimball D 1933 Cholesbury Camp, *J British Archaeological Association* **39**, 187–212

King S 2013 *Holmer Green Bloomery, Preliminary Report* (unpublished)

Mahoney T & Fregni G 2009 *An Analysis of Metalworking Residues from the Chiltern Hills, Review, Results and Potential* (unpublished)

Marshall G 2008 A Hidden Landscape Revealed: Archaeology in the Lakes and Streams at West Wycombe Park, Buckinghamshire, *Recs Bucks* **48**, 185–214

Matthews W & Wainwright A 1990 *The National Trust Archaeological Survey, Bradenham*

Morris J 2009 *Historical Metallurgy Society News,* Spring 2009, 2

Morris M & Wainwright A 1995 Iron Age and Romano-British Settlement, Agriculture and Industry in the Upper Bulbourne Valley, Hertfordshire, an interim interpretation, *in* R Holgate (ed.) *Chiltern Archaeology, Recent Work: A Handbook for the Next Decade*, 68–75

Neal DS 1987 Excavations at Magiovinium, Buckinghamshire, 1978–80, *Recs Bucks* **29**, 1–124

Rehren T, Charlton M, Chirikure S, Humphris J, Ige A, Veldhuijzen HA 2007 Decisions set in slag: the human factor in African iron smelting, *in* S LaNiece, DR Hook, PT Craddock (eds), *Metals and Mines – Studies in Archaeometallurgy,* 211–218. Archetype/British Museum (London)

Schrüfer-Kolb I 2007 What Did the Romans Ever Do For Us? Roman Iron Production in the East Midlands and the Forest of Dean, *in* A Fleming & R Hingley (eds) *Prehistoric and Roman Landscapes.* Windgather Press

Sim D 2002 *The Roman Iron Industry in Britain.* The History Press

Thompson I 2002 *The Roman Settlement at Cow Roast, Northchurch' Extensive Urban Survey Report.* Herts County Council

Thompson I 2015 When was the Roman conquest in Hertfordshire?, *in* K Lockyear (ed.) *Archaeology in Hertfordshire: recent research. A Festschrift for Tony Rook*, 117–134. Univ Hertfordshire Press

Tylecote RF 1963 *Metallurgy in Archaeology* (London)

Wainwright A, Marshall G, Salkeld G 2010 *Archaeological Survey of the Ashridge Estate*, *Land Use History.* National Trust

Wilson DR 1975 Roman Britain in 1974, *Britannia* **6**, 257

Yeoman PA & Stewart IJ 1992 A Romano-British Villa Estate at Mantles Green, Amersham, Buckinghamshire, *Recs Bucks* **34**, 107–182

Zeepvat B & Radford D 2010 Roman Buckinghamshire (AD 43–410), *in* M Farley (ed.) *An Illustrated History of Early Buckinghamshire*. Bucks Arch Soc (Aylesbury)

Zeepvat B 1997 *A Project Design for the Publication of the Cow Roast Sites: BDAS & HAT Excavations, 1977–1993.* Herts Archaeol Trust Rep. **230** (unpublished)