English steelmaking in the seventeenth century: the excavation of two cementation furnaces at Coalbrookdale

Paul Belford and Ronald A Ross

ABSTRACT: This paper describes the excavation of the first cementation steel furnaces in England, built by Sir Basil Brooke at Coalbrookdale early in the 17th century. The coal-fired furnaces were in operation from c*1619 to the end of the 17th century, and formed part of a much larger ironworking complex. Excavation revealed the remains of two furnaces and associated buildings, constructed in at least two phases. This paper also includes the metallurgical analysis of refractory materials, as well as discussion about the rôle of the furnaces in the broader context of English steelmaking of the period.*

Introduction

Although much is known about 19th and 20th century cementation steelmaking in England, the introduction and early development of the process is not well understood. Excavations at Coalbrookdale between 2001 and 2005 have revealed the first two cementation furnaces constructed in England. The work took place as part of the Coalbrookdale Historical Archaeology Research and Training programme (CHART), developed by Ironbridge Archaeology in conjunction with the University of Birmingham and Wilfrid Laurier University. The CHART programme explored aspects of the pre-18th century landscape and technology of the Ironbridge Gorge World Heritage Site, with the main focus being an excavation at the Upper Forge, Coalbrookdale (Ordnance Survey NGR SJ 6693 0422). Historical research had identified the site as the possible location of an early 'steelhouse'. The term 'steelhouse' was used in the 17th and early 18th centuries to describe a cementation furnace; the street names 'Steelhouse Lane' survive in Sheffield, Wolverhampton and Birmingham near to known locations of early steelmaking sites (Belford 1997). The project also investigated other activities on the site, including non-ferrous industries and domestic occupation (Belford 2003; Belford and Ross 2004; Belford and Ross in preparation).

Cementation creates steel through the heating of wrought iron and carbon in an airtight container, increasing the carbon content of the iron. There are descriptions from continental Europe of this process (as opposed to case-hardening of individual artefacts) using pots or crucibles, dating to the latter part of the 16th century (Smith 1964, 152). By the early 18th century, carburisation of wrought iron was achieved by heating iron bars in powdered charcoal. The iron and charcoal were packed into rectangular chests, sealed to achieve a reducing atmosphere. The chests were situated in a reverberatory chamber, with a fire below and heat transmitted through a series of flues. A description of the process as it existed in 19th-century Sheffield has recently been summarised in this journal (Mackenzie and Whiteman 2006, 138–9).

Most of our knowledge of cementation steelmaking comes from 18th-, 19th- and 20th-century descriptions and examples, notably through the work of the late Kenneth Barraclough (1984). South Yorkshire's dominance of the English steel trade during the 19th century naturally attracted learned study of its techni-

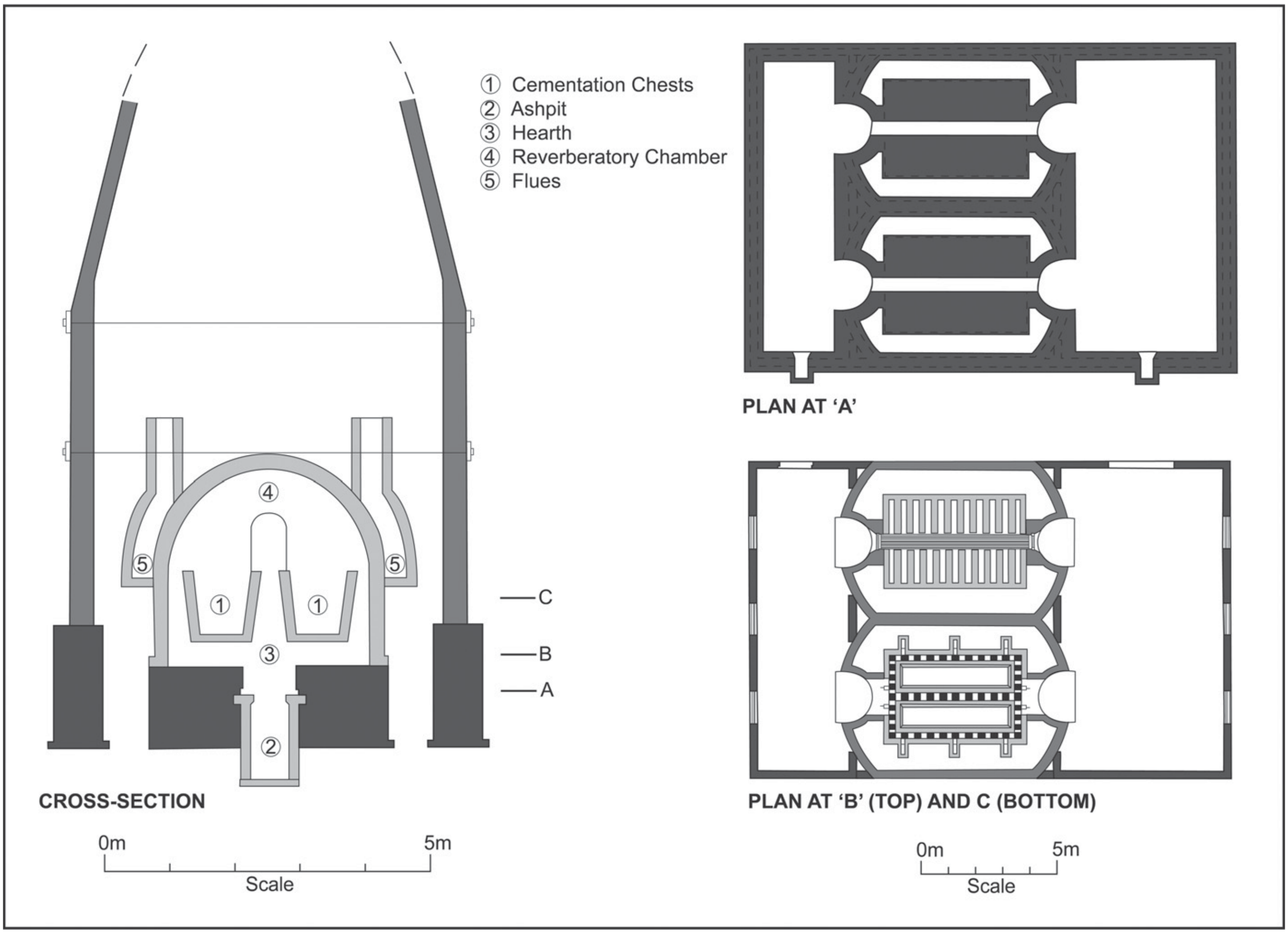

Figure 1: Typical 19th-century cementation furnace: cross section and plan views. Redrawn after Percy (1864) by Sophie Watson.

cal, scientific and historical aspects. As a result most of the published work since the 1860s has examined the Sheffield process in its final, most sophisticated phase. Barraclough's study was unashamedly Sheffield-centred, and almost all subsequent archaeological and metallurgical investigations have followed suit. Prior to the CHART programme, the only study of a pre-19th-century steelmaking site outside south Yorkshire was the early-18th-century furnace at Derwentcote, County Durham (Cranstone 1997). Consequently our understanding of furnace technology is largely based on the classic two-chest furnace, with a superimposed conical chimney, coal fired, converting Swedish wrought iron, with a typical load of between 15 and 35 tonnes of iron/steel per furnace (Percy 1864, 768–773; Barraclough 1984, 102; Belford 1997, 21–29; see Fig 1). However, evidence suggests that there was considerable regional and temporal variation in the design, construction and operation of cementation steel furnaces before the dominance of Sheffield in the post-Huntsman era. Eighteenth-century descriptions hint at significant variations in practice and product, suggesting adaptations of the basic principles to suit different raw materials, fuels, methods, customs and markets.

The Coalbrookdale furnaces represent the earliest archaeological evidence for 17th-century steelmaking to be excavated in Britain. Their significance is not only in being the first known examples of their type, but in representing the transition from 16th-century continental practice to 18th-century English steelmaking. The Upper Forge complex at Coalbrookdale was the prototype for the first stage of steelmaking in the Severn hinterland and the West Midlands.

Historical Background

Coalbrookdale lies on the north bank of the River Severn in Shropshire. In the middle ages it formed part of the Manor of Madeley, which was part of the estate of Much Wenlock priory (a Cluniac house from the 12th century, with 8th-century origins). The Manor was acquired at the dissolution by Sir Robert Brooke. At this time, in addition to substantial agricultural and woodland

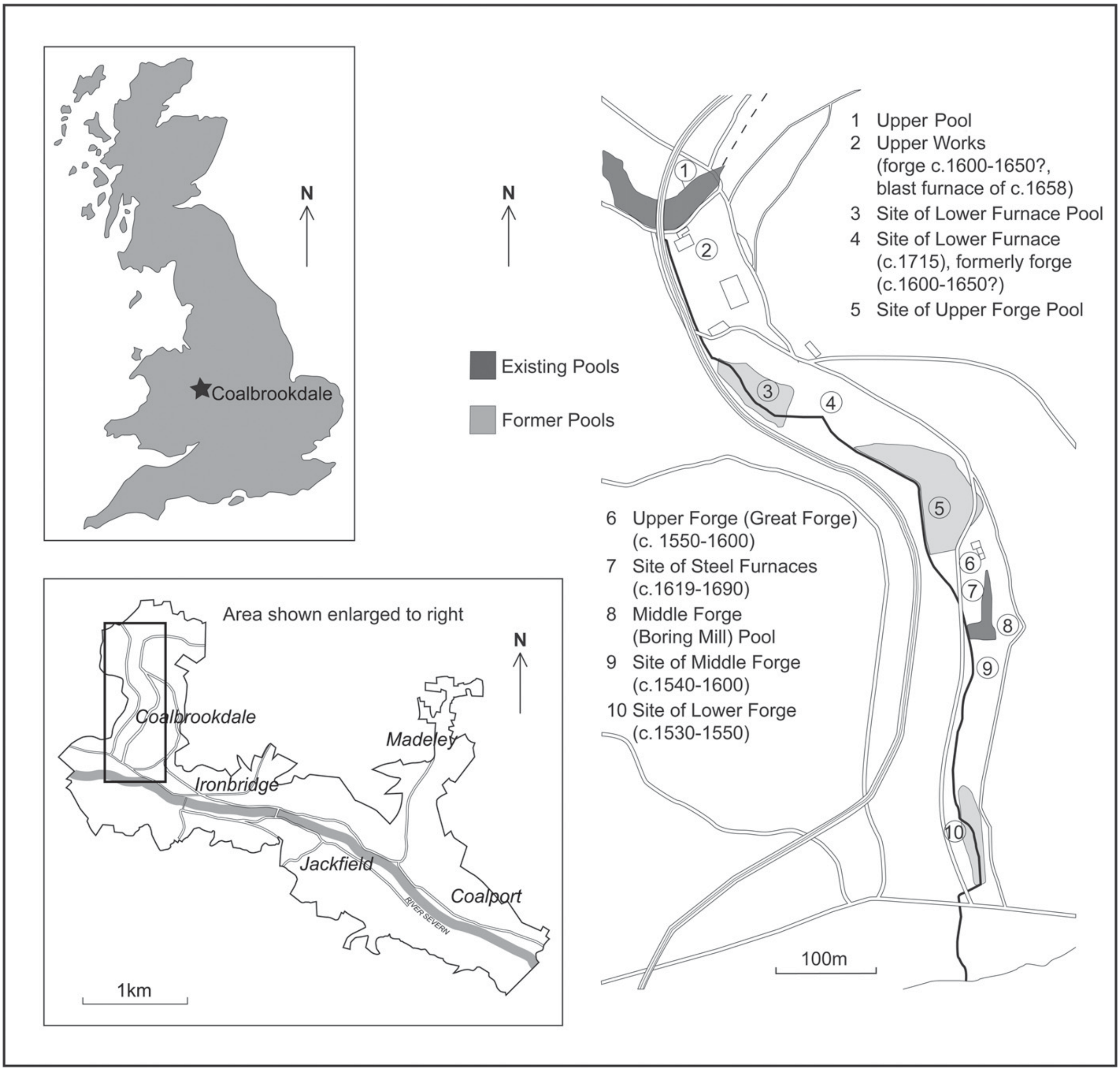

Figure 2: Location plan. Location of Coalbrookdale within the Ironbridge Gorge World Heritage Site, and ferrous metal working sites referred to in the text. Drawing by Sophie Watson.

holdings, it also contained long-established coal mines and two 'smithies' or forges (Baugh 1985, 35; Randall 1880, 59–60). On the death of Sir Robert, in 1558, the estate passed to his widow Dorothy, and to their son John *c*1572. On John's death in 1598, Madeley was inherited by Sir Basil Brooke. Coalbrookdale by then included extensive ironworking facilities. There were at least three forges in Coalbrookdale, including the 'Great Forge' or Upper Forge, which became the centre of the Coalbrookdale ironmaking business in the first half of the 17th century (Belford 2007, 135; see Fig 2).

Iron was the primary concern of the Brookes, and Sir Basil invested in various ferrous enterprises. These included leasing Crown ironworks in the Forest of Dean from 1615 to 1636. In 1615 Brooke also became involved with a steel patent (Hammersley 1972, 149–153). By this time the cementation process had spread throughout northern Europe. Several monopolies for the production of steel in England were granted early in the reign of James I, but all were soon withdrawn for lack of performance under testing (Jenkins 1923, 18; Brownlie & de Laveleye 1930, 457–470). Sir Basil's initial attempts were unsatisfactory, and failed to get the required approval of the Royal Armoury, leading to loss of the monopoly in 1619 (Schubert 1957, 234).

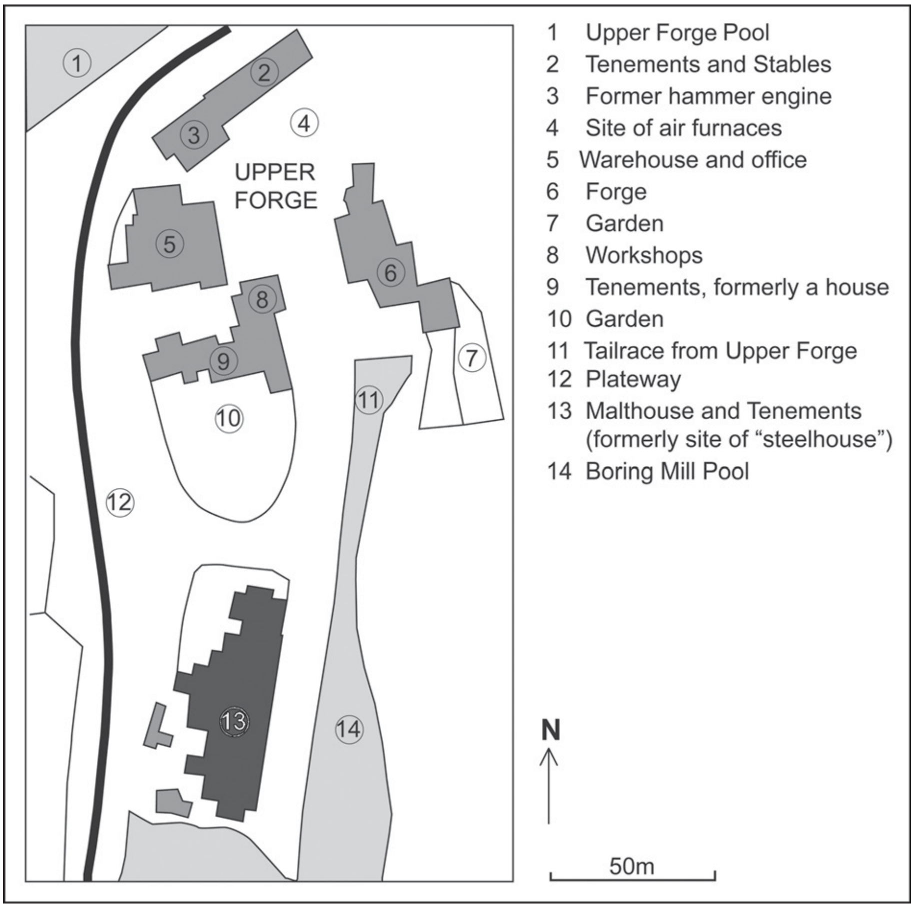

Figure 3: The Upper Forge complex c*1800, showing the location of the steelhouse, malthouse and tenements (dark shading shows building footprint) in relation to surrounding landscape features. Redrawn from 1753, 1786, 1805 and 1826 maps by Paul Belford and Sophie Watson.*

Nevertheless, the production of steel would have been an obvious adjunct to the forging business, adding significant value to wrought-iron bar through a relatively simple process.

From 1619 steel was being shipped down the River Severn (GPR 1247/08/02/20). It seems reasonable to conclude that, after some experimentation, the new process had been mastered. The scale of shipments is small (two to five tonnes at a time), suggesting that only a single furnace was operational. This view is supported by the evidence of the excavations. Fieldwork has also gone a long way towards explaining why Brooke decided to set up his steelworks in Coalbrookdale rather than near his source of iron in Gloucestershire (see below). The process was clearly commercially successful, as a second furnace was added, probably in the 1630s. A lease of 1645 refers to the 'old' and 'new' steel furnaces as part of the extensive forge complex (Clark and Alfrey 1986, 31; Wanklyn 1973, 4–5).

Sir Basil died in 1646. Steel production seems to have continued through the 1660s, as suggested by shipments down the Severn (*eg* GPR 1249/04/02/24). However, Sir Basil's investments, together with the vicissitudes resulting from the civil war, meant that his son Thomas Brooke had some £10,000 worth of debt by *c*1655 (Baugh 1985, 35, 46). Thomas appears to have been more enthusiastic about investing in the increasingly lucrative cast-iron trade than following his father's footsteps in the steel industry (building a blast furnace in the Upper Dale in 1658), although steelmaking continued at the Upper Forge until late in the 17th century. By this time any Brooke monopoly in the steel trade had been broken. Steel furnaces were operational in Bristol by the 1660s, and in Birmingham by the 1670s respectively closer to sources of iron (either from the Forest of Dean or, more likely, imported from Sweden) and to the market for the finished product (Evans and Ryden 2007).

Sir Thomas' grandson, another Basil, inherited the estate in 1675. The younger Basil became increasingly preoccupied with coal mining. He invested 'great sums of money' in the extractive industries, possibly at the expense of the ironworking business. By 1695 the estate was so debt-ridden that it had to be placed in trust. The ironworks in Coalbrookdale were leased to Shadrach Fox (Baugh 1985, 46, 49; Clark and Alfrey 1986, 31). Fox sublet the forges in lower and central Coalbrookdale, including the Upper Forge with its 'steelhouse', focusing his attention on iron casting and foundry operations (King 2002, 43–45; Belford 2007, 138). After the blast

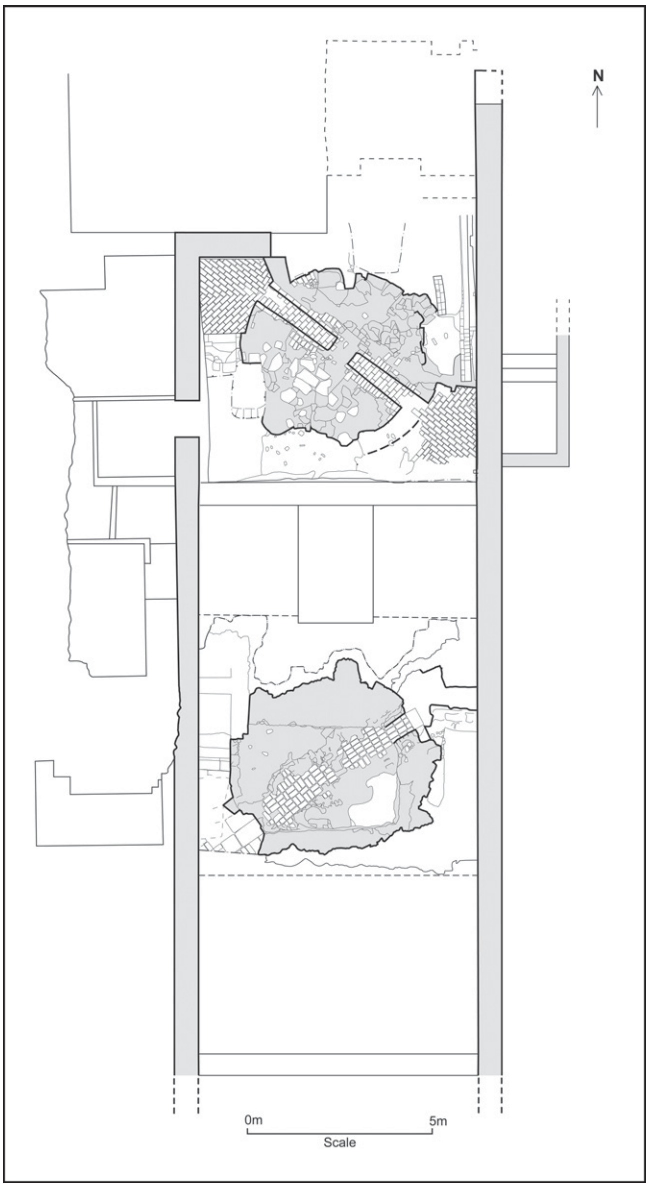

Figure 4: Overall site plan, showing the steel furnaces and associated buildings. Later structures which re-used the earlier foundations are omitted for clarity. Drawing by Sophie Watson.

furnace exploded in 1705, Fox absconded to Russia. The partly-abandoned upper works was taken on three years later by Abraham Darby, a Quaker brassfounder from Bristol. Like Fox, Darby concentrated on smelting iron, and did not consolidate the Coalbrookdale complex as a whole until well into the following decade.

The 'steelhouse' was converted to a malthouse in the summer of 1726 (Coalbrookdale Cash Book 1718–1732, 140ff), and this new building was depicted on the first map of Coalbrookdale in 1753. By 1847 it had been converted again, to tenement housing, although occupying the same footprint as the earlier buildings. Map regression identified the location of the malthouse and tenements, and therefore the probable location of the steelworks (Belford and Ross 2004, 215–217; see Fig 3). The tenements were themselves demolished in 1967, and the site subsequently landscaped as a park and picnic area.

The excavations

Excavation revealed the remains of two furnaces, matching the 1645 lease. The southern furnace was the first to be discovered. It was excavated in 2003 and 2004, with further minor investigation in 2005. The northern furnace was discovered and fully excavated in 2005. Both furnaces had been truncated, and the surrounding structures radically modified, during the 18th-century conversion to a malthouse. They had been further affected by the 19th-century conversion of the malthouse into tenements, and yet again during attempts to improve drainage within the tenement cellars. Nothing remained above the level of the ash pit in either furnace, and even the ash pit was compromised in the southern furnace. Despite this, it could be seen that the northern furnace had two phases, and that the second phase of the northern furnace was similar to the southern furnace. Fragments of the buildings that would have surrounded the furnaces also survived. These would have contained fuel and raw materials. In south Yorkshire they were known as a 'tenting house', whereas in the north-east the term 'feasing house' (variously spelt) was used (Belford 1997, 115; Cranstone 1997, 13; D Cranstone, pers comm). Lacking knowledge of contemporary west midlands terminology, they are described as 'ancillary buildings' throughout this report.

The adaptive re-use of the structures prevented relative dating of the furnaces by direct stratigraphic sequencing within them. Parts of the ancillary buildings were, however, physically and stratigraphically linked through their fossilisation within the eastern wall of the malthouse range. However, the construction fills and structure of the furnaces lacked any dateable artefacts. Scientific dating methods were considered but rejected. The ashpit floors were too far removed from the main source of heat to be suitable for thermoluminescence or archaeomagnetic dating; those elements of the furnace which were closer to the heat source were dismantled and *ex situ*. Even had these been usable, they would have only provided the date for the final firing. This can be deduced within a reasonable margin of error from historical and artefactual evidence. Radiocarbon dating was also ruled out. Although both furnaces had carbon deposits in the ash pits, the margin of error for radiocarbon dating is too great to reliably differentiate within such short time spans, especially for such recent periods. The chance of contamination was also high,

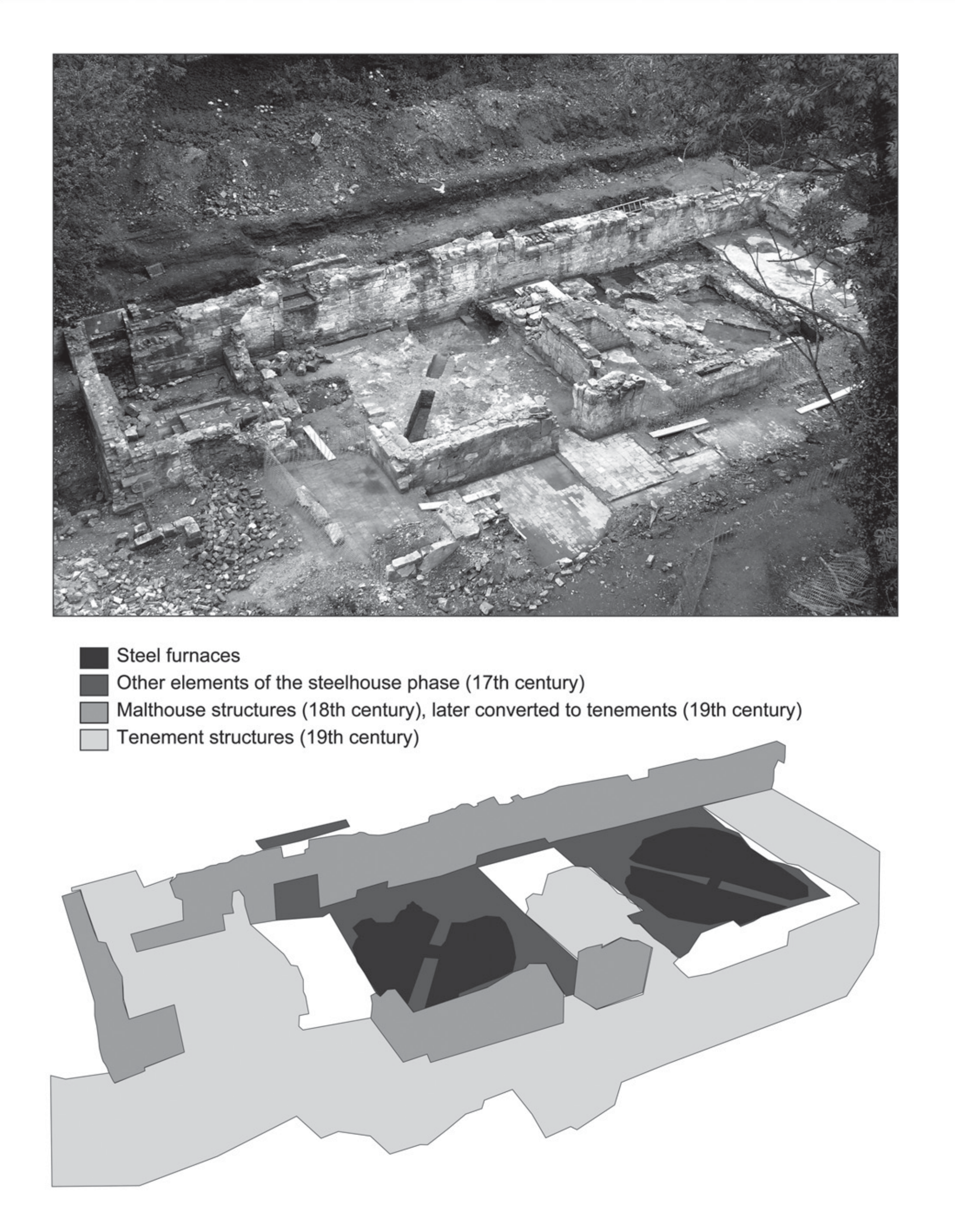

Figure 5: Oblique overhead view of the site after excavation in 2005, showing the furnace bases, ancillary structures and other features. Photograph courtesy of Telford and Wrekin Council; key drawing by Paul Belford and Sophie Watson.

since the site was surrounded by layers of blast furnace and forge waste, and was later used for industrial processes involving coke, coal, charcoal, oil and grease. Parts of the site sat at or below the water table; during the wet summers of 2003 and 2004 water levels on the site rose sufficiently to fill the ash pit of the southern furnace with oily water. Radiocarbon dating, even if otherwise suitable, would also only have reflected the date of the last firing.

While these factors rule out complete certainty as to which furnace is older, scrutiny of the construction of both furnaces suggests that the northern furnace was built first. As noted above, this furnace was built in two phases. The first phase stratigraphically predates the second phase. This first phase measured 4.57m (15ft) in diameter; the second phase, and the single-phase construction of the southern furnace, both had a diameter of 5.48m (18ft). Because of this, and details of the construction (see below), it seems likely that the second furnace also post-dates the first phase of the northern furnace. Furthermore, the overall construction of the southern furnace is less careful, with less attention paid to detail. Finally, it also appears that the ancillary buildings were extended southwards to allow for the construction of the new furnace, although the structural evidence has been

Figure 6: The northern ash pit of the northern furnace after excavation. Scale 2 metres. Photograph by Paul Belford.

compromised to some extent by later modifications. No firm temporal priority can be assigned between the later (rebuild) phase of the northern furnace, and the southern furnace, although there is reason to believe the northern rebuild is first (see discussion, below).

All three furnaces/phases were broadly similar. Despite later destruction, it can be seen that the furnace superstructures were circular or nearly circular (Figs 4, 7 and 8). The foundations of the furnaces were constructed of irregular sandstone blocks up to 600mm by 330mm by 300mm. These were set in an irregular, loosely spaced pattern into a very hard, very fine buff to reddish lime mortar, with frequent flakes and flecks of charcoal up to 25mm square. In places where the foundation was not protected by subsoil, such as the ash pit entrances, the mortar was faced with brick. Neither the sandstone nor the mortar showed any signs of significant heating, which is consistent with their location below firebox level.

There is no direct evidence for the construction materials used in the superstructure. Both refractory bricks and sandstone fragments were recovered from the ashpit fills, but these seem most likely to relate to the lining or interior of the reverberatory chamber. While the use of sandstone may have been limited to the foundation and lining, it is probable that it was used for the whole chimney superstructure. The best evidence for this are impressions in the mortar on the northern furnace. These seem to indicate the base of a stone facing around a rubble and mortar core. Comparable structures are scarce, but examples such as Derwentcote (1733) and Huntsman's first cementation furnace at Attercliffe (1743) suggest that stone was used for cementation furnace superstructures before the mid-18th century (Hadfield 1894, plate XV; Cranstone 1997: 29–30). It is also suggestive, although far from conclusive, that some very similar heat-reddened and softened sandstone blocks were used in the construction of the malthouse.

Each furnace had two brick-lined ash pits on the same axis of the furnace, not quite meeting in the middle. The pits in the southern furnace were almost completely destroyed by the insertion of brick-lined steeping tanks for the malthouse, but the authors believe that the northern pit (Fig 6) survived to approximately its full height of 610mm (2ft). This is evidenced by mortar remains showing stone impressions on the top of the central pillar.

Each pit could be accessed from a paved space on either side of the furnace. This would have enabled regular removal of ash deposits, since the ash pits would not have been large enough to contain all the ash produced during a single firing. These were below the 17th-century ground level, and were accessed by stairs. There was no sign of any doorways or other means of regulating access or air flow to the ash pits, although there could have been doors at the top of the stairs. The ash pits were separated by a substantial central pillar, brick in the northern furnace, and stone in the southern. This pillar was possibly to support the weight of the cementation chest (or chests) above. The fact that the pit was divided into two suggests that the firebox above was also divided into two. This would have allowed stoking from either end, or indeed from both ends, as was common practice known from later examples (Barraclough 1984; Cranstone 1997). It also has implications for air flow, as the primary draught would likely have been through the ash pits. Either there was no concern to control the fire by regulating air flow, or any such controls are no longer extant.

Both the second phase of the northern furnace and the southern furnace had evidence for buttresses. These were not as substantial as those at Derwentcote, but suggest that both faced similar technical problems—namely the development of considerable sideways stress on the structure due to thermal expansion. Buttressing on the Coalbrookdale furnaces was less substantial than that at

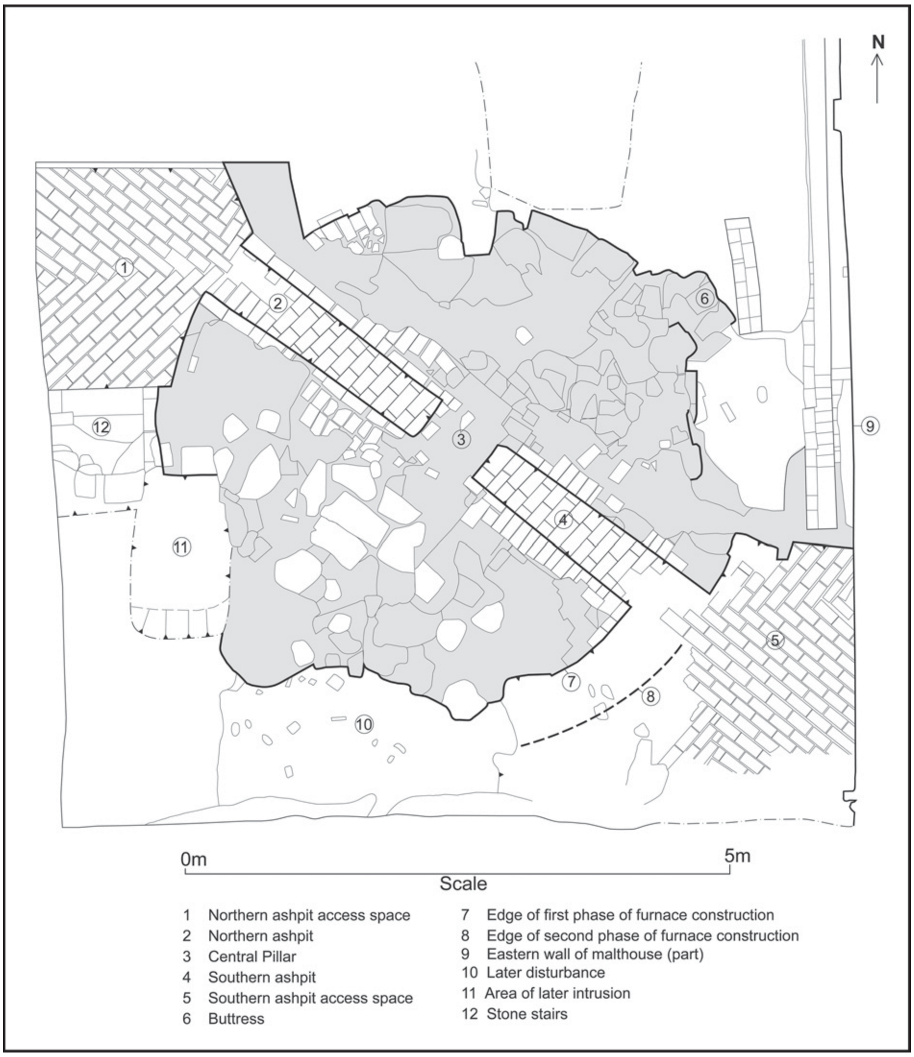

Figure 7: Plan of the northern furnace (c1619) as excavated, showing the brick flooring and extent of the furnace foundation, and ancillary structures. Drawing by Sophie Watson.

Derwentcote, where timber strapping was also utilised in an attempt to contain these stresses (Cranstone 1997, 104). There was no evidence for strapping of any form at Coalbrookdale, probably due to the later truncation of the site; moreover timber strapping would have been difficult to apply to a circular structure (unlike the square Derwentcote furnace). It is probable that wrought-iron straps would have been used, easily sourced from the adjacent Upper Forge, and subsequently lost due to later modifications to the site.

The construction of both the southern and northern furnaces seems to have followed the same pattern. First, all soils and sediments had been cleared from the area of the furnace and its infrastructure, down to the level of the natural boulder clay subsoil. This is a very hard, very compact yellow to yellow-green clay with substantial rounded cobbles. It provides an extremely solid, stable foundation. Next, a furnace-sized flat-bottomed bowl, with protrusions for the ash pit entrances and buttresses, was hollowed out to the depth of the ash pit. This bowl had a smooth bottom where the ash pit ran, but was rather irregular elsewhere. Neither furnace bowl was fully excavated, so the profile (Fig 8) is reconstructed from a series of investigations and is therefore partly conjectural.

The floor of both ash pits and their entrances was then laid as a continuous unit. In the northern furnace, bricks were used throughout. In the southern furnace, bricks were used for the ash pit floor, while flagstones were used for the entrances. In the northern furnace, the pit floor bricks were all laid at 90 degrees to the axis of the pit, while in the south they were more haphazard. This has no obvious significance. The flooring in all cases was set directly on to the boulder clay. The ashpit walls, central pillar, and walls of the ashpit access areas and other ancillary buildings were built up after the floor was laid. This was not a haphazard process, as the facings were integrated with the ash pit walls. Once these were constructed, the remaining bowl was filled with stones and hard mortar, and construction of the stone furnace superstructure and ancillary buildings began.

Despite these similarities, there are interesting dif-

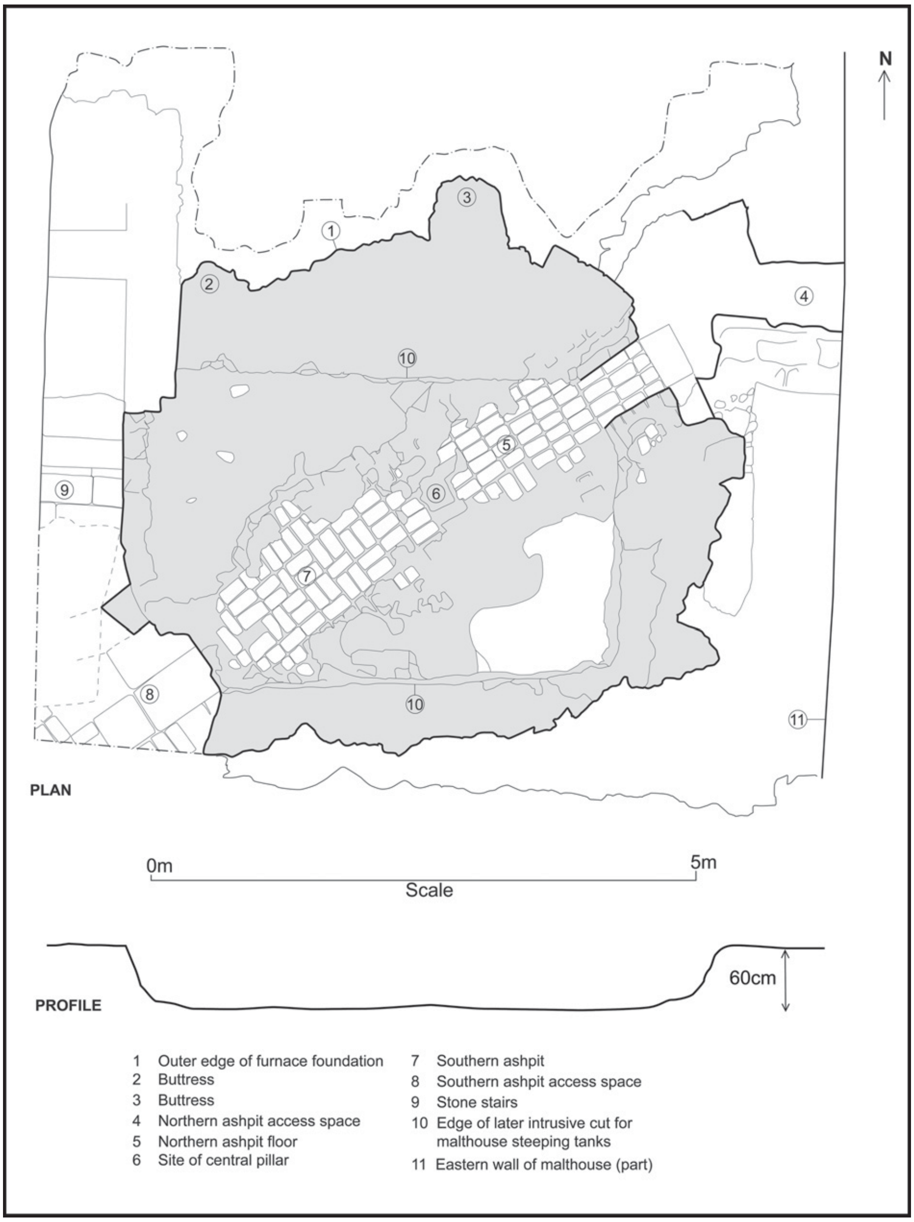

Figure 8: Plan of the southern furnace (c1630) as excavated, showing the extent of the furnace foundation and associated flooring. Note the later truncation in the central part of the furnace by the 18th-century malthouse steeping tanks. The profile is reconstructed from various investigations and does not represent a measured cross-section. Drawing by Sophie Watson.

ferences between the furnaces. The first phase of the northern furnace was smaller than the others, at 4.57m (15ft) in diameter. The ash pits were oriented north west to south east. Both ash pits were 406mm (16in) wide at the central pillar, gradually expanding to 504mm (20in) wide at their mouths. The central pillar was 610mm (2ft) by 406mm (16in), constructed of brick. The floor and wall bricks themselves were dull red, and heavily soot stained. They measured 240mm (9.5in) by 115mm (4.75in) by 55mm (2.25in). There were no buttresses evident on this first phase; this could be because they were not part of the original design, or more likely they were subsumed into the new build.

In its second phase, the northern furnace was extended by 406mm (16in) at each end, or 810mm overall (32in), making a total diameter of 5.48m (18ft). The abutting extension was clearly evident in the ash pit (see Fig 6 above). The bricks used for the expansion were very similar to the original, but were not properly keyed in to the previous build. In addition, the south side of the north-western pit entrance steps out to 610mm (24in). There was no clear indication of two builds in the foundation mortar impressions. This may be simply because of the irregular nature of the construction, or it may reflect the extent of rebuilding. On the north-east side there are impressions of more regular blocks, up to 600mm (2ft) long, suggesting the presence of a stone facing-course. Three buttresses were identified, in various states of preservation. A fourth probably existed on the south side.

The southern furnace was 5.48m (18ft) in diameter, with the ash pit oriented north east to south west. The ash pit walls were missing, but there was no evidence of any rebuilding or expansion. Mortar impressions indicate that the ash pit was 410mm (16in) wide along its entire length. The tapering ash pit seems to have been abandoned, although mortar impressions suggest the pits had curved inner ends. The bricks were 245mm (9.75in) by 115mm ± 5mm (4.5in, irregular) by 60mm (2.4in), set in a fine soft buff sandy lime mortar with occasional flecks of charcoal. The central pillar appears from mortar impressions to have been made from stone, and about 200mm (8in) wide. This may be an under-estimate due to later destruction. Two buttresses were identified on the north-west side. On the south-east side, none were seen, but the foundations there were more severely impacted by later construction.

As with most furnaces, there were ancillary buildings, of which only fragments survived. However, it was clear that rectangular buildings abutted at least the east and west sides of both furnaces, and may have extended north and south to link the two furnaces together. The extent of the ancillary structures was limited to not more than 3m from the furnaces in any direction, considerably smaller than other known examples. It seems likely that other structures were destroyed by later uses of the site, and may also have been located outside the excavation area.

One goal of excavation was the recovery of residues. However, the cementation process produces relatively few byproducts. There are no slags. The metal is never in the molten state, so it does not adhere to the structure, nor does it produce spatter prills that might be found by careful sieving. Charcoal used in the cementation chest, while it can be expected to be finely powdered, is not likely to be chemically altered. Its presence and analysis would prove nothing. The Derwentcote furnace was sealed with sand, which after firing produced a distinctive fritted residue. In Sheffield, the wheel-swarf used to seal the box turns into a highly distinctive angular material known as 'crozzle'. Neither material was found during the excavations at Coalbrookdale. Given the proximity of forging operations (as at Derwentcote) rather than widespread grinding (as in Sheffield), it seems more likely that sand would have been used as a sealing material in Coalbrookdale. However site conditions were not conducive to the preservation of fritted sand, and in any case such residues are likely to have been deposited off-site and subsequently lost due to the intensive development of the Coalbrookdale area in the 18th and 19th centuries. A close eye was also kept for any potential bars or fragments from failed firings. None were found.

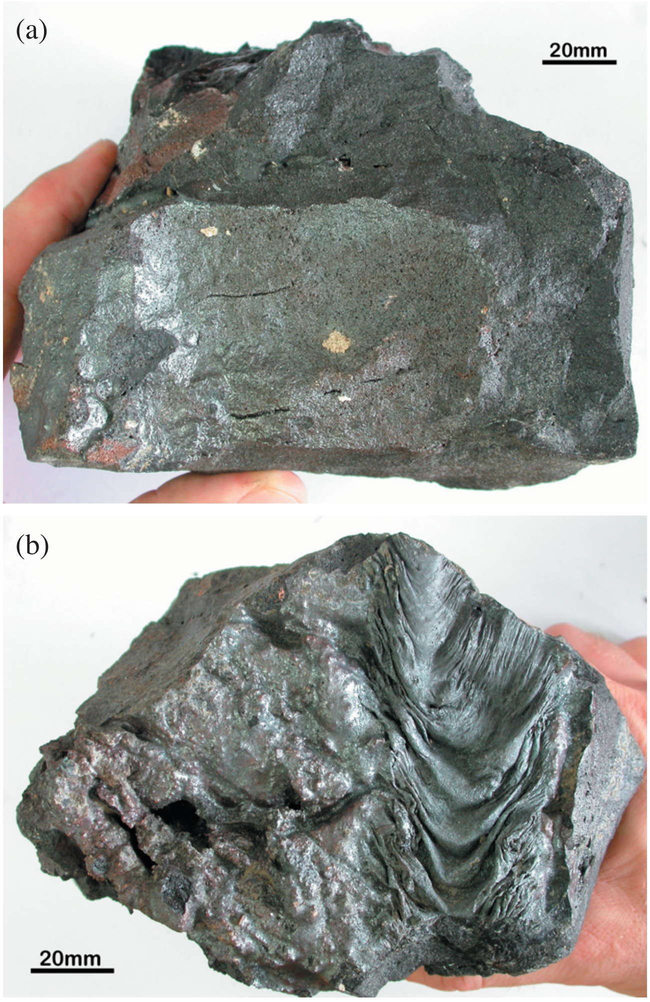

Figure 9: Sample 1, (a) refractory stone, (b) another face with vitrified and slumped surface.

The only residues recovered were refractory materials from the demolition fills, and ash scraped from the ash-pit walls and floors. The refractory materials have been analysed by Dr David Dungworth of the English Heritage Centre for Archaeology. Four samples of refractory material were examined. Two of these (Samples 1 and 2) were believed to have formed part of the demolished superstructures of the Coalbrookdale furnaces. A third sample (Sample 7) was of the ordinary building stone used (and re-used) on the Upper Forge site for the ancillary structures and later phases. Samples 1, 2 and 7 were taken during the final season of excavations in 2005. A fourth sample (Sample 6) was a fragment of refractory sandstone from Derwentcote, recovered in November 2007 from the adjacent spoil heaps, and identified by David Cranstone in the field as cementation chest material.

Figure 10: Sample 2, (a) refractory stone and brick and (b) after sectioning.

Analysis of refractory materials by David Dungworth

Aim, and description of samples

The analysis had two primary aims. The first was to establish the fuel used and the likely operating temperature achieved in the Coalbrookdale furnaces. Sample 1 is a fragment of stone (Fig 9a) with a vitrified and slumped surface (Fig 9b). It is presumed that the vitrified and slumped surface originally formed part of the interior surface of the furnace. Sample 2 comprises a fragment of stone adhering to a fragment of brick (Fig 10a). Since Samples 1 and 2 were recovered from demolition rubble it was not clear whether they originally formed part of the reverberatory chamber or of the cementation chests. The second aim of the metallurgical analysis was therefore to try and compare the properties of Samples 1 and 2 with the local ordinary building stone (Sample 7), and with known cementation chest material from Derwentcote (Sample 6, see also McDonnell 1997).

Table 1: XRD analyses.

No.	Description	Minerals
1a	stone	Tridymite, Cristobalite (low)
1b	vitrified surface	Magnetite
2a	stone	Quartz, Tridymite, Cordierite
2c	brick	Mullite, Tridymite, Cordierite, Iron Cordierite

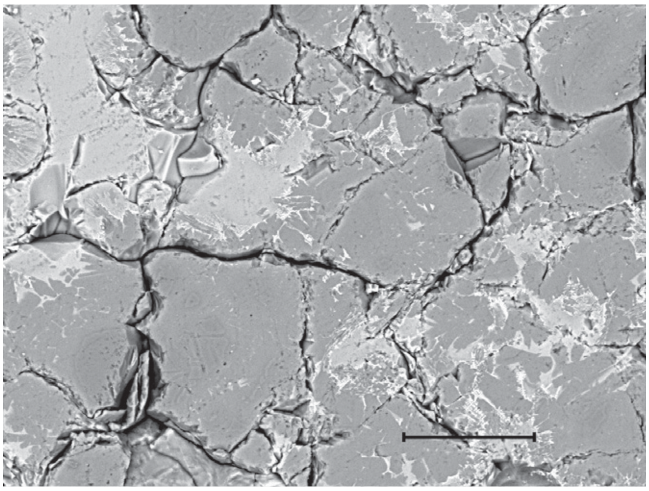

Figure 11: SEM image (BSE detector) of the core of Sample 1. This consists of grey grains of silica with small paler areas of intergranular vitrification (scale = 100µm).

Methods

Samples 1 and 2 were examined using a scanning electron microscope (SEM) and the chemical composition determined using an energy-dispersive X-ray spectrometer (EDS) attached to the SEM. The samples were cross-sectioned with a rock saw. The cross-section through Sample 1 includes the vitrified surface and the underlying stone. Sample 2 includes stone, mortar and brick (Fig 10b). The cut samples were embedded in epoxy resin and ground and polished to a 1μm finish. SEM images were obtained using the back-scattered electron detector which produces atomic number contrast images (bright areas indicate a high atomic number). Chemical data was acquired using an energy-dispersive X-ray spectrometer (Oxford Instruments germanium detector with Link software) attached to the Scanning Electron Microscope (SEM-EDS). This was applied to relatively large areas to obtain chemical data that would be representative of the material as a whole, as well as to small areas of interest. The mineral compositions were determined using approximately 0.5g of powdered material which was ground to a fine powder for X-ray diffraction (XRD) analysis (Table 1).

Sample 1

Sample 1 has two distinct regions: a silica-rich core (Fig 11) and a glassy vitrified surface which contains iron

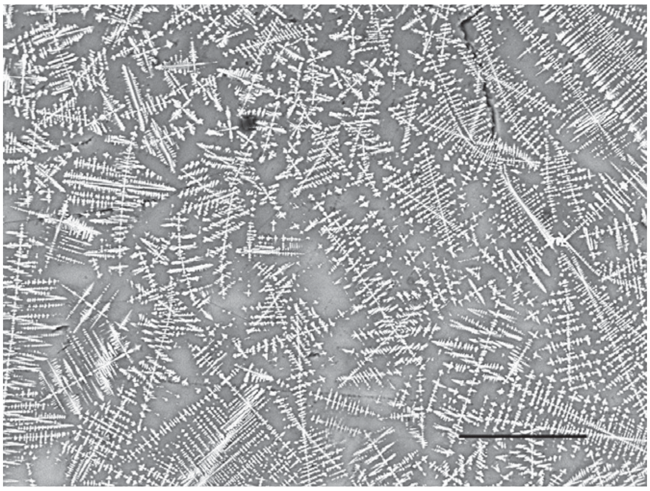

Figure 12: SEM image (BSE detector) of the vitrified surface of Sample 1. This consists of iron oxide (Fe_3O_4) dendrites in a glassy matrix (scale = 100μm).

oxide dendrites (Fig 12).

The core of Sample 1 is composed of grains of silica polymorphs (tridymite and low cristobalite) with small fields of intergranular material. The intergranular material would originally have comprised a range of minerals (especially feldspars and clay minerals) but these have all undergone melting at high temperatures. The average composition of the sandstone (Table 2) shows a high silica content which would help to ensure that it was sufficiently refractory. The average composition of the core suggests that the sandstone would not become fully molten below 1600ºC (Levin *et al* 1956, Figs 372–3). The XRD analysis shows the presence of tridymite (the stable form of silica between 870 and 1470ºC) and cristobalite (the stable form of silica above 1470ºC) (Deer *et al* 1966, 341). Cristobalite, however, can be produced as a reaction product during the heating of clay minerals at temperatures as low as 1200ºC (Eramo 2005). Therefore, the minerals present in the core of Sample 1 indicate that it was heated to a temperature in excess of 1200ºC but less than 1600ºC.

The surface of Sample 1 had clearly undergone partial melting at some stage; the surface shows signs of slumping (Fig 9b). Modelling the viscosity-temperature relationship (Bottinga and Weill 1972) suggests that this surface would have started to soften at *c*1300ºC but would not have flowed appreciably under its own weight below *c*1400ºC. The relevant phase diagram (Levin *et al* 1956, Figs 372–3) shows that this vitrified surface would be completely molten by approximately 1450ºC. The absence of cristobalite suggests that this sample was never heated above 1470ºC. Therefore, the vitrified surface of Sample 1 is likely to have formed at between 1300º and 1450ºC. The presence of fine magnetite (Fe_3O_4) dendrites in the vitrified surface of Sample 1 (Fig 12) indicates that it cooled relatively quickly.

The vitrified surface is chemically different from the core, which suggests that another material has reacted with the stone. Within solid fuel furnaces, the ash from the fuel often attacks exposed surfaces of the furnace. The chemical composition of the vitrified surfaces of furnace components can help to identify the fuel: wood ash is rich in calcium and potassium (Turner 1956) but coal ash is rich in aluminium and iron (Dungworth 2003). Figure 13 shows the alumina and potassium oxide content of Upper Forge Sample 1 compared with that of coal ash and wood ash. Analysis of a fragment of refractory sandstone (and its vitrified surface) from the glass furnace at Shinrone (O'Brien *et al* 2005) confirms that this was wood fired (Fig 13). The elevated levels of alumina (and iron oxide) in the vitrified surface of Sample 1 from Upper Forge shows that it formed as a result of reactions between the stone and coal ash, and that the furnace was coal-fired.

Table 2: Average chemical composition of the vitrified surface and core of Sample 1 (n = number of analyses).

	n	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO
Surface	4	0.3	0.8	15.9	61.3	0.2	1.8	1.2	0.8	0.1	17.7
Core	7	0.4	0.8	7.2	83.7	0.2	1.2	0.2	0.5	0.1	5.5

Table 3: Average chemical composition of the stone, brick and mortar of Sample 2 (n = number of analyses).

	n	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO
Stone	5	0.3	0.6	5.2	86.4	0.2	1.0	0.3	0.7	<0.1	5.3
Brick	15	0.3	0.8	19.1	70.4	0.1	2.5	<0.1	1	<0.1	5.7
Inclusions	9	0.1	3.5	33	46.3	<0.1	0.5	<0.1	0.3	0.1	16.2
Mortar	4	0.4	0.7	22	70.5	<0.1	2.3	0.2	1.2	<0.1	2.8

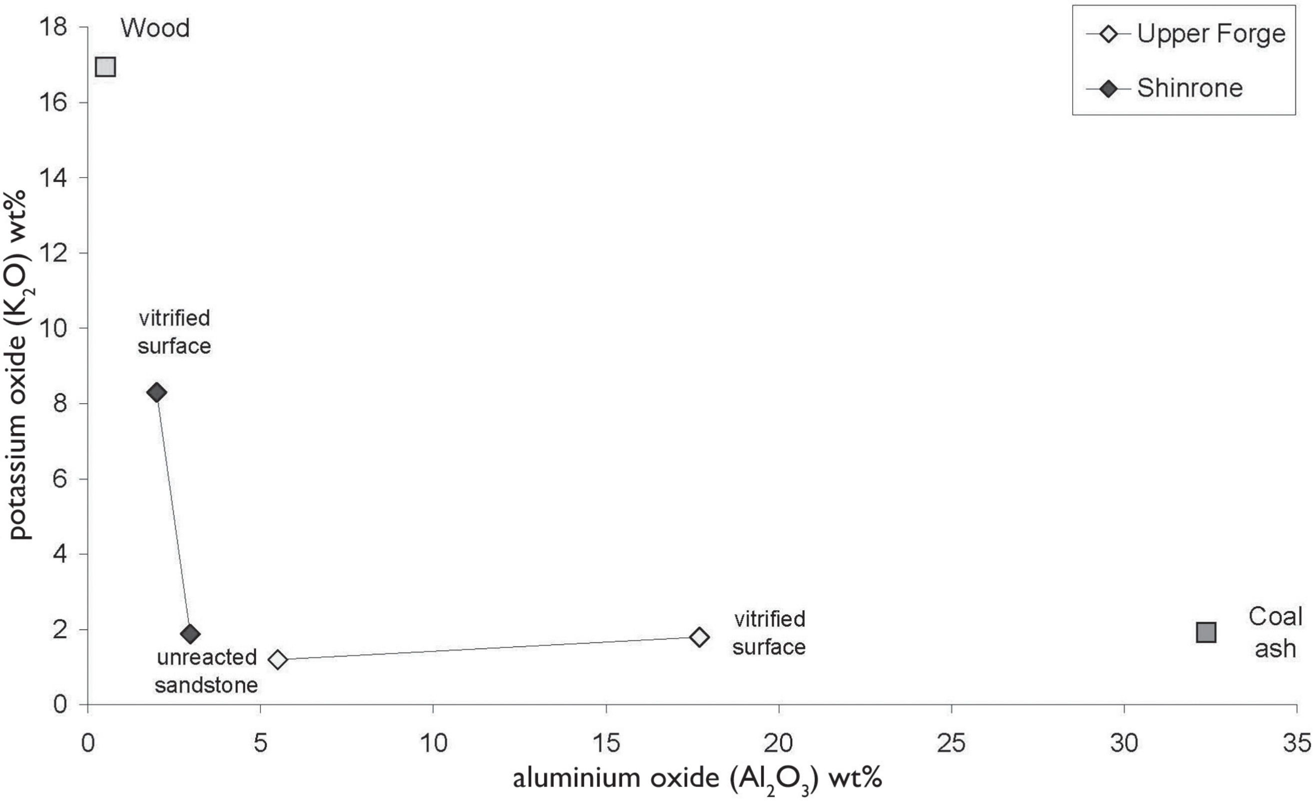

Figure 13: Aluminium oxide and potassium oxide contents of refractory sandstones and their vitrified surfaces from Upper Forge and Shinrone (O'Brien et al *2005). While the Shinrone vitrified surface has formed by reactions with wood ash, the Upper Forge surfaces have formed by reactions with coal ash.*

Sample 2

Sample 2 comprises a piece of sandstone adhering to a brick (Fig 10). The junction between these two components was clearly deliberate, as there is a line of clay mortar between the two.

The sandstone consists of grains of silica polymorphs (quartz and tridymite) with vitrified intergranular regions which contain small amounts of cordierite and iron cordierite (Fig 14a). The composition and petrology of this stone is very similar to Sample 1 and it would have had comparable refractory properties, *ie* it would melt at *c*1600ºC.

The brick portion of Sample 2 comprises grains of silica (XRD analysis confirmed the presence of tridymite) with intergranular zones of vitrification (Fig 14b). The average chemical compositions of the brick and mortar are not significantly different (Table 3) and it is likely that both were obtained from the same source. The average composition of the ceramic would not be fully molten below *c*1600ºC. The average compositions of the intergranular inclusions indicate that they would become fully molten at only slightly lower temperatures (*c*1500–1600ºC). XRD confirms the presence of mullite ($Al_6Si_2O_{13}$), cordierite ($Mg_2Al_4Si_5O_{18}$) and iron-cordierite ($Fe_2Al_4Si_5O_{18}$). The SEM-EDS spot analyses of the intergranular inclusions shows that some have compositions which approximate to iron cordierite (inclusions, Table 3). These are likely to have formed as a result of reactions between the silica and detrital minerals (*eg* biotite, garnet and spinel). The formation of cordierite as a result of high-temperature reactions would tend to strengthen the brick as it does not melt until 1465ºC (Deer *et al* 1966, 86), and it is well known for its thermal shock resistance (it is used to form the active components of catalytic converters in cars). The formation of iron cordierite would have been less beneficial as it melts at 1210ºC. Even if the brick was heated above the temperature at which some of these inclusions became fully molten, it is likely that it remained refractory. The inclusions occupy such a small volume that, even when molten, they would have been constrained by the surrounding silica grains.

Discussion

The examination of Samples 1 and 2 confirms that they are composed of refractory stone and ceramic. The stone in both samples displays similar chemical com-

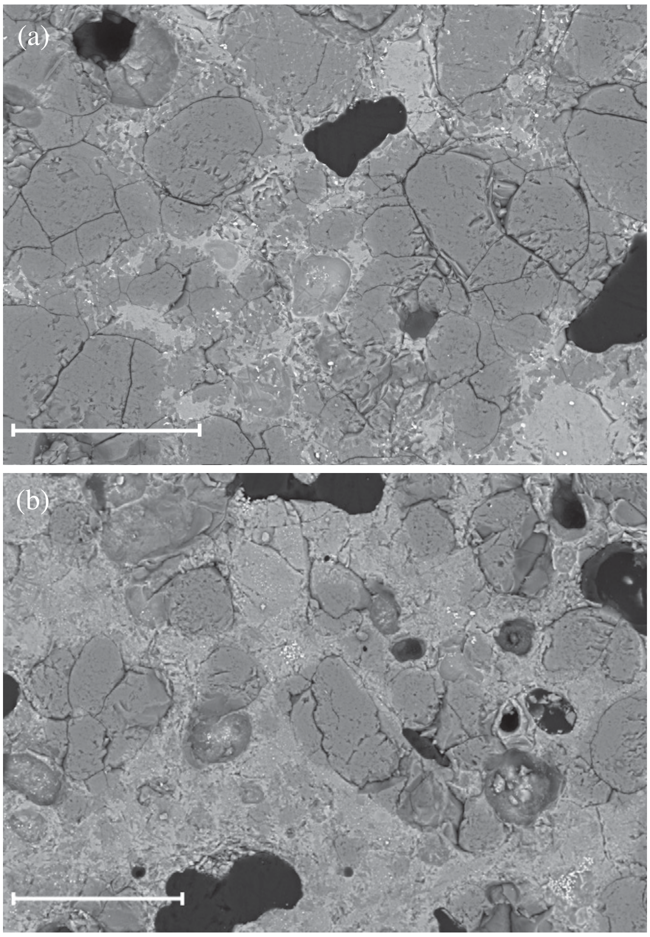

Figure 14: SEM images (BSE detector) (a) of the stone part and (b) of the brick part of Sample 2 (scales = 200µm). Both samples have porosity voids (black) and silica grains (darker grey) in a glassy matrix (lighter grey). There is less silica in the brick than in the stone.

position and petrology and they are likely to have been obtained from the same source. The stone would have suffered from some reduction in strength above 1210ºC (at least partially offset up to 1465ºC by the formation of cordierite) but would have been capable of exposure to temperatures up to *c*1600ºC. The nature of the vitrified surface of the stone in Sample 1 indicates that it was exposed to a maximum temperature of *c*1400ºC. The composition of this vitrified surface shows that the furnace was coal-fired. The brick and mortar are both ceramics with similar chemical compositions and may have been obtained from the same source. The ceramic is a highly refractory alumino-silicate which would have been capable of resisting temperatures up to at least 1500ºC. Analysis of the comparative samples confirms the initial impression from fieldwork that Samples 1 and 2 were from the sides or roof of the reverberatory chamber.

Sample 6, from Derwentcote, had a much higher silica content than the refractory stone from Coalbrookdale and would probably have been able to withstand higher temperatures and be less susceptible to chemical attack. Interestingly, Sample 7 contained even higher levels of silica (Table 4), so might have been even more refractory; however, the high silica content would have left this stone relatively soft. Refractory sandstones need to remain solid and resist chemical attacks at high temperatures. These two requirements are met by high silica content, however, the silica grains need a matrix to provide a bond. It is suspected that Sample 7 is too rich in silica to be a satisfactory refractory sandstone.

Overall discussion

The excavation and analysis of the Coalbrookdale furnaces has raised five main issues relating to our understanding of 17th century cementation steelmaking.

Location of the steelworks

Prior to the Coalbrookdale excavations, some authors suggested that Brooke's first furnace was in the Forest of Dean, with a move to Coalbrookdale only when he lost the Forest of Dean ironworks leases in 1636 (Schubert 1957; Mott 1960). The argument was that the furnace would be built close to the source of the iron and fuel (charcoal was assumed). The current excavations support the already-strong arguments for the first furnace being in Coalbrookdale (*eg* Wanklyn 1973). Brooke would have had compelling reasons to build there. First and foremost, he actually owned Coalbrookdale and Madeley and its extensive ironworking complex. This ensured stability, and provided him with a ready-made metallurgically-aware workforce. In the Forest of Dean, he was only a leaseholder of the iron furnaces, leaving him in a much more tenuous position. Outsider leaseholders in the Forest of Dean encountered significant local opposition and even sabotage, found the political situation difficult, and complained that the workforce was unreliable (Hammersley 1972). It would have been difficult to maintain full control of the process there, and maintenance of the secrecy necessary for

Table 4: Average chemical compositions of sandstone Samples 6 and 7.

Sample	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	K_2O	CaO	TiO_2	MnO	FeO
6	<0.1	0.4	5.9	92.0	<0.2	1.2	<0.1	0.3	<0.1	0.3
7	<0.1	0.4	2.9	96.1	<0.2	0.2	<0.1	0.2	<0.1	0.2

the protection of the patent would have been almost impossible.

Raw materials were plentiful at Coalbrookdale; indeed charcoal and wrought iron would have been ready to hand in the adjacent Upper Forge. Local iron may not have been ideal for conversion; however Brooke's links with the Forest of Dean ensured that sufficient supply of the low-phosphorus iron from that source could have been brought up-river at minimal cost. In the early period of the furnace it seems likely that there was considerable experimentation with different charges. Coal to heat the furnace would have been readily available locally, already exploited for at least 300 years before cementation steelmaking took place. Indeed the use of coal for ferrous metallurgy is extremely significant, albeit in an indirect process. The local stone evidently had good refractory properties, and selection of stone with suitable mechanical characteristics to resist chemical attack was probably made on the basis of experience. River transport, as already noted, was well developed by the early 17th century, with substantial cargoes of iron and coal being shipped down the river.

Design and construction of the furnaces

Although both furnaces were severely truncated, enough survives to show that the overall form was circular. This is significantly different from the next known cementation furnace, at Derwentcote (1733), which has a square base with conical chimney. It is however broadly similar to the later steel furnaces in Sheffield, albeit somewhat smaller. Intriguingly, the Coalbrookdale furnaces also have many similarities with contemporary glass furnaces, and the question of cross-fertilisation between different technologies is a particularly interesting one. Mineral fuel was being used in the glass industry by 1611, and excavations at the furnace of *c*1615 at Kimmeridge (Dorset) revealed an arrangement of two opposing flues with a central pillar, just as with the Coalbrookdale steel furnace (Crossley 1987). In this case the surrounding structure was square, rather than circular. In the case of glassmaking, the material to be melted was contained in crucibles resting on seiges (platforms) within the reverberatory chamber. Drawing on the evidence of the patents, Barraclough (1984) argues that the early cementation steelmaking process also made use of crucibles rather than the more conventional chest.

It is clear that the form of chest-based cementation furnaces varied widely before settling down to the two-chest design. This arrangement was certainly prevalent in the north east by late in the 17th century. Several examples of the type are known from mid-18th century sites at Newcastle, Blackhall Mill, Swalwell, Winlaton and Derwentcote, all with total capacities of between five and 14 tonnes (Barraclough 1984, 39, 65–67; Cranstone 1997, 38). In Birmingham, which had active steelmakers from at least the late 17th century, three-chest furnaces of between five and seven tonnes capacity had become more or less standard by the 1770s, despite requiring a longer firing period than a two chest furnace of similar size (Andersson 1767, 366–367). Sheffield itself had a long tradition of single-chest furnaces probably going back to the pre-Huntsman era; they were certainly predominant in the 1770s and remained in common use in the city until the 1790s (Jars 1774, 256–7; Barraclough 1977, 88–89; Belford 1997, 24–26). Excavations at Marshalls steelworks near the River Don encountered a single-chest furnace in use into the 19th century (Raistrick 1968, Belford 1996).

Reasons for the enlargement and rebuilding of the northern furnace cannot be determined from the archaeological evidence. Expanding the furnace may have been merely the easiest means of repairing and reinforcing a deteriorating structure. However the fact that the southern furnace is identical in diameter to the rebuild suggests that the expansion may have been functional. Brooke's earliest results, although clearly steel, failed to satisfy the Royal Armouries (Schubert 1957, 234). By increasing the size of the furnace base, both chimney height and furnace capacity could potentially be increased. Such modifications could lead to increased furnace temperatures, perhaps with the intention of reducing firing times. However regulation of the firing process, and perhaps quality control of the product, might have been more difficult. It is also a possibility that the modification of the furnace represents a change from crucible-based cementation to a chest-based process more in keeping with later developments.

Although equivocal, the evidence from the Coalbrookdale excavations tentatively suggests single-chest furnaces, at least in their later period. The dimensions of the structure would be in keeping with a mid-17th century description of the 'perfect furnace' in which 'the vault is 4 ells [2.38m] long and three ells [1.78m] wide inside' (Bjorkenstam *et al* 1982, 181). The central pillar could have supported a single chest, with a central fire beneath, stoked and serviced from the two ash pits which also served as flues.

Ancillary structures

These structures present two interesting problems. The first is the relatively small extent of the supporting infrastructure compared with other excavated examples.

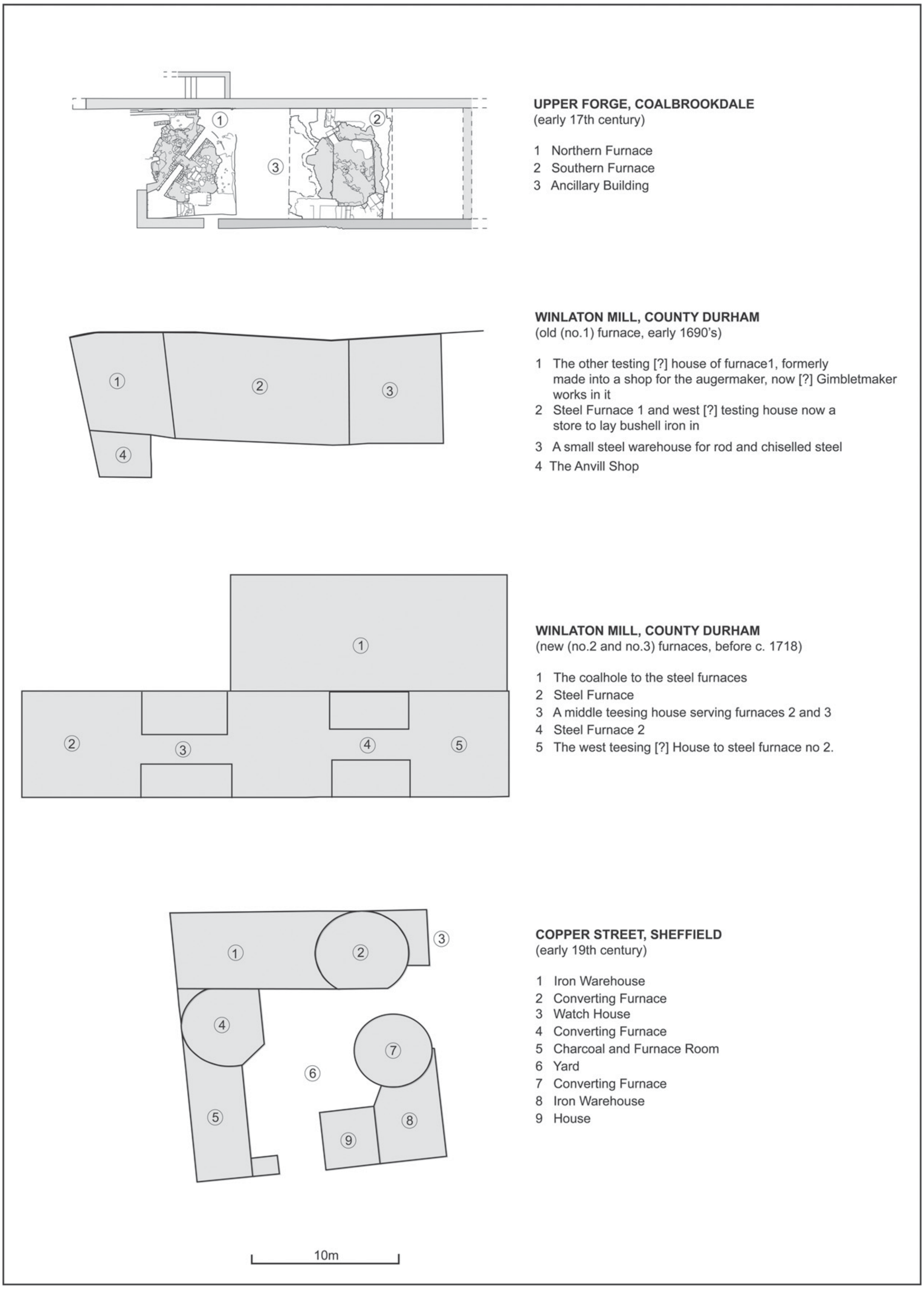

Figure 15: Arrangements of cementation furnaces and ancillary buildings. Top: Upper Forge, Coalbrookdale: shaded walls represent confirmed foundations of steelhouse ancillary buildings (from excavated evidence); Upper Middle: Winlaton Mill, old furnace of c*1690 (as shown on a map of* c*1718); Lower Middle: Winlaton Mill, early-18th-century furnaces, built before* c*1718 and evidently 'new' on a map of that date; Bottom: Copper Street, Sheffield, early-19th-century cementation site (as shown on a Fairbank plan of 1834).*

At Derwentcote, the southern 'feasing house' measures 12.7m by 7.8m, and the northern is 6.3m by 4.3m (Cranstone 1997, 43–45). At Winlaton Mill, the overall length of the ancillary buildings surrounding Nos. 2 and 3 furnaces (built sometime before *c*1718) is approximately 38m (Fig 15). However the 17th-century description cited above states that 'a building for 2 such steel furnaces must be 18 ells [10.69m] long and 8 ells [4.75m] wide' (Bjorkenstam *et al* 1982, 181). The Upper Forge falls somewhere in between. The comprehensive remodelling of the site to build the furnaces rules out constriction by earlier buildings, although the presence of the tailrace from the Upper Forge to the east and the main stream itself to the west, would have imposed the north-south orientation of the complex. The absence of substantial ancillary structures may be the result of later destruction. More likely, the adjacent Upper Forge complex would have already had significant charcoal and bar iron storage facilities, and the ancillary structures for the steel furnaces may simply have comprised shelter for access during firing periods. Derwentcote and Winlaton Mill, sites with comparably-sized ancillary buildings, were also both located within, or adjacent to, established forging complexes.

More significant, and more puzzling, is the rather odd orientation of the ancillary buildings in relation to the furnaces. At later furnaces, from Derwentcote onwards, the ancillary building opens directly off the end of the firebox/ash pit. This makes practical sense: workers with tools and wheelbarrows could approach the ash pit and fire box directly. Here, a worker approaching any ash pit has to make a 120-degree turn at the bottom of the stairs. Air flow would also be impeded compared with later known designs. In either case, however, there is no obvious functional reason to put the furnace axis diagonally across the building. One possibility is that the orientation of the ashpits may have been a deliberate attempt to mitigate against excessive wind-flow from a particular direction; the opposition in alignment of the two furnaces may have enabled the variations in prevailing wind direction to be evened out (assuming that both furnaces were in operation at the same time). However the problem remains unresolved.

Operation of the furnaces

Some elements of the operation of the furnace have been addressed. The furnace was fired using coal. The analysis of refractory material suggests that the operating temperature was a minimum of 1300° and maximum of 1400° to 1500°C. This is substantially higher than the 1050–1100°C reported by Barraclough (1984, 35). Indeed cementation could produce a steel with 1.7wt% carbon which would begin to melt above 1130°C. This apparent discrepancy may result from the fact that not all parts of the cementation furnace would be at the same temperature. The contents of the cementation chests would need to be in the region of 1050–1100°C but the combustion zone in the furnace would need to be somewhat higher, due to the loss of some heat as exhaust gases. As noted above, the refractory material appears to have come from the lining of the reverberatory chamber, where localised temperature variation may have been considerable (for example adjacent to the flues). The temperature difference seen in this case might indicate a poor heat efficiency for the Upper Forge furnace. However, there are no comparable data for later cementation steel furnaces.

There are, of course, many operational questions that we have not yet been able to answer. The length of each individual firing or 'heat' is clearly unknown. In general practice from the 17th to the 20th centuries a period of between ten days and two weeks was common, but the experimental nature of the Coalbrookdale furnaces may have resulted in different working practices. It is not yet clear how much iron and charcoal was used in each charge, and how the two materials were arranged. Nineteenth-century furnace charges contained between 30% and 40% iron (Barraclough 1984, 108). The efficiencies of conversion were extremely variable. Mid-17th century accounts suggest that around 6.5 tonnes of bar iron would produce around 5.4 tonnes of steel, using '18 to 20 barrels of charcoal' fuel every 24 hours (Bjorkenstam *et al* 1982, 175, 181). In the second quarter of the 19th century, Sheffield furnaces with a capacity of between 15 and 20 tonnes were producing between 0.9 and 1.3 tonnes of steel per tonne of coal burned (Barraclough 1984, 236; le Play 1843, 625–626).

Loading and emptying the furnace would also have taken several days (Hoglund 1951, 11–15). Allowing for cooling time a typical cycle may have been as long as a month. Certainly at Newcastle late in the 18th century it was 'customary not to carry out more than twelve campaigns in the year...[but]...the furnaces in Sheffield, Rotherham and Birmingham are kept going all the year round, or as much as possible, provided there is no lack of bar iron' (Andersson 1767:163–169). A related question is the nature of the labour force: were people deployed from the forge, or was a specially trained group of workers initiated into the secrets of steel manufacture?

Raw materials and products

The source of iron is as yet unknown, although it seems most likely that Brooke would have used local Shropshire bar as well as low-phosphorus iron from the Forest of Dean. It is possible that Swedish wrought iron was imported via the River Severn during the later operational life of the Coalbrookdale steelworks. Trade via Bristol was increasingly vigorous during the 17th century (Evans and Ryden 2007). The limited documentary evidence suggests that steel bar was being exported rather than finished products such as weapons or other goods (GPR). However It is also unclear to what extent forging took place after conversion, although the proximity of the Upper Forge suggests that the steel may have been further refined by forging prior to shipment.

Conclusions

The excavations of Basil Brooke's two cementation steel furnaces at Coalbrookdale have clarified many issues surrounding the introduction of this technology to Britain, and its development through the seventeenth century. Inevitably they have also raised a number of new questions. A more complete report on the excavations, covering all phases, is in preparation (Belford and Ross in preparation). Sample analysis and documentary research is continuing. These are likely to shed light on some of the issues that remain unresolved.

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The authors

Paul Belford is Head of Archaeology and Monuments at the Ironbridge Gorge Museum Trust. A field archaeologist with diverse research interests including post-medieval ferrous industries, early post-dissolution industrialisation, colonialism and contemporary and historical archaeology. He has been the Conservation Officer of the Historical Metallurgy Society since 2003.
Address: Ironbridge Gorge Museum Trust, Coach Road, Coalbrookdale, Telford, Shropshire, TF8 7DQ.
e-mail: paul.belford@ironbridge.org.uk

Ronald A Ross is a CAS Professor at Wilfrid Laurier University, Waterloo, Canada, in the Department of Archaeology and Classical Studies, and the Medieval Studies Program. He is currently researching late Medieval and early Post-Medieval industrialisation. He has concurrent interests in experimental iron smelting and archaeological epistemology.
Address: Department ofArchaeology and Classical Studies, Wilfrid Laurier University, 75 University Avenue West,Waterloo, Ontario, Canada, N2L 3C5.
e-mail: rross@wlu.ca

David Dungworth obtained a degree in Ancient History and Archaeology from the University of Birmingham in 1991 and a PhD (*Iron Age and Roman Copper Alloys from Northern Britain*) from the University of Durham in 1995. Since 1999 he has been employed by English Heritage as a materials scientist.
Address: English Heritage, Fort Cumberland, Eastney, Portsmouth, PO4 9LD.
e-mail: david.dungworth@english-heritage.org.uk