# 3 KNOWLEDGE AND UNDERSTANDING

This section contains selected examples of what we know about metalworking in the past. It does not cover all metals at all periods, but gives examples of topics where either considerable progress has recently been made or, on the other hand, where there are still fundamental matters to be addressed. The examples have been chosen to provide a wide chronological spread of both ferrous and non-ferrous working.

- The earliest metallurgy in the British Isles belongs to the Bronze Age and Iron Age. For the Bronze Age the concentration is on metal mining, because so much new information has recently come to light (section 3.1). For the Iron Age, understandably, the focus is on the introduction of iron as an everyday metal (section 3.2), though copper alloys continued in use.
- The Roman period saw a massive increase in the scale of metal use and hence metalworking; the examples we give are the iron industry of the Weald (section 3.3), and the widespread adoption of brass as a common copper alloy (section 3.4).
- In the post-Roman and medieval periods, the lack of evidence for copper production is highlighted (section 3.6) and the fluctuating fortunes of various copper alloys are discussed (section 3.5). Medieval methods of steel production are considered in section 3.8, with later steelmaking processes.
- After the medieval period there is a second major change of scale with the industrialization of many metal industries. In contrast with earlier periods, significant documentary evidence is available. Neither archives nor archaeology can provide all the answers, but together they can answer more questions than either can alone. An overview is presented of our current knowledge of two important metal industries in post-medieval and modern Britain: the lead industry (section 3.7) and the iron and steel industry (section 3.8). The point is also made that archaeometallurgy seeks to go further and show how inextricably linked these industries, and the questions surrounding their development, are to the changes in British society and the lives of its people.

## 3.1 Prehistoric metallurgy in the British Isles

### Copper mines

The earliest metallurgical sites in Britain are copper mines (Table 3) which have been identified by the discovery of stone hammers, and dated by radiocarbon measurements of charcoal or preserved wood, where suitable material exists.

Stone hammers are one indicator of prehistoric mining activity, as are the tell-tale indentations left by their use; however they are not conclusive in isolation as it is not clear how long their use continued. Irregular hollows that form naturalistic arched openings commonly relate to prehistoric working (O'Brien 1996; Timberlake 1990). Fire-setting was used in the Bronze Age but remained common in some mines up to the early 18th century (Barnatt and Worthington 2006). The discovery of small pick-cut shafts and levels indicates that the mine was

*Table 3: Early Bronze Age mine sites (the numbers relate to Figure 50)*

| | Mine | References | Date |
|---|---|---|---|
| | Tyn y Fron (Ceredigion, Wales) | Timberlake 1996 | |
| 1 | Cwmystwyth (Ceredigion, Wales) (Fig 49) | Timberlake 1991; 2001a; 2001b; 2003 | *c*2000–1600 BC |
| 2 | Nantyreira and Llancynfelin (Ceredigion, Wales) | Timberlake 1995 | |
| 3 | Great Orme (Gwynedd, Wales) | Dutton and Fasham 1994; Lewis 1996 | *c*1900–1500 BC (20 dates) |
| 4 | Parys Mountain (Anglesey, Wales) | Jenkins 1995; Timberlake 1988 | |
| 5 | Bradda Head (Isle of Man) | Davey *et al* 1999 | |
| 6 | Alderley Edge (Cheshire) | Garner *et al* 1993; O'Brien 1996; Timberlake and Prag 2005 | *c*1750 BC |
| 7 | Ecton Hill (Staffordshire) | Barnatt and Thomas 1998 | |

*Figure 49: View of the mining landscape at Copa Hill, Cwmystwyth. The Bronze Age workings are at the top of Comet lode (running vertically down the hillside in the centre of the picture).*

operating at some time after the development of iron tools but before the widespread use of gunpowder. It is likely that more mines were worked in the prehistoric period but later mining has obliterated evidence for this. Alderley Edge is a good example of a multi-period site with prehistoric, Roman and 18th/19th century exploitation, and at Cwmystwyth there is archaeological evidence for Early Bronze Age, medieval and 18th/19th century working as well as documentary evidence for Elizabethan and 17th-century mining (Timberlake 2001a). There are areas of copper mineralization, *eg* in south-west and north-west England, which could have been exploited in prehistory (and were exploited in later periods) that have not been identified as prehistoric sites, because no stone hammers have been found (Fig 50). No prehistoric copper mines have been identified in Scotland, although there is strong circumstantial evidence for Early Bronze Age copper production, based on artefact typology and composition (Northover pers comm). The discovery of a plano-convex copper ingot at Edin's Hall broch (Scottish Borders, only 1.4km from the historical mine at Hoardweel) indicates that this source was probably used in the Iron Age, but field evidence for prehistoric working has yet to be identified (Hunter 1999; Fig 51).

## Lead mines

The extraction of metals other than copper in prehistory has been even less-well recognized. Lead was clearly used in prehistory and more and more lead artefacts are being identified. A cannel coal necklace has been found in an EBA infant burial in Peeblesshire, Scotland, with a second string made up of lead beads (Hunter and Davis 1994; Fig 52) and two lead artefacts are known from Derbyshire, one a fragment of a lead torc (Barnatt 1999, 21–22). These finds show that lead must have been smelted in the Early Bronze Age as it is never found in its metallic form in nature. No evidence for its smelting has

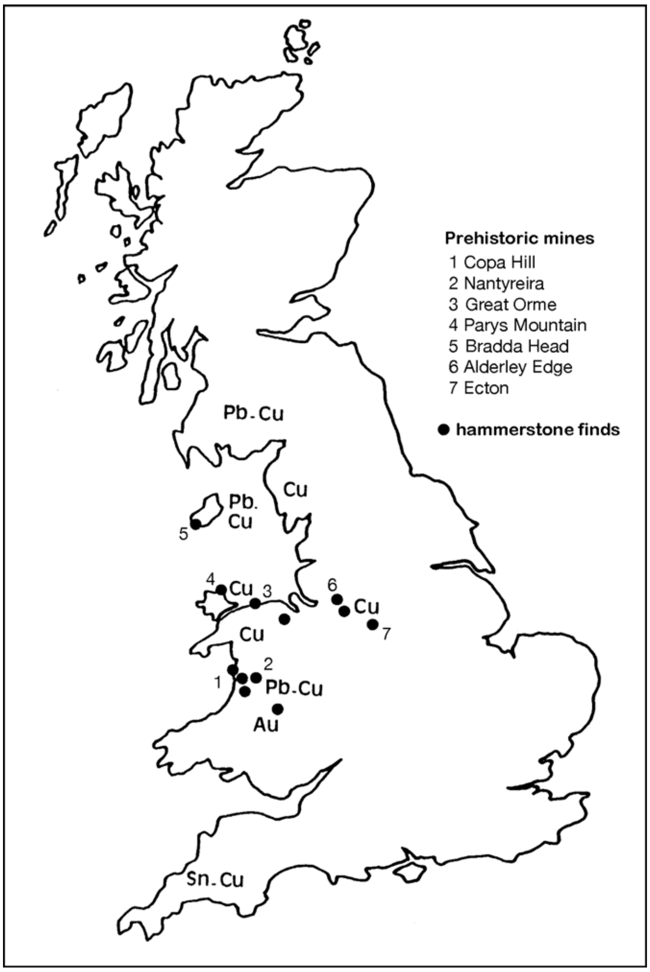


*Figure 50: Map showing finds of stone hammers, and known British prehistoric mining sites in relation to ore-bodies.*

been found although it can easily be reduced from its ore in a bonfire (Craddock 1995, 205) and this would leave little archaeological trace. In areas of Britain where lead mineralization is known, *eg* the Mendips and Derbyshire, traces of mining seem to have been largely removed by later exploitation. However, it is likely that evidence for prehistoric lead mining will be found in one or both

*Figure 51: Plano-convex copper ingot from Edin's Hall broch, Borders. Diameter 260mm.*


*Figure 52: Early Bronze Age cannel coal and lead necklace, as excavated, Peebleshire.*

areas, especially as prehistoric copper mining has been confirmed at Ecton, Staffs (Barnatt and Thomas 1998), and very early Roman lead mining at Charterhouse on the Mendips (Todd 2007), suggesting an earlier inception of mining there. The greatest concentration of known prehistoric metal mines in Britain is in Central Wales and all the mineral veins mined are of lead containing small amounts of copper ore (Timberlake 2003). At Cwmystwyth the early miners appear to have worked around the galena veins and apparently rejected lumps of galena. However, on the working floor of the mine layers of crushed galena have been found and some of the veins worked appear to have contained nothing but this mineral (Timberlake 2001a). Indeed, it has been argued by some that the site was a Bronze Age lead mine (Bick 1999; Mighall *et al* 2000) rather than a copper mine.

### Tin

Tin production is of crucial importance to our understanding of the Bronze Age, especially as it is rare elsewhere in western Europe, yet there is limited evidence for tin mining and smelting in Britain before the medieval period. Tin slags are known from Bronze Age contexts in Cornwall (Tylecote 1986, 43), and many prehistoric and Roman artefacts were recovered during 19th-century tin-streaming (though their association with tin extraction is circumstantial) (Penhallurick 1986; Gerrard 2000), so it may be that deposits of alluvial tin that have long since been worked out were exploited (see Section 1.1). Questions of tin supply in northern Britain have recently been brought into sharper focus by the discovery of a jet button inlaid with metallic tin, part of a set from a rich dagger grave in Fife, Scotland (Baker *et al* 2003), while recent analytical work on MBA faience points to the deliberate addition of tin to the glaze (Sheridan 2003).

### Precious metals

There is no evidence for prehistoric British gold or silver extraction; there are no silver artefacts from Bronze Age Britain and few from the Iron Age before *c*70 BC (Craddock pers comm). Many gold artefacts are known from all phases of the Bronze Age (Northover 1999b); the earliest are from Beaker contexts and accompany the arrival of copper-working technology from the Continent (Fig 53). Gold objects seem to disappear from the archaeological record at the end of the 8th century BC, and indeed metal of any kind is scarce at the beginning of the British Iron Age, in contrast to the Halstatt heartlands where metal objects are known in abundance. The re-dating of ribbon torcs to the Iron Age (Warner 1993) shows the continued use of gold in Scotland (and Ireland); in southern Britain gold only reappears with the first Celtic coins in the late 3rd or 2nd century BC. Pre-Roman gold mining has recently been suggested at Dolaucothi in Wales (Burnham and Burnham 2005, 229–230).

### Bronze Age metalworking

Our understanding of early smelting and production techniques is as sketchy as that of mining. There is very little direct archaeological evidence for Bronze Age metal smelting and much that we do have is from the Middle Bronze Age, considerably later than the beginnings of metallurgy in Britain. The lack of smelting evidence means we do not yet know where it was done; was it close to the mines or on settlement sites? Does this vary from phase to phase? Pieces of pure copper, including plano-convex ingots, have been


*Figure 53: Two Bronze Age gold discs imitating the gold-bound amber discs of Wessex. Found as a grave group of the Food Vessel Period, Barnhill, Broughton Ferry, Angus.*

found in founders' hoards and on settlement sites (Tylecote 1986, 22). Recently a Middle Bronze Age copper-smelting hearth was found at Pen Trwyn, a cliff-top location on the Great Orme. The site is poorly preserved, but copper appears to have been smelted in a small open hearth and the slags produced were crushed to extract the copper prills (Chapman 1997). The oldest crucible fragment is from Grimes Graves, Norfolk, and the earliest raw copper that can be reliably associated with local smelting is from Pen Trwyn and Llwyn Bryn Dinas (Northover, pers comm).

The range of Early Bronze Age stone moulds from the NE of Scotland provides a source of evidence unmatched elsewhere in Britain (*eg* Coles 1969; Schmidt and Burgess 1981) and recent excavations have expanded the number of Late Bronze Age workshop sites, including previously blank areas such as the Western Isles. Nationally, such early metalworking evidence is still rare: less than 50 sites are known from the UK as a whole, and many of these have produced small unrepresentative amounts of material. Scotland is particularly fortunate in having some unusually large assemblages — in particular Jarlshof (Hamilton 1956) and Traprain Law, and these have recently been augmented by significant new groups of material from Galmisdale, Isle of Eigg (Cowie 2002) and Cladh Hallan, S Uist (Parker Pearson *et al* 2002).

## Artefact analyses

We are still a long way from a full knowledge of the production, supply and dissemination of Bronze Age metal-work. Our present knowledge of how, when and where metallurgy started in Britain is based on the study of the artefacts themselves. The copper wire ring straps and gold-covered bead from Barrow Hills, Radley (Oxfordshire) are currently the earliest metal finds in Britain (2490–2200 BC at 1σ) and as yet only have parallels on the Continent. Their chemical composition has no parallel amongst later British copper artefacts, the closest being objects from France (Northover 1999a, 212). One can see these first British copper finds as the result of Continental contacts. Two awls, one from Abingdon and the other from Basingstoke, have also been shown to have Continental-type compositions; a date of 2700 BC has been given to that from Abingdon and copper blades of similar composition are associated with the Amesbury archer burial (Northover pers comm).

Evidence for the first use of bronze is only slightly better; daggers from burials in Oxfordshire (including one from the Radley group) have given radiocarbon dates of 2460–2040 BC (1σ) and there is a handful of other objects from various locations in association with Beaker material extending the date-range to *c*1750 BC (Northover 1999a, 213). What is clear is that the adoption of tin-bronze over copper and arsenical copper was rapid, but this remains to be explained. Groupings of artefacts by their minor- and trace-element compositions that can be related to date and provenance are now quite well established yet remain based on relatively small numbers of analyses. Inappropriate emphasis is placed on the analyses of small numbers or even single artefacts with exceptional compositions; statistically-valid composition groups are still needed in some areas. The routine analysis of Bronze Age metal-work would enlarge the available database and refine existing groupings. The application of lead isotope analyses to Bronze Age copper-alloy metal-work has also yielded important results (Rohl and Needham 1998) and the combination of both chemical and isotopic techniques has been shown to be particularly useful in addressing archaeological problems (Needham 2007) (see section 2.4).

## Iron Age bronze-working

The transition from the Bronze Age to the Iron Age is a topic of particular interest and importance, though our knowledge of it is scanty. By definition, metalworking technology would seem to have played an important role, but many books on the subject divide the Bronze from the Iron Age, thus neatly avoiding the transition. The extractive metallurgy of later prehistory is even less well known than that of the Bronze Age and there has been a concentration on Iron Age iron production (see section 3.2) at the expense of the non-ferrous metals. Northover's (1984) analyses of material from the hillfort of Danebury indicated that copper was being obtained from south-western England as well as mixed continental sources, but clear evidence for Iron Age mining is scant. At Alderley Edge there is evidence of Roman as well as Bronze Age mining, and it may therefore have continued to supply copper during the Iron Age. At Llanymynech, Powys, a large 'cave-like' mine within the Iron Age hillfort has yielded a Roman coin hoard, proving Roman or earlier mining. Finds of 'raw' smelted copper with zinc in the associated hearth material strongly suggests that the mine was active in the Iron Age; the distinctive copper-lead-zinc ores match the composition of a specific compositional group of Iron Age copper-alloy metal-work (Craddock and Northover pers comm). There is evidence too for a crucible process at nearby Llwyn Bryn Dinas (Northover 1991 and pers comm).

Evidence for copper-alloy working is much more common, with many sites providing evidence (see Table 4).

*Table 4: Selectd Iron Age copper-alloy working sites*

| Site | References |
|---|---|
| Gussage All Saints, Dorset | Wainwright 1979 |
| Weelsby Avenue, Grimsby, Lincolnshire | Foster 1995 |
| Bagendon, Gloucestershire | Clifford 1961 |
| Glastonbury Lake Village, Somerset | Gray 1911; Coles and Minnett 1995 |
| Fison Way, Thetford, Norfolk | Gregory 1991 |
| Hengistbury Head, Dorset | Cunliffe 1987 |

Morris (1996) provides a more comprehensive list of sites.

In general terms, one of the changes that can be seen occurring between the Late Bronze Age and the Iron Age is the increase in known locations for bronze-working (Morris 1996, 54). Relatively large numbers of crucible and mould fragments are found, and wrought-bronze-working is also important. Coin pellet moulds provide widespread evidence of minting; gold and silver coins were struck from the metal blanks (pellets).

Bronze (with or without lead) was almost the only alloy used during the Bronze Age and early Iron Age, but with increasing continental contacts brass objects begin to appear in the later Iron Age. Recent analysis of a La Tène sword (Fig 54) from Isleworth revealed brass foils which put the earliest use of the metal in Britain back by between one and two centuries, certainly before the Roman conquest of Gaul (Craddock and Cowell 2006). Previously, brass objects were known only in the period immediately preceding the Roman invasion of AD 43 (Bayley 1998) when continental influence and Roman material culture began to become established in southern Britain — though even then there is so far no good evidence that brass was made or even melted here.

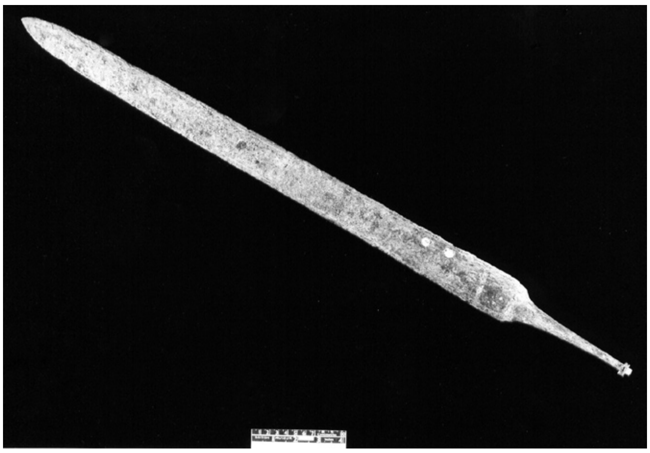

*Figure 54: Iron Age sword with brass appliqués from Isleworth, Middlesex. Length 750mm.*

*Figure 55: Iron Age slag heap at Moore's Farm, Welham Bridge, East Yorkshire, during excavation. After Halkon 1997.*

## 3.2 The beginnings of iron technology

There are two main issues in the study of early iron working: the emergence of iron smelting (primary production) and that of iron smithing. They are not the same, and may have taken place in quite different locations. Smithing evidence is usual on settlement sites, and there is plenty of evidence from sites like Danebury or Maiden Castle (Salter 1991a; 1991b), where hammer scale distributions could be used to study the scale and organization of iron smithing.

The first iron-smelting technology was the bloomery process, a solid-state, single-stage process where iron ore was reduced to metallic iron in a charcoal-fuelled furnace. The reducing agent, carbon monoxide, was provided by the charcoal. The product was a bloom of mainly low-carbon iron, which could be forged into an artefact, the forging also serving to remove most of the slag that had become trapped within the bloom (Fig 55). Since early bloomery furnaces rarely survive to any height archaeologically, it is very difficult to establish how they were constructed and operated (Fig 56). The earliest bloomery furnaces appear to have retained the slag produced during smelting within the lower part of the furnace, or in a purpose-built pit below. Experimental archaeology and further archaeological investigation has cast doubt on the early assumption that these were bowl furnaces (Clough 1985; Pleiner 2000); instead the furnaces are now thought to have had a superstructure of some kind, a shaft or dome. Subsequent developments allowed the slag to be tapped at ground level from the furnace in a molten state; it is conventionally assumed that slag-tapping furnaces were introduced late in the Iron Age, not becoming common until the Roman period, but this assumption has been challenged (Salter 1989) and more evidence is needed.


*Figure 56: Roman furnace at Laxton, Northamptonshire. The basal slags have been removed and the lower deposit of ore fines sectioned. The right hand side of the furnace has been damaged by a recent pit. After Crew 1998b.*

Iron ores are widespread throughout Britain, and many lesser-known deposits were used in small-scale smelting operations of the Middle Ages and earlier (Kendall 1893; Paynter 2006;Tylecote 1986, 124–8). Iron smelting required not only ores but access to adequate supplies of fuel (*ie* charcoal, which required substantial reserves of natural woodland or coppice), and to refractory clays and/or sandstones for the inner linings of furnaces.

Little is known about Iron Age iron mining; early extraction sites have been hard to recognize, sometimes obscured or destroyed by later working. Within the last ten years there has been an increase in our understanding of bloomery iron smelting which is bringing a re-assessment of archaeological evidence (*eg* Paynter 2007b). While it is clear that some iron smelting was conducted within non-specialized settlements, there may also have been separate production sites. These Iron Age bloomeries are less easy to identify due to the sometimes small quantity of slag, often with an unusual morphology. These features are also hard to date, due to difficulties in radiocarbon dating (because of the flatness of the calibration curve at this period and because oak charcoal was the commonly used fuel and oak is a long-lived species), difficulties in archaeomagnetic dating (because smelting furnaces cooled whilst containing magnetic material) and the usual lack of closely-datable artefacts. Excavations of Iron Age settlements have concentrated on the Chalk downlands and the gravel terraces of southern and Midland England, not areas renowned for their iron ores, and this may partly explain the small number of known smelting sites. The syntheses by Tylecote (*eg* 1986, 124–54) remain the standard overview, but much of his information **was** derived from old fieldwork, and many aspects of his dating and interpretations urgently require review. More recent work by Peter Crew at Bryn-y-Castell and Crawcwellt in North Wales (Crew 1998a), and by Peter Halkon at Welham Bridge (dating to *c*400 BC) and other sites in the Holme-on-Spalding-Moor area of East Yorkshire (Halkon 1997, Halkon and Millett 1999) and current work by the Wealden Iron Research Group (WIRG) point the way. Work of similar quality is needed in areas such as the Jurassic orefields of Northamptonshire and Lincolnshire, which later were centres of the iron industry. The paucity of surviving furnace structures adds to the importance of fragments of refractories, slags and other process residues, and of the few iron artefacts that survive in good enough condition for full metallurgical analysis.

## Iron slags

Iron slags are common on archaeological sites across England and scientific investigations of this durable waste product have great potential. Morphological details can provide information on how furnaces, long-since destroyed, were constructed and operated. Compositional data can provide information on the raw materials and conditions used and the metal produced. Estimations of quantity can suggest the scale of the industry and the economic significance.

The quantity of slag recovered from the earliest smelting sites is often small, usually of the order of tens of kilograms (Bayley *et al* 2001; Starley 1998; Paynter 2002), but can exceed a tonne (McDonnell 1988; Crew 1998a). Analyses of slag from Iron Age sites (Paynter 2006) has shown that it is generally similar to that of the Roman period, allowing for differences in the ores used (Fig 57). This suggests that broadly similar amounts of energy were used, in terms of a combination of the temperature and duration of the smelt. The temperature required to form the slags has been estimated from mathematical models (Paynter 2007b), and this suggests that a forced draught was probably used from an early date.

The differing morphology of smelting slag from sites of different dates is indicative of technological developments. Samples of Early Iron Age slag and some from Late Iron Age sites have a cake-like form (also known as furnace bottoms), a coarse microstructure, and contain occasional small particles of trapped iron (Paynter 2007b). The slag appears to have had a high viscosity and surface tension as it collected. This evidence suggests that the smelting furnaces were constructed with deep hearths or pits below ground-level where the slag accumulated and cooled, as discussed by Pleiner (2000) and Tylecote (1986, 133). These pits were probably packed with organic material

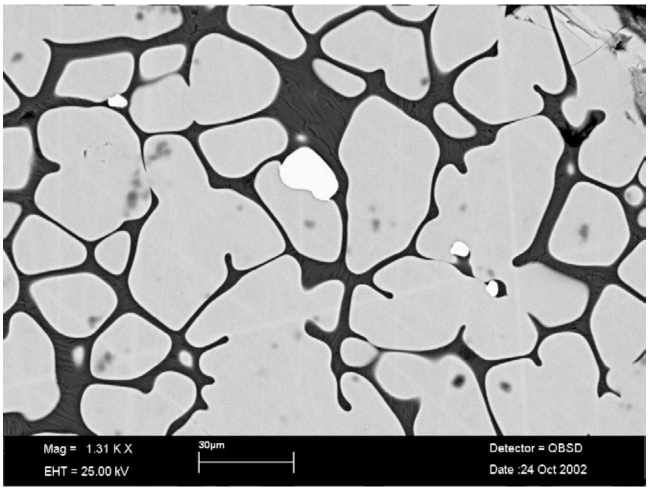


*Figure 57: Backscattered SEM image of Late Iron Age/Roman iron slag (slag cake) showing metallic iron (white) and wüstite (iron oxide, light grey) in a dark glassy matrix.*

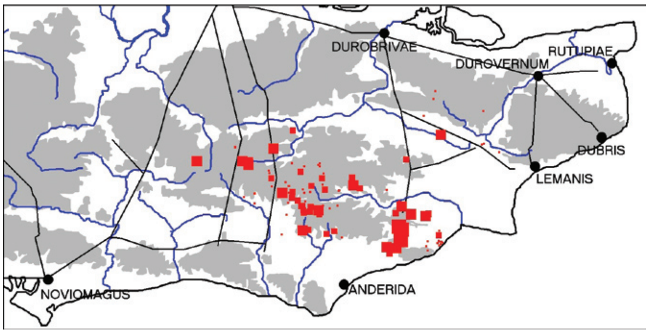


*Figure 58: Map showing the location of Roman iron-smelting sites in the Weald. The four sizes of red squares represent sites with over 10,000m³ of iron slag, 1,000–10,000m³, 100–1,000m³, and under 100m³ of iron slag respectively.*

(such as charcoal, straw or wood) that burnt away during the smelt as slag accumulated. The impressions of wood, charcoal or straw in some slag samples (Paynter 2007b; Starley 1998) are consistent with this interpretation.

In contrast, slag-tapping furnaces, which were widespread by the Romano-British period, were constructed so that slag could be tapped whilst molten, often in large amounts. Tapping slag during smelting kept the base of the furnace clear, enabling smelting to continue for longer and the furnace to be reused. This method is efficient but requires a robustly-built furnace structure and fairly frequent repairs, evidence for which is quite common from Romano-British smelting sites (Cleere and Crossley 1995; Paynter 2007a). Current work has revealed the shortcomings of existing typologies and especially chronologies, hinting at regional variations rather than clear-cut chronological progression.

## 3.3 Roman ironworking in the Weald

Iron working during the Roman period was widely spread throughout Britain, with concentrations in the Weald, the Forest of Dean, in the East Midland counties of Northamptonshire, Rutland and Lincolnshire, in E Yorkshire, and on the Blackdown Hills and Exmoor in SW England. Recent research in the Weald presents a good example of what an integrated study of a Roman iron-producing landscape can reveal.

In the Weald, 102 Roman-period sites have been dated by test-trenching and recovery of pottery. These represent about 17% of the bloomery sites of all periods known in the region, and about 63% of the dated bloomeries there (Fig 58). However, continued use of native pottery into the second century AD, types which are subject to differing interpretations (Green 1980), makes precise differentiation of late Iron Age and early Romano-British sites difficult, and indeed points to continued production of iron by native workers, presumably with changes in markets and in the control of the industry.

Wealden bloomeries of the Roman period vary in size. A recent review suggests that the largest sites contain up to 3000 times the quantities of residues of the smallest (Hodgkinson 2000). This has implications for estimating the overall output of the industry at different periods during Roman times. The juxtaposition of larger and smaller sites has suggested that some smaller sites operated as satellites. Many of these, with less than 100m³ of iron slag, will have had short working lives, and the dating methods used by WIRG do not show whether they were worked during a short period during the Roman occupation, or throughout the period.

Iron slag was used in the Roman period to make roads in the Weald. A substantial part of a 30km length of the trans-Wealden section of the road from Lewes to London was thus surfaced (Margary 1965). These roads, as well as providing access to the south coast and to the agricultural produce grown in the coastal areas, enabled iron from the Weald to be carried to London and on to other markets.

A factor in the development of iron smelting in the Weald during the Roman occupation was the involvement of the *Classis Britannica*, the British fleet, which operated as a logistical, as well as a naval, arm of the Empire (Cleere 1974). Roofing tiles stamped CLBR from three iron-working sites — Beauport Park, near Battle (Brodribb and Cleere 1988), Bardown, Ticehurst (Cleere 1974), and Little Farningham Farm, near Cranbrook (Aldridge 2001) — point to the direct involvement of the fleet in iron making (Fig 59). At Beauport Park, which is


*Figure 59: The stamp on a* Classis Britannica *roof tile from Beauport Park, East Sussex.*

**Example: Scientific investigation of Roman iron smelting**

The excavation of the Romano-British settlement at Westhawk Farm retrieved approximately 1.65 tonnes of iron-working waste (Paynter 2007a). About 6ha of the settlement were excavated and two structures were identified where iron-working took place; one dated to *c*AD 110–160 the other to *c*AD 200–250. Careful excavation, recording and sampling enabled the layout of the workshops to be reconstructed. Smelting and smithing both took place in the same enclosures, although the areas for each activity were distinct. A small proportion of smithing slag was identified and a large deposit of hammerscale was found in one of the workshops indicating that primary smithing of the iron produced took place on site. The hammerscale deposit covering one of the workshop floors indicated that the hearth and anvil are likely to have been situated near to each other and close to a large, sunken ceramic vessel; examples of the latter were found in both workshops. The ore was ironstone from the Lenham Beds, 9km from the site. It was roasted before smelting, possibly in shallow fired features observed in the workshops. Charcoal, predominantly oak, was used as a fuel. The waste was largely tap slag, with some furnace slag, including large, bowl-shaped furnace bottoms. The ore contained variable but significant quantities of phosphorus, which led to the production of smelting slag with a diagnostic phosphorus content. Some of the iron produced may have been smithed into large billets for trade, since a billet of 4.5kg was found at the site. The total quantity of iron-working waste on the excavated area of the site was estimated at 29 tonnes. The amount of refined iron produced was estimated as a minimum of 2.7 tonnes (equivalent to 600 billets of 4.5kg each). A minimum of 38 tonnes of ore and 250 tonnes of wood (38 tonnes of charcoal) would have been consumed. These figures are likely to be underestimates as some slag was probably removed from the site in the past for reuse, for example as road metalling, and the efficiency of the smelting and smithing processes may have been underestimated.

the largest Roman iron-making site in the Weald, a substantial bath-house has been discovered. The existence in the south-eastern part of the Weald of a number of other large sites suggests that the fleet's involvement may have been even greater, but proof awaits field evidence.

The earliest discoveries of evidence of Roman iron working in the Weald were made as a consequence of the re-use of slag for metalling turnpike roads in the nineteenth century. Later, Ernest Straker studied field names recorded on tithe maps and visited likely sites, which he described in his pioneering monograph, *Wealden Iron*, which lists nine sites dated by finds of pottery to the Roman period (Straker 1931). His successors, Barry Lucas and James Money, respectively pursued fieldwork and excavation, the latter devoting eleven seasons to the excavation of the multi-period site at Garden Hill, Hartfield.

A significant step in research into Roman iron working in the Weald was the establishment of the WIRG in 1968, by Henry Cleere and David Crossley. Cleere had been excavating at Bardown and Beauport Park, and he published an examination of the connection of the *Classis Britannica* with the iron industry, in which he catalogued 33 sites of Roman date (Cleere 1974). Led by Fred Tebbutt, WIRG undertook systematic fieldwalking which provided much new evidence for the extent of iron making in the region. In the 1970s WIRG concentrated on an area of the central Weald, establishing the density of bloomery sites, and sampling to ascertain their approximate age (Tebbutt 1981). The publication of *The Iron Industry of the Weald* brought the number of Roman sites to 76 (Cleere and Crossley 1995). WIRG continues to publish results of field work in its annual bulletin. The Group is currently extending the area of study; some sites, especially where all or part is under cultivation, are yielding information, on location if not on period, non-invasively, through geophysical survey. It has become apparent that the distribution of Roman bloomeries differs from that of the medieval period, when iron working was more, but by no means exclusively, concentrated in the north of the Weald.

Excavations of three sites associated with the Roman iron industry in the Weald await definitive publication. For Broadfield, Crawley, which contained several types of bloomery furnace covering a wide date range, the published report had to be edited from inadequate contextual material (Cartwright 1992). Garden Hill, Hartfield, was well served by annual summaries dur-

*Figure 60: A Romano-British bloomery (iron-smelting furnace) at Little Furnace Wood, Mayfield, East Sussex.*

ing the eleven years over which the excavations took place, but has not been fully published (Money and Streeten 1979). An interim monograph is available for the excavation of the *Classis Britannica* site at Bardown, Wadhurst (Cleere 1970). It should be remembered that when these excavations were carried out, the significance of hammer scale distributions was not known. The metalworking evidence from a more recent excavation slightly to the north of the Weald, at Westhawk Farm near Ashford, Kent, has been published (Paynter 2007a; see example) and shows the benefits of using modern scientific techniques.

The small number of sites that have been excavated have revealed a variety of smelting furnace types — both slag tapping and, possibly, non-slag tapping. It has been postulated that the native British and imported Roman technologies utilized differing types of furnace (Cleere 1972; Gibson-Hill 1980). However, the evidence for such differentiation is far from convincing. Nevertheless, the spatial and chronological distribution of furnace types is an area of research which could yield important data both about developments in furnace technology (Fig 60) as well as possible pre-Roman origins and socio-tribal influences in the Wealden iron industry.

## 3.4 The introduction, development and spread of brass

Brass is a metal with an interesting history: it was introduced two millennia after bronze and required a different manufacturing technology. The study of how early brass was manufactured and used has provided information on a wide range of themes that go far beyond metallurgical technology. A few brass artefacts are known in the Middle East from the 13th century BC

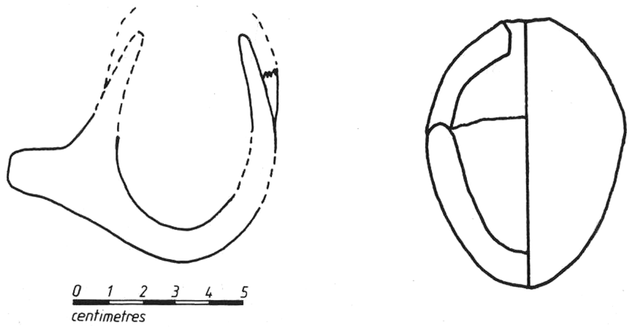


*Figure 61: Early Roman brass-making crucibles from Culver Street, Colchester, Essex (left), and Palace Street, Canterbury, Kent (right). After Bayley 1984.*

but mass production of brass coins only began in the 1st century BC in Asia Minor (Craddock *et al* 1980). In the late 1st century BC the Roman Empire adopted brass as the metal for some coins (*sestertii* and *dupondii*), implying an increased scale of production, and at the same time certain items of Roman military equipment began to be made of brass. The scale of the Roman Empire indicates that brass must have been manufactured on an enormous scale. The earliest brass found so far in Britain probably dates to the 2nd century BC with production beginning in the 1st century AD.

### Brass production

Brass is an alloy of copper and zinc but before the 18th century metallic zinc was extremely rare or unknown in Britain. This is because when zinc ores are smelted zinc is formed as a metallic vapour which is immediately oxidized by the furnace gases. Other metals used in copper alloys (especially tin and lead) are more easily smelted. The production of brass relied on a cementation technique, in which small pieces of copper were heated with zinc ore and charcoal in a sealed crucible. Under these reducing conditions the zinc vapour was not oxidized but diffused into the copper, making brass (Bayley 1998). Experimental work by Haedecke (1973) and Newbury *et al* (2005) reproduced this process, and demonstrated that the maximum zinc content of cementation brass is normally 28%. Analyses of early brasses show some contain 22–28% zinc and up to 2% of tin and/or lead (Ponting 2002, 560) but most have only 15–25% zinc (Bayley and Butcher 2004, fig 182; Fig 61).

There is relatively little evidence for where and when brass was made or how the Roman industry was organized and controlled. In Britain there were abundant zinc ores in the Mendips but there is currently no evidence that the Romans exploited them, although they did mine argentiferous lead there. On the Continent there is some evidence of Roman mining near Aachen in Germany. Evidence for the brass cementation process in the form of crucible fragments is rather more abundant in the 1st century AD. In Britain, fragments of small, lidded crucibles, of a form and fabric unparalleled among contemporary metal melting crucibles, have been found in both Colchester and Canterbury (Fig 61). Analysis detected unusually high levels of zinc on the inner surfaces of these vessels which are interpreted as brass-cementation crucibles (Bayley 1984). Larger numbers of even smaller vessels have been recovered from Xanten in Germany (Rehren 1996a), and larger vessels from Lyon in France (Picon *et al* 1995). There are differences in the size, shape and fabric of the cementation vessels but they are all characterized by zinc-rich interior surfaces.

## Uses of brass

Brass initially came into Britain from those areas of the Continent which were already part of the Roman Empire — it was inextricably linked to Roman material culture. There is currently no evidence for any pre-Conquest making or melting of brass in Britain, although small quantities of the metal were finding their way here as early as the 2nd century BC (see section 3.1). Brass moved across the boundaries of the Roman Empire and probably formed a minor component of the gifts made to client kings (Braund 1984). A high proportion of copper-alloy artefacts decorated in a 'Celtic' style are made from brass, although some of them may have been made after the Conquest and many of the hoards which contain 'Celtic' metal work also contain items of Roman military equipment. Nevertheless, the appearance of brass prior to the actual Conquest has been noted at some *oppida* in Gaul (Hamilton 1996) and at the late Iron Age temple at Hayling Island, Hampshire (Bayley 1998).

A study of copper alloys from northern Britain provides data on their usage on over 30 Iron Age and Roman sites (Dungworth 1996a; 1997). While excavations of rural sites produce few copper-alloy artefacts (due to lower population density), these include a high proportion of brass — higher than in Roman forts or towns (Dungworth 1997). This high proportion of brass suggests that the inhabitants of these sites made deliberate choices about the use of this metal, which could have been acquired through trade, gift or theft. In some cases the distinctive colour of brass (it is golden compared to the pink of copper or the brown of bronze) probably played a significant role in how the alloy was identified and perceived by users rather than producers.

An extensive study of the alloy composition of Iron Age and Roman brooches (Bayley and Butcher 2004) illustrates the complexity of alloy choice and the ways in which colours were important to brooch wearers. About a third of all Roman brooches are brass while the remainder are a mixture of bronzes and gunmetals containing very variable amounts of zinc, tin and lead. Individual brooch types tended to be made of one specific alloy. The Colchester-type brooch comes in two variants: one made from a single piece of metal and the other in which the bow and spring are separate components. The one-piece Colchester brooches are almost all brasses while the two-piece ones are mainly leaded bronzes. There are other cases where the differences in alloy composition are much more subtle: various types of brooch popular in the 1st century AD were made of brass, but each has a slightly different composition (Fig 62). For example, one-piece Colchester (Types 89–91) and Aucissa (Type 51) brooches were made from brass with just under 20% zinc, while Hod Hill brooches contain on average only 17% zinc (*ibid*). Aucissa brooches from France and Israel have the same composition as the British examples (Ponting and Segal 1998), and the production of typologically- and

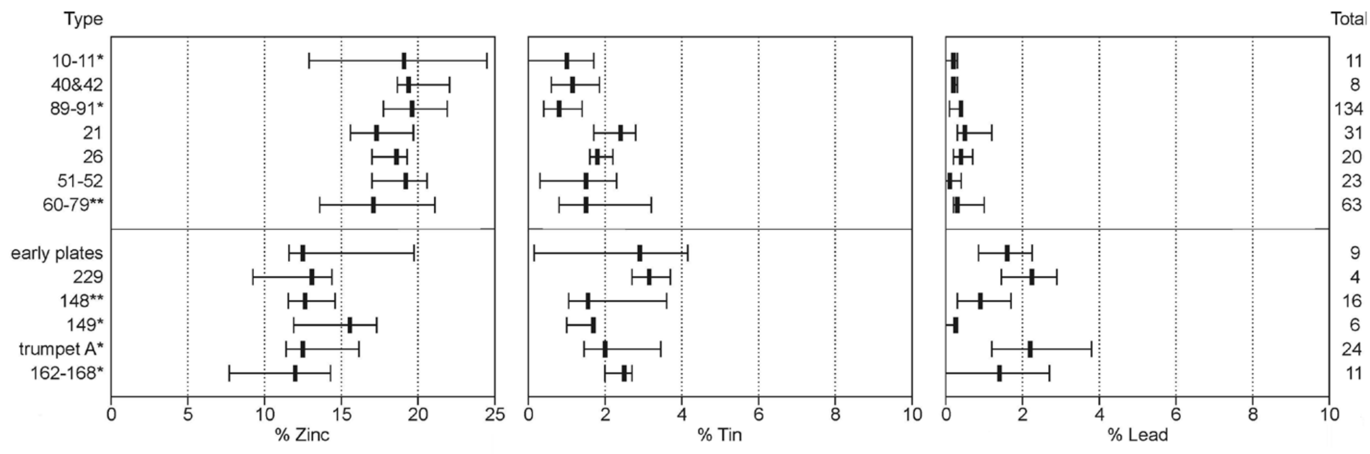


*Figure 62: Graph showing alloy composition of different of 1st-century brass brooch types. After Bayley and Butcher 2004.*

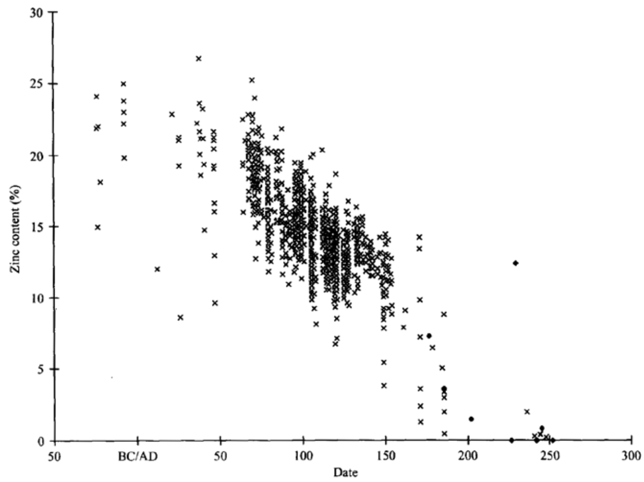


*Figure 63: The zinc content of Roman brass coins dropped steadily from the 1st century AD onwards. After Dungworth 1996b.*

metallurgically-identical artefacts across possibly the whole Empire suggests some centralized production (or at least control of production).

While brass was widely used during the early Empire, there are fewer late-Roman brasses; a phenomenon that can be seen in many categories of artefact including coins, military equipment and items of personal adornment. While early-Roman brass coins contain high levels of zinc but low levels of tin and lead, later coins contain less and less zinc and more tin and lead (Fig 63). This decline in zinc content starts by the middle 1st century AD, and by the end of the 3rd century Roman 'brass' coins contained almost no zinc (Dungworth 1996b). This zinc decline was interpreted by Caley (1964) in terms of metal availability: he argued that either supplies of zinc ore became scarce or that the cementation technology was lost. Caley suggested that after the first century AD, the zinc in 'brass' coins derived only from the re-melting of old issues. A model of the decline in zinc content following Caley's explanation does not, however, match the observed zinc decline (Dungworth 1996b). The actual zinc decline closely matches the decline in the silver content of Roman denarii and it has been argued that the metal for 'brass' coins was 'debased' by mixing varying proportions of brass and leaded bronze. This may have been undertaken to maintain a sense of parity between silver and brass coins.

The use of brass for items of military equipment is seen most clearly in the early Empire where the iron components of the legionary armour (*lorica segmentata*) were held in place by brass fittings. Later, changes occur in the design of military equipment, in particular there is a decline in use of *lorica segmentata*, and at the same time mixed alloys containing tin, lead and zinc become the norm for the fittings. This change in alloy composition is related to the ways in which the metal was worked. The fittings of the early Empire were hammered to shape: the ductility of brass made it an ideal alloy. The fittings of the late Empire, however, required only casting for which mixed copper alloys were most suitable. What remains to be discovered is whether military equipment design changed to cope with the restricted availability of brass or whether the change in design removed the demand for brass.

There are chronological changes in the composition of copper alloys used to manufacture brooches which are mostly correlated with changes in the sorts of brooches made (Bayley and Butcher 2004). Most 1st-century brooches, in particular the one-piece brooches, were made from brass. Like the early military equipment described above, these required a degree of forging in their fabrication, for which brass was well suited. Brooches made from the late 1st century onwards (*eg* trumpet brooches) increasingly used mixed alloys with minor amounts of zinc; however, these were all two-piece brooches. As with military fittings, the changes in the alloy compositions of brooches were bound up with changes in fabrication techniques, and again it is difficult to be sure if new designs or the scarcity of particular alloys were driving the changes.

## 3.5 Brass in the early medieval period: the case for discontinuity and decline

Post-Roman brass and other copper alloys have received less attention than those of earlier periods (Fig 64). Our knowledge of early post-Roman copper alloys is hampered by the fact that much of our material comes from burials; indeed there are almost no analyses of early-Saxon copper alloys that are not from cemeteries. Because of the bias in the types of sites excavated there is a distinct lack of evidence for early-Saxon metalworking; even metalworking waste is rare. There are far more metalworking finds for the middle- and late-Saxon periods (Bayley 1991), with those from Coppergate, York (Bayley 1992a) being one important group. Analyses of artefacts have been conducted by Bayley (1992a; 1992b), Mortimer (Mortimer *et al* 1986; Mortimer 1991; 1993), Northover (1995) and Blades (1995).

Despite the limitations of the data for post-Roman period, Figure 65 summarizes the results obtained by Dungworth (1997) and Blades (1995) from the 1st to the 17th centuries AD. There is a gradual decline in the use of brass during the Roman period, as discussed above (Section 3.4),

Figure 64: Anglo-Saxon copper-alloy square-headed brooch from West Heslerton, Yorkshire, decorated with mercury gilding and soldered-on silver foils. Length 245mm.

with the lowest incidence occurring in the immediate post-Roman/early-Saxon period (AD 400–650). Mixed alloys containing significant proportions of both zinc and tin (gunmetal) were the norm in England for early Anglo-Saxon metal work, with the occasional brass object appearing (Mortimer *et al* 1986) but the picture is as yet far from clear. Nevertheless, Figure 65 shows that the changes in alloy usage that occurred in the early Saxon period were a continuation of trends which began in the 1st century AD. The decline in the use of brass in the early-Saxon period is accompanied by the almost complete disappearance of unalloyed copper. This apparent absence of fresh metal may indicate a period of re-cycling with little or no production of new metal (copper or brass). It seems on present evidence that there was no continuity of

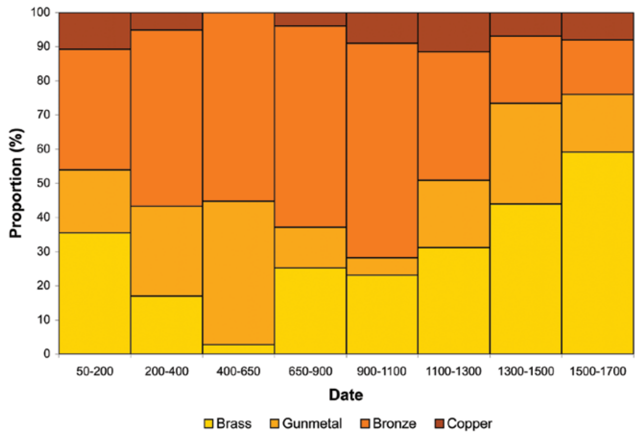


Figure 65: Bar-chart of copper alloys in use from the Roman conquest to the Industrial Revolution. Based on data from Dungworth 1997 and Blades 1995.

brass production in Britain during the early Anglo-Saxon period. The use of brass increases later, but is still on a relatively small scale, with bronze rather than gunmetal becoming the commonest copper alloy. In Scotland a different picture seems to be emerging, with both brasses and gunmetals being rare and tin bronze being the norm (Bayley 2000). A similar pattern has been noted for late 'Celtic' metal work in the British Museum (Craddock *et al* 2001, 121–2).

The manufacture of brass coinage in 9th century Northumbria (Gilmore and Metcalf 1980) provides an early example of the regular use of fresh cementation brass in Britain (Fig 66). This probably represents the beginnings of a revived European brass industry, though exactly where this brass was being produced is not known. Certainly, good-quality brass was a common decorative alloy amongst the Vikings of Scandinavia (Paterson 2001, 125) and the Northumbrian evidence may represent the importation of Scandinavian fashion. There was a significant increase in brass use from the early-mid 10th century (Bayley 1992a, 808–9). Could this be reflecting the strengthening of York's Scandinavian culture occasioned by the city's recapture by the Norse in 939 and the setting up of a Norse kingdom based in

Figure 66: Obverse and reverse of a Northumbrian brass styca, now in Manchester Museum.

York? Similarly, if the picture of alloy use at Dunadd, Argyll, is shown to be common to the 'Celtic' areas of post-Roman Britain, we may suggest that bronze was the copper alloy most commonly used by the native population of Britain (Fig 67) — though more hard data is needed before these suggestions can be proven.

Brass (and copper) continue to become more popular after the Norman Conquest and by the end of the medieval period copper and brass account for about 50% of the copper alloys in use. The increase in the use of these alloys is again reflected in the fabrication techniques used. Brass and copper are popular in periods when most artefacts require forging to achieve the desired shape, while mixed alloys are popular when most artefacts are cast directly in moulds.

## 3.6 Copper: the medieval gap

While the work on Roman brass can be seen as an archaeological success story, medieval copper mining and working is little more than a string of references in documentary sources. Evidence for an indigenous British copper industry between the Roman period and the injection of German technology in the Mines Royal in the 16th century is currently very scant. It has generally been thought that the copper needs of Britain were met through imports, first from Germany (Rammelsburg

*Figure 67: The upper valve of a piece mould which was used to cast a bronze penannular brooch at Dunadd, Argyll. Length ~50mm.*

*Figure 68: Agricola's illustration of 16th-century copper smelting in Germany. After Hoover and Hoover 1950.*

and Harz; Fig 68) and later from Sweden. But how true is this? Again, a large part of our knowledge has been gleaned from documentary evidence and has not yet been matched with the archaeological record.

### Copper mining

There is as yet no archaeological evidence for copper being mined and smelted beyond the period of Roman occupation. Even after 1086 there are only occasional references to copper mining. Copper ores of some form were being worked at Bere Ferrers, south Devon, early in the 14th century, probably for their silver content, but their origin is unclear (Claughton pers comm). There is also some evidence for copper mining during the 13th century in Cornwall, Cumberland and Yorkshire (Blair and Blair 1991). Tradition has it that copper was worked in north Devon at North Molton 'by the Romans' and during the reign of King John, but the earliest documentary reference to the mine there is 1346. There is no evidence of sustained production although the mine was again noted as working copper in 1524 (Claughton pers comm). Because of the possibility of a silver content, copper was subject to royal prerogative and was regularly included in royal grants of mines from the 1260s. In 1319 copper/silver deposits in the Caldbeck Fells of Cumbria were investigated but again there is little evidence of sustained production although the mines there were worked to an unknown depth prior to the arrival German miners in the area in 1568. A mine of copper and silver was also reported in Shropshire on the demesne of Wenlock Priory in 1394, although nothing further is heard of its working. In 1475, a royal grant included the mine (not necessarily of copper) at Keswick, and 'the copper mine of Richmond' (Raistrick and Jennings 1983, 88–9). The available evidence (primarily documentary) suggests that the attraction of these deposits was their silver content with only limited demand for copper metal. Despite an increased military use of copper in the manufacture of cannon during the last years of the medieval period this appears from the documentary evidence to have been satisfied by imports from the continent. Despite the obvious strategic advantage of controlling supplies of copper there is no evidence for large scale exploitation until the latter half of the 16th century and then with only limited success. Non-argentiferous copper was worked at Ecton, Staffordshire, in the 1630s. But it was not until the end of that century, and the successful application of reverberatory smelting techniques to copper ores, that English copper mining took off.

The application of detailed trace element and lead isotope studies should establish whether a significant proportion of early medieval copper was extracted from British mines (Fig 69) or whether it was all imported from the continent. The identification of specific artefact types with particular trace-element and/or isotopic signatures would also assist in understanding the organization of the medieval copper-alloy industry. Additionally, it may prove possible to establish which European copper sources were supplying Britain and at which periods — but all these hypotheses need adequate data sets to test them.

The sites and areas with documentary evidence for medieval copper mining should be targets for field research in order to establish the location, survival, nature and importance of the medieval mining. Archaeological evidence for medieval copper smelting should also exist in these areas, and its identification is also important. The technology of medieval silver extraction from copper (presumably by liquation and cupellation) is not understood so archaeological evidence of this process too would be of importance. The introduction of German technology by the Mines Royal in the third quarter of the 16th century, centred on the Lake District, is normally credited with being the foundation on which post-medieval British mining and metallurgy was based. If the nature of British copper extraction in the 15th and earlier 16th centuries can be established, it should be possible to test this hypothesis. Later still there was major development of all the English and Welsh copper orefields with a massive smelting industry centred on Swansea. It then expanded, dominating world supply for much of the 19th century.

*Figure 69: Coniston copper mines: the site descends from the Mines Royal opencast at Simon's Nick (skyline right of centre), through later adits and spoil tips to the 18th- and 19th-century ore-dressing floors in the foreground.*

## Working of copper alloys

In contrast with the Roman period when evidence of metalworking is found on all types of sites, from the middle Saxon period onwards, non-ferrous metalworking was essentially an urban industry. Evidence for early English copper-alloy metalworking comes from over 90 excavations. This sounds impressive, but these are concentrated in only six urban centres: Lincoln, London, Northampton, Thetford, Winchester and York (Bayley 1991). Furthermore, little of this material dates to before AD 700, with most belonging to the period after AD 900. Additionally, this distribution includes both Saxon and Anglo-Scandinavian centres, but little has been done to compare the potentially different traditions. Some work has been done on Scottish sites, notably Bayley's (2000) analyses of material from Dunadd, Argyll. Bayley has also analysed a substantial amount of metalworking process waste, including moulds and crucibles from some of the most important excavations. This has provided an insight into the types of alloys being used, the production technologies available and the organization of the craft workers (Bayley 1991; 2000).

Finds from English sites demonstrate a continuity of metalworking practice from the mid- and late-Saxon period through to around the end of the 12th century. From around the 13th century there were changes in the organization of metalworking, with more centralization of production and the setting up of guilds in towns to exercise control and protection. The increased concentration of individual crafts in particular streets or areas means that randomly-sited excavations rarely find much evidence of later medieval metalworking, a rather different picture from that of the widespread craft activity of earlier periods. There were also differences in the scale of operation of the crafts or industries, and in the types of objects being manufactured. Both these changes mean that there are some notable differences in the nature of the manufacturing debris that is found compared with that of the earlier medieval period (Fig 70 and *cf* Fig 14). For example, the production of large castings such as bells and cauldrons becomes more common; the evidence is casting pits and large quantities of clay mould fragments (*eg* Blaylock 2000; Taylor *et al* 2004).

## 3.7 Bole to cupola: lead and silver production from the medieval period onwards

Exploitation of lead ores in Britain was directed at the production of lead itself or lead in combination with silver, which is found in small but extractable quantities in many lead ores. In outline, there was a progression in smelting technology from the bole (or bale in northern England) to the shaft furnace or ore-hearth smelt-mill, and then to the reverberatory furnace (cupola).

*Figure 70: 16th-century crucibles used for melting copper, from the Tower of London. Note the increased size compared with the earlier crucibles in Figure 14.*

*Figure 71: Two small lead-smelting bales beside Fell End mine, Arkengarthdale, Yorkshire. After Murphy and Baldwin 2001.*

### Bole smelting

The bole produced good-quality soft lead, suitable for roofing; it retained most of the silver (when smelting argentiferous lead), but required large pieces of good-quality ore (Fig 71). The method has been suggested (Blanchard 1992) as originating in the transition from argentiferous to non-argentiferous lead smelting late in the 12th century, but this is not based on strong archaeological or documentary evidence. Recent radiocarbon dating of charcoal from bales in Yorkshire, Northumberland and Cumbria has suggested dates from around the early 11th century (Smith 2006; Fairbairn 2007). The only fully-excavated example, at Cwmystwyth (Timberlake 2005), has been tentatively dated to the middle of the 13th century. The introduction of boles into Devon on the opening of silver mines in 1292 suggests that the method was in use in ore-fields across England and Wales, and the currently limited archaeological evidence suggests that it was in use until the second half of the 16th century. Kiernan (1989, esp 40–43), on the basis of 16th-century documents, re-constructs the Derbyshire bole as an open-fronted stone stall, containing a layered charge, of log-wood (shankerds) in the base, then partially smelted ore from a previous firing ('blackwork'), then wood from smaller trees, topped with fresh ore mixed with brushwood (Fig 72). It was sited on a south-west-facing ridge and was fired when the prevailing wind was blowing. The fresh ore was oxidized in the upper part of the bole, and as the charge burnt down this then reacted with unoxidized ore and slag in the lower (reducing) interior of the bole to produce metallic lead (Gill 1992). It is uncertain how closely this re-construction can be applied to earlier, probably smaller, boles in other parts of Britain. A survey of the many bales in Swaledale and Wesleydale, Yorkshire, showed that 73% were probably simple clearings on exposed positions, others being

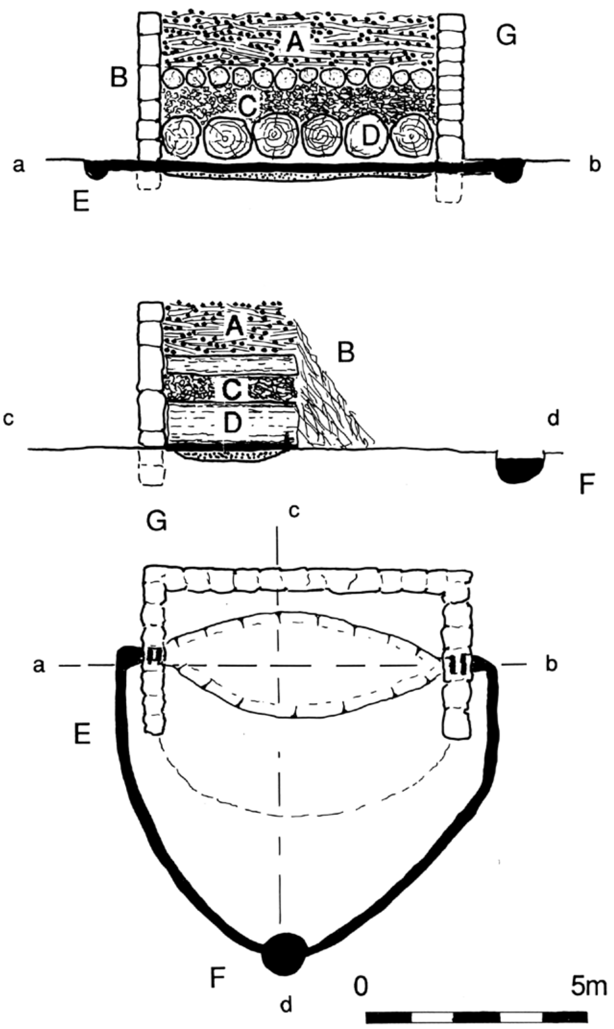


*Figure 72: Reconstruction of a Derbyshire 16th-century lead-smelting bole. In the stone enclosure (G) were placed wood (shankerds B and blocks D), with blackwork (part-smelted ore C), beneath ore and small wood (A). The smelted lead flowed by channels (E) to a mould (F). After Kiernan 1989.*

forms of pit bales where the lead was collected in a shallow pit or run out through a sloping channel. A map of Fremington Edge in the Yorkshire Pennines of *c*1592 shows boles, labelled as bales, still in use (Murphy and Baldwin 2001, 3).

At least by the 14th century, the slags from the bole were re-smelted in separate blackwork ovens, and it is suspected that some excavated features which have been suggested as boles were in fact for re-smelting. In addition, fieldwork sometimes reveals slag sites that do not fit the conventional bole/blackwork picture (*eg* Pickin 1992), and medieval documentary references suggest the existence of a water-powered smelting process that does not correspond with the conventional picture. In the argentiferous areas of Devon, lead began to be smelted by the 'fynyngmyll' by at least 1480 — there is good documentary evidence for 1480–1481 (Claughton 1994, 58). This was probably a water-blown shaft furnace adapted to deal with ores not smeltable by the bole, and required ore to be roasted prior to smelting, to initiate the oxidation process.

### Ore-hearth lead smelting

In the middle of the 16th century, the use of water power became general. Kiernan has shown that in the Derbyshire industry the bole was superseded by smelt-mills comprising bellows-blown furnaces (ore-hearths) and a secondary stage, also bellows-blown, for extracting residual lead from slags (slag hearths). For a brief period in the middle of the 16th century there are Derbyshire references to 'foot-blasts', a furnace-type known from the Mendips, but the water-powered ore-hearth was universal in the county by 1600 (Kiernan 1989, 119–191). The ore-hearth enabled the use of smaller-sized ores, some discarded by the bole-smelters, at a time when the technology of ore-separation was developing, marked by the appearance of the jigging sieve. There is archive evidence for experimentation in the 16th century: attempts were made to smelt lead with coal from the 1520s onwards in County Durham; early in the 16th century high-shaft water-powered 'Almain' furnaces were introduced to Devon (Claughton 1992; 2003; 2004). In the 1550s the Almain furnace was tried unsuccessfully in Derbyshire. The ore-hearth dominated lead smelting until around 1700, and remained in use in some areas, notably the north Pennines, until the end of the 19th century. The archive material for this period is geographically patchy, the 17th-century representation of a smelt-mill on a map of Rowsley, Derbyshire (Fig 23), being an unusual survival. Archaeological evidence for the development of the ore-hearth is lacking. The ore hearth was initially fuelled with kiln-dried wood ('white coal'). From the late 17th century some smelters used a mixture of peat with low-grade coal (King 2001–2, 46); this development appears to be poorly documented historically, and requires archaeological and scientific examination.

### The coal-fired cupola

The next change was the development of the reverberatory or 'cupola' furnace, from the 1680s onwards. This technology originated in Britain, perhaps in the Bristol area (King 1999). The furnace comprised a melting chamber with a brick-arched roof, into which the ore was charged, and a separate fire-box in which coal could be used without contaminating the lead with sulphur from the fuel. The flame from the firebox was drawn into the furnace, and reflected ('reverberated') on to the charge. Lead was tapped to pig-beds outside the

**Example: Lead smelting at Combe Martin**

Recent excavations by Trevor Dunkerley at Combe Martin in Devon have identified 16th/17th century slags that are a by-product from smelting argentiferous lead for its silver. Overall the slag contained around 2wt% lead oxide and slightly more zinc, but no silver was detected (Paynter *et al* 2003). These results, together with documentary evidence, are indicative of a very efficient two-stage smelting process being used at Combe Martin. The first smelt, for example using an 'ore hearth', produced a relatively lead-rich slag, similar to the 'blackwork' slags from boles, together with some lead metal. This was then re-smelted at high temperatures under highly-reducing conditions, for example in a slag hearth, to remove nearly all of the remaining metal (Crossley 1990, 189). Under such conditions there would be significant losses of lead through volatilization, but the silver yield would be maximized. The resulting slag had a glassy, opaque green appearance and fairly uniform composition, being predominantly an iron silicate (Fig 73). The concentrations of iron and manganese in the slag were correlated, suggesting that these two elements were introduced in siderite (iron carbonate) gangue from the local lead orebodies. The slag also contained lime, some of which may be from the gangue of imported ores, as suggested by historical references and the presence of non-local gangue minerals amongst the waste. These may have been added to help solve the well-documented difficulties that were encountered smelting the Combe Martin ore. The slag would probably have a melting temperature of around 1200–1300°C, which could be achieved using bellows. It is known from documentary sources that water-powered bellows were used in conjunction with a charcoal-fuelled furnace for smelting lead at Combe Martin by the early 16th century.

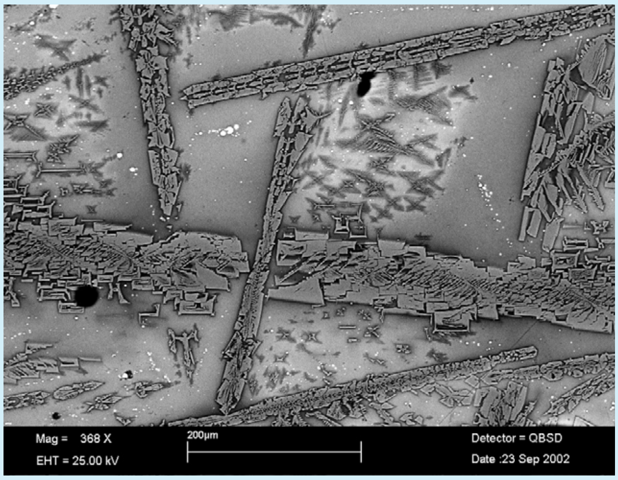


*Figure 73: Backscattered SEM image of lead-smelting slag from the earlier (16th century) deposits at Combe Martin, Devon. The dendrites are olivine and the bright droplets are sulphides of lead, copper, iron and zinc in a glassy matrix.*

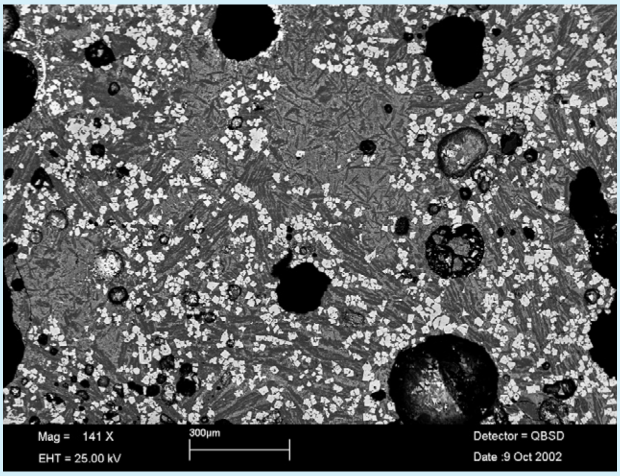


*Figure 74: Backscattered SEM image of lead smelting slag from the 19th-century deposits at Combe Martin, Devon. The bright phase is spinel (hercynite), the dark needle-like crystals are corundum ($Al_2O_3$) and the mid-grey phase is anorthite ($CaAl_2Si_2O_8$)*

The lead metal was then processed by cupellation to extract the silver it contained, which would have been the primary product at Combe Martin, but no waste from this refining stage was found in the excavations. However the quantities of phosphorus detected in the slag suggest that some lining material from the cupellation hearth, probably bone ash, was smelted in the ore hearth together with the local and imported ore. This is further evidence that the refining works were located near to the smelting furnace. Reworking the cupellation hearth lining would enable any silver-bearing lead remaining in the lining material to be recovered, and would have further increased the lime content of the slag.

Some 19th-century smelting slag from Combe Martin was also examined, but no lead, silver, zinc or copper was detected in the bulk composition (Fig 74). This shows that the process had been improved significantly over that of the 16th/17th century as virtually all of the metal has now been extracted. This would require higher temperatures (of the order of 1400–1500°C) but despite this the alumina-rich slag was quite viscous when it was removed from the furnace, resulting in high porosity and an uneven surface. The high temperatures led to increased volatilisation of the lead, and long flues were incorporated into the furnaces to act as condensers, so that lead could be recovered. The flues still survive in Combe Martin.

structure. No bellows were used, the furnace draught being induced by a lengthy flue terminating in a chimney. Condensed lead was recovered from the horizontal part of this flue. The cupola was a further step in the use of lower-grade ores, but the water-powered slag-hearth component of the smelt-mill continued in use, recovering lead from cupola slags. Cupola technology had been used for some time for melting brass in the foundry; its adaptation for smelting lead, copper and tin is an innovation which requires archaeological study.

## Processing argentiferous lead ores

Percy (1870, 261), Crossley (1990) and Willies (1991) discuss lead-smelting and silver-refining technologies of the 19th century. The work at Combe Martin (see example) has shown the importance of excavated slag assemblages — even in the absence of structures — in charting developments in processes. Excavation of all early lead-smelting sites and analysis of slags from firm archaeological contexts is needed to document and allow a comprehensive understanding of the complexities of lead smelting in Britain.

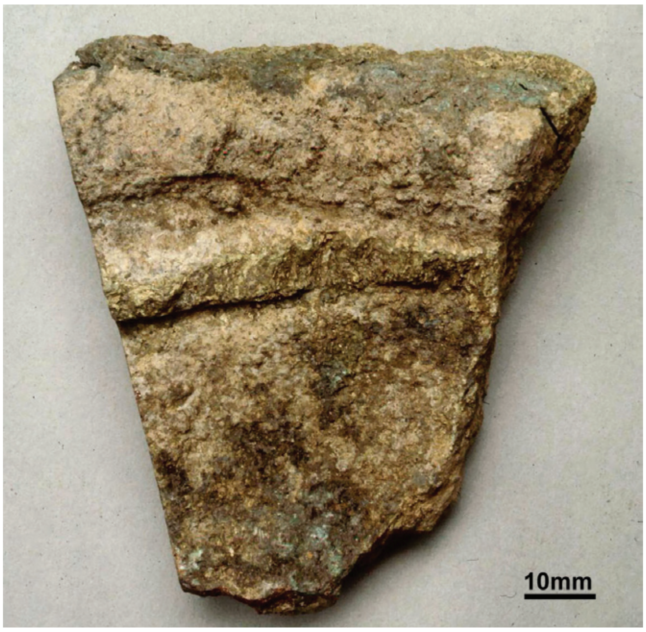


*Figure 75: Fragment of the lining of a 13th-century cupellation hearth impregnated with lead oxide (also known as a litharge cake) from Thetford, Norfolk.*

The separation of silver from lead was done by cupellation; the argentiferous lead metal was placed on a hearth and melted under oxidizing conditions. The lead metal was gradually oxidized to lead oxide (litharge), whilst the silver eventually remained as a pure metal pool untouched by the fire. The litharge was continuously removed as a liquid, either tapped or being absorbed into the purpose-built porous hearth lining. This litharge could then be re-smelted to form soft lead, now almost free of silver, for building purposes etc. Finds of massive litharge are known from a number of ancient sites across Europe, from the Bronze Age up to the modern period, indicating that the process changed little. The re-smelting of litharge probably explains the scarcity of litharge finds in the archaeological record when compared with the amounts of silver produced. Finds of cupellation hearth lining, on the other hand (*ie* the hearth lining soaked with litharge) are relatively frequent finds from Roman and later sites, but the majority are rich in copper in addition to lead oxide, indicating that they served to refine debased silver rather than to produce silver from freshly-mined lead (Bayley and Eckstein 2006, Fig 75). This practice is closely related to the quantitative chemical analysis known as fire assay, from which it differs in scale and purpose, but not in principle.

This process also saw changes in the 18th century, with the adoption of Robert Lydall's reverberatory furnace (patented in 1691), applying the principle of the reverberatory furnace to the extraction of silver from lead (Willies 1991, 119–20; Earl 1991, 69; King 2001–2, 44). This innovation is hardly discussed in the historical reference works, and no significant archaeological work has been undertaken on it.

Fire assay allows the determination of the precious metal content of a given sample of metal alloy or ore by using small-scale smelting operations in crucibles rather than in furnaces. In addition, these experiments give the experienced assayer necessary indications about the nature of the ore, and the need for specific treatments such as fluxes to be added, etc. Archaeologically, this is reflected in finds of specialized technical ceramics, particularly scorifiers, crucibles and cupels, from the 16th century onwards (Rehren 1996b, Martinon-Torres and Rehren 2005). Such finds are known from the Elizabethan site of Kodlunarn in north-eastern Canada resulting from the Frobisher expedition, when they were assaying what was hoped to be gold ore near to the mining site before shipping it back to Britain (McGhee 2002). More often these finds appear in urban contexts (Bayley 1996; Fig 76). While the technology is the same, the context can vary from mining and extraction to coin assaying and production, as was probably the case at the Tower of London. The analysis of such finds may shed light on the nature of urban metallurgy, although the inherent limitations of urban archaeology can mean that no complete contexts are available. In addition, these finds are important, as

*Figure 76: A bone ash cupel from Cripplegate, London, with the silver that was assayed in it still in position. Scale in mm.*

they map the development and spread of fire-assaying across Europe; by the mid to late 16th century, assay crucibles occur all over Europe in standardized shapes and sizes, but little is known about their earlier development. Particularly noteworthy are the so-called Hessian triangular crucibles, used for a range of slag-forming operations and to collect precious metals from lead bullion, and cupels made from bone ash and used to separate any silver and gold from that lead bullion (Martinon-Torres and Rehren forthcoming).

## 3.8 The development of iron and steel production from the Middle Ages to the 19th century

The technology of iron smelting in Britain may be divided into four phases: the unpowered (hand-powered) bloomery, the bloomery blown by water power, the charcoal-fuelled blast furnace and the blast furnace fuelled with coke. The following sections summarize the state of knowledge of each, as well as the state of research into the making of steel.

### The unpowered bloomery

Current research by McDonnell (see below), Cranstone, Crew and others is suggesting a greater range of size among medieval bloomeries than has hitherto been accepted. Small units, with slag deposits of no more than a few cubic metres, have been thought of as normal, those found in the Lake District being typical, but recent research has shown that the Lake District sites range up to ~1,000m$^3$ in size (Cranstone 2003). There is no inherent reason why medieval ironworks should not have been on such a scale, slags coming from multiple furnaces over long periods, as had been the case in the Weald during the Roman period. However, recognition of operations on this scale must raise questions of relationships between technology, size, site morphology, dating, and socio-economic factors such as ownership. The question of whether 'mega-bloomeries' (Cranstone pers comm) used an as-yet unidentified variant of the traditional solid-state bloom-hearth has yet to be answered. The date-range of the use of unpowered bloomeries has not yet been established, but references peak in the 13th–14th centuries. However, mills paying rent in iron, on a scale which makes the use of water power a possibility are documented as early as Domesday (Tylecote 1992, 76), but it is not clear whether water power was used for bellows, hammers, or both, or indeed whether the mills were smelting sites at all, or smithies forging iron smelted at unpowered bloomeries, as was the case at the 12th–14th-century water-powered forge at Bordesley Abbey, Worcestershire (Astill 1993).

### Medieval iron and steel technology: solid or liquid?

Medieval iron production is generally thought to have been a solid-state process similar to that of the Roman period. One early-9th-century Middle-Eastern treatise on sword production (Hoyland and Gilmour 2006) supports this by making it clear that European steel production was carried out by the direct (solid state) bloomery process. Steel could be produced directly during the bloomery smelt by careful control of fuel-to-ore ratios. But was this always the case? Recently a debate has opened which questions this assumption. Liquid steel production is known from medieval and earlier contexts in the Near East, Sri Lanka, Turkmenistan and China (Craddock 1995). In Britain steel produced from the decarburization of cast iron was only available after the introduction of the blast furnace, first documented in 1491 (Awty 2003). There have been isolated occurrences of pre late-medieval cast iron in Britain, but these are rare and are usually regarded as accidental.

However, recent research on Saxon material of the 8th or early 9th century from Southampton (Hamwic) has been used to suggest that liquid steel was intentionally produced much earlier and was, in fact, a parallel technology used alongside the bloomery process (Mack *et al* 2000; Fig 77). Metallographic examination of a number of edged tools from Hamwic revealed knife blades manufactured by welding a small steel strip with an unusually high microhardness to a soft iron back (*ibid*, 89). Such hardness is rare in both preceding and later periods (Tylecote and Gilmour 1986) and the metal is unusually free of slag. A liquid steel-making process has been

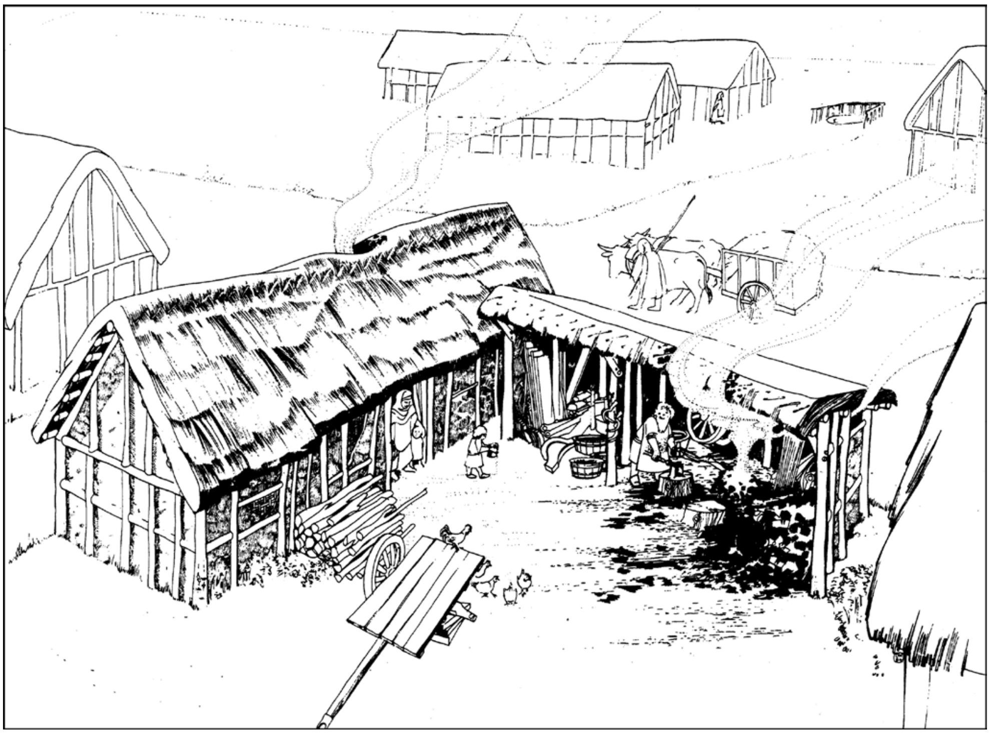

*Figure 77: Reconstruction of the blacksmith's forge on Site 31 at Hamwic (Saxon Southampton), Hampshire. After Mack* et al *2000.*

suggested as the origin for this metal based on examination of metal fragments from the excavations. A small bar, a billet and some metal fragments, all from 8th–9th century smithing contexts, are high-carbon steels, and there are fragments of white cast iron. Because there is no archaeological evidence for liquid-iron production in the Saxon period, it is suggested that cast iron was being brought into Hamwic where it was converted to high-carbon steel through a liquid decarburization process. However, much additional research is required before this interpretation and the actual decarburization process can be established, and further examples of material relating to this process will need to be analysed before it can be proven that a liquid-steel production process was known in Britain in the 9th century. However, the results of this investigation have forced a reassessment of the development of ferrous metallurgy in Britain and also demonstrated the need for an increased awareness amongst archaeologists of the debate surrounding early iron and steel production, because it is only through archaeology that the key evidence will be retrieved.

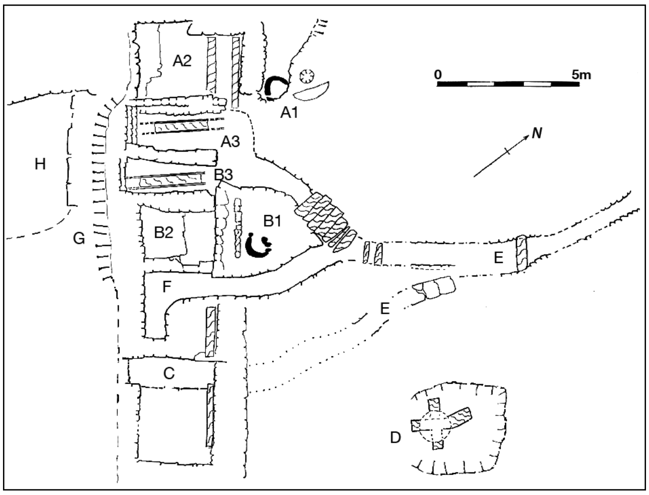


*Figure 78: Rockley, Yorkshire. Plan showing the bloomery furnace (A1), bellows house (A2) and water-wheel (A3). The string hearth (B1) for reheating blooms also had bellows (B2) driven by a water-wheel (B3). The purpose of the third wheel-pit (C) is uncertain, being too far from the anvil (D) to be likely to have powered a hammer. The overflow (F) took water from the pond (H) over the dam (G) to the tail-race (E). After Crossley 1990.*

## Water-powered bloomeries

By the 15th century, the water-powered bloomery, a term which may have covered a range of water-powered technologies, was becoming common. Its life was short, being superseded by the blast furnace over the period from the end of the 15th century until the early part of the 18th century. This short span is reflected in the excavated bloomeries of this type (Table 5).

The Kyrkeknott bloomery-site was only tentatively associated with 15th-century documentation, and the excavation at Aldridge was too limited to provide reliable results. The work of University of Bradford researchers at Timberholme, North Yorkshire, has suggested the existence of late-medieval high-shaft furnaces, perhaps precursors of blast-furnace technology. The preservation of features at Rockley was unusually good: the bloom-hearth and string-hearth (for reheating blooms for forging) survived (Fig 78), with substantial fragments of water-wheels in wheel-pits (Fig 79), as well as the foundation for an anvil, which however could not be satisfactorily proved to relate to a water-powered hammer. The Fasagh site was partially excavated, to show the anvil, but the presumption of the use of water power relies on surface indications of water-courses. Muncaster Head poses problems of identification: an adjacent site is suggested as relating

*Table 5: Excavated water-powered bloomeries*

| Site | Date | Notes | References |
|---|---|---|---|
| Chingley, Kent | 14th century | Water-mill foundations with tap slag found under later forge | Crossley 1975a, 7–17 |
| Kyrkeknott (formerly spelt Byrkeknott), Harthope, Durham | 1408 | Documented bloomery forge, but only traces of smelting | Lapsley 1899; Tylecote 1960; Mott 1961 |
| Aldridge, West Midlands | *c*1474–1495 | Water-powered bloomery (very limited excavation) | Gould 1969–70; Morton and Wingrove 1969–1970 |
| Timberholme, North Yorkshire | 15th century | Water-powered probable high-shaft bloomery | Vernon *et al* 1998 |
| Rockley Smithies, Yorkshire | *c*1500–*c*1640 | Water-blown bloom-hearth and apparently un-powered hammer | Crossley and Ashurst 1968 |
| Muncaster Head, Cumbria | ?17th century | Interpretation as bloomery now questioned | Tylecote and Cherry 1970; Bowden 2000, 45–47; Cranstone pers comm |
| Fasagh, Wester Ross, Highland | 17th century | Probable water-powered bloomery | Photos-Jones *et al* 1998, 24–27 |
| Stoney Hazel, Cumbria | 1718–1725 | Water-powered bellows and hammer, originally published as a finery forge | Davies-Shiel 1970; Awty and Phillips 1979–80; Bowden 2000, 73–76; Cranstone pers comm |

to the 17th-century archive references to a forge, leaving the identification of the site excavated by Tylecote in doubt. Stoney Hazel Forge was very late, and when first excavated was thought to be a finery.

This resemblance underlines the general similarity of the elements of the finery to those of at least the latest variants of the water-powered bloomery. Each required two hearths and a hammer: the bloom-hearth and the string-hearth of the bloomery could be rebuilt as the finery and chafery of a forge, even if these latter needed to be larger over time. Both required a hammer to forge blooms; indeed the term bloom was commonly used at the finery forge. There are several cases in the Weald of exposed stratigraphy of successions of bloomery and finery residues (Cleere and Crossley 1995, 108).

## The charcoal blast furnace

The introduction of the blast furnace to Britain is conventionally dated to the construction of the ironworks at Newbridge, Sussex, in 1496. Recent historical research has provided evidence for a blast furnace at Buxted in 1490, but does not affect the view that this was technology imported from France; French ironworkers are recorded to have migrated to the area in the 1490s and are associated with the first generation of British blast furnaces (Crossley 1990, 156). The blast furnace could either produce pigs of cast iron, the metal being run into sand moulds (Fig 85), or cast directly into large objects such as guns. The 'Walloon' finery forge, which converted most of the cast iron from the blast furnace into wrought iron, was introduced at the same time. The blast furnace was also important for providing cast iron for gun casting (Awty and Whittick 2002; Cleere and Crossley 1995, 111–6; Crossley 1990, 156; Figs 80 and 81). Blast-furnace technology transformed the English iron industry and formed the basis for its expansion over the 16th century. While a bloomery could make 20–25 tons of bar iron per year, 16th-century blast furnaces could make up to 250 tons of pig iron, which a finery forge could convert into c160–170 tons of bar iron (King 2003). The features of the 16th–17th-century blast furnace are by now well known, from excavations carried out since the 1960s. That at Chingley, Kent (Figs 12 and 13) is typical of mid-16th-century practice.

*Figure 79: Part of a water-wheel in position in a wheel pit at Rockley, Yorkshire.*

The conventional picture has been questioned from two directions. Firstly, the work at Timberholme (see above) has suggested the existence of high-shaft furnaces, capable of producing cast iron as well as wrought iron, blurring the distinction between the bloomery and the blast furnace. Secondly, work in Sweden and elsewhere has changed the Continental evidence for the development of the blast furnace, although few publications of this work, and no overall syntheses, have appeared in English. To summarize this evidence (see various papers in Magnusson 1995 and Crew and Crew

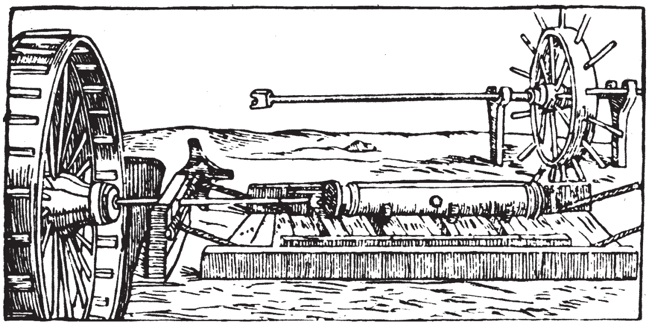

*Figure 80: 16th-century gun founding: an illustration from Biringuccio's* Pirotechnia *showing how castings were bored.*

*Figure 81: Early-18th-century gun-boring mill at Pippingford, East Sussex. Two of four trolley wheels are shown, with rotted timber rails. The hemispherical object is a chuck to hold a boring-bar, as seen in Fig 80.*

1997; Cranstone pers comm), it is now known that blast furnaces (such as the excavated Lapphyttan site) were widespread in the Berslagen area of central Sweden late in the 12th century. By the 13th century, blast furnaces are also known from Germany and Switzerland, although the overall distribution of early blast furnaces in Europe is not yet clear.

The implications for Britain are threefold. Firstly, blast-furnace technology was available in north-west Europe from the 13th century, and could have been introduced to Britain. Secondly, the Nordic development of the blast furnace, and the possible link with oxide/non-phosphoric ores, suggest that an early introduction to Britain might be found in the North, rather than in the Weald as has traditionally been assumed. Thirdly, the possible existence of medieval fineries (not necessarily water-powered, for the fineries at Lapphyttan were unpowered) becomes both possible, and crucial to the use of the blast furnace as a route to wrought iron. Conversely, if the conventional picture is correct and the blast furnace was not introduced until the late 15th century, the reasons for this non-adoption of an available technology would themselves be of great interest.

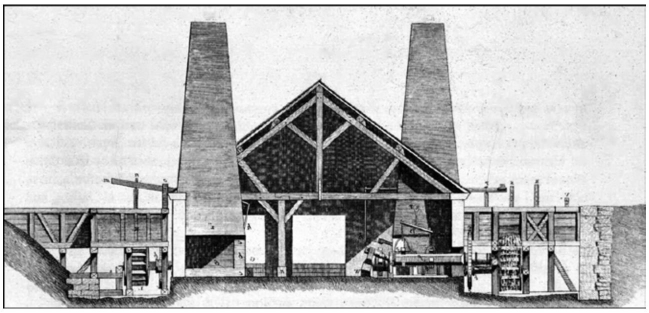

*Figure 82: Drawing of a French conversion forge showing a finery hearth (left) and water-powered forge hammer and chafery hearth (right). After Diderot (Gillispie 1959). This can be compared with Figure 83.*

*Figure 83: Chingley finery forge under excavation, showing the dam at the top, water courses on both sides, the finery (lower left) and chafery (lower right). The hammer area is in between, with the anvil base in the centre (under the 3ft scale). In the first phase, it appeared to be driven from a wheel to the left, with fulcrum posts surviving, and in the second from a wheel to the right (in the same race as the chafery) with the base-frame showing. Figure 82 shows the same arrangement of two wheel-races.*

As indicated above, a crucial factor in the adoption of the blast furnace was the ability to use the finery forge to convert high-carbon (3–5%) pig iron into low-carbon (0.1%) wrought iron useable by the smith (Figs 82 and 83). Little work has been done on the archaeology of the finery, documented as introduced from NE France by immigrants around 1500. The process removed the carbon by re-melting pig iron in an open charcoal-fired hearth (the finery) blown by water-powered bellows. Slag was released from the iron, so fining took place in a bath of molten slag. There was a residue of cinder from this stage of the process which was periodically removed from the hearth as solid lumps; these discarded furnace-bottoms were often used as hard-core. At the end of the process, the bloom of iron was lifted out, and consolidated using a water-powered hammer. It was then worked up into bar iron by forging under the hammer, with reheating in a second hearth (the chafery), also blown by water-powered bellows. The alternative 'German process', in which all the heatings


*Figure 84: The bellows arch of Abraham Darby's furnace at Coalbrookdale, Shropshire.*

were performed in a single hearth (Awty 2006) does not seem to have been used in England. A further method of Continental origin, the osmond process, was introduced at Tintern about 1570 (though conceivably not for the first time) and used solely at certain forges in that area to produce osmond iron as the raw material for wire production (King pers comm).

Finery forges have been little studied archaeologically, although recent archive work by King (2003) has provided a national gazetteer. Only three sites, all in the Weald, Ardingly, Blackwater Green, and Chingley, have been excavated and published (Crossley 1990, 166–7). These forges were frequently built on the sites of water-powered bloomeries, both processes requiring two hearths and a hammer. Stony Hazel Forge shows how the basic similarities can lead to confusion for although exhibiting finery-derived technology, it is now interpreted as a bloomery on the basis of finds of ore during excavation. The range and detailed process origins of finery-forge slags, and their distinction from water-powered bloomery slags, are not well understood. The archaeology of the finery forge is therefore a priority for research, for which King's (2003) gazetteer now provides an excellent starting-point.

## The use of mineral fuel by the iron industry

The first successful use of coke in a blast furnace, by Abraham Darby at Coalbrookdale in 1709, is common knowledge (Fig 84). For the archaeologist, there are two associated problems. There is good historical evidence for experimentation with the use of mineral fuel for iron smelting throughout the 17th century, notably that of Dud Dudley in the Black Country (King 2001–2; 2002); archaeological evidence for these experiments appears to survive in South Wales (Page 2007) and west Cumberland (Blick 1984, 48), although smelting with charcoal continued there into the 18th century (Fig 85). The technology used by experimenters before Darby is not known in detail, and it is possible that on-site residues may hold the necessary evidence. Secondly, the coke-fired blast furnace was slow to be adopted, being limited until *c*1750 to the production of castings and of pig iron for the foundry trade, rather than for conversion at the finery forge. Whether the reasons for this delayed adoption were primarily technological or economic remains contentious, and excavated residues are likely to be crucial to this debate. Further, until late in the 18th century ironmasters used coke in furnaces originally built to use charcoal, with minor modifications such as the second tuyere arch at Rockley, Yorkshire (Crossley 1995). Purpose-built coke-fired furnaces, such as those preserved at Blaenavon, Gwent (Fig 5), were rare before the 1750s.

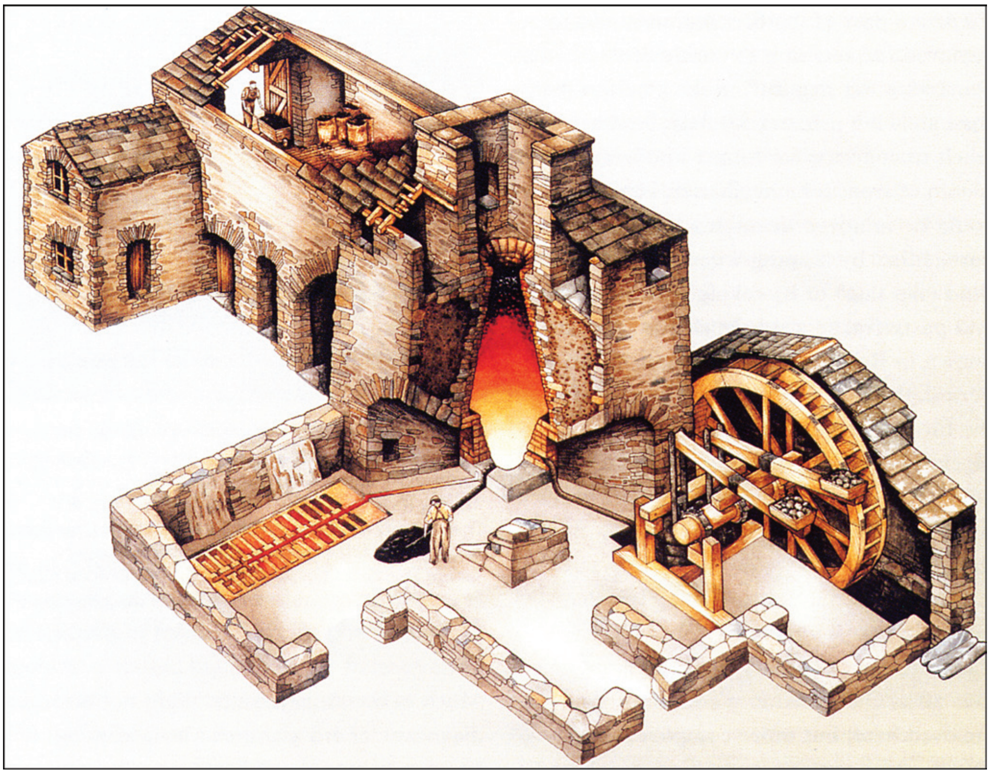

*Figure 85: Reconstruction of the charcoal-fuelled blast furnace at Duddon, Cumbria, built in 1736.*

Darby's innovation was based on his experience and knowledge of the Bristol brass and copper industries, where he had patented the use of green-sand moulds for casting thin-walled vessels, to produce cast-iron open-work objects direct from the blast-furnace (Cox 1990). In this way he had, by design or accident, avoided confrontation with the traditional charcoal-fuelled blast furnace industry by specializing in the iron-foundry trade. The charcoal-blast furnace industry produced cast iron for conversion to wrought iron, a process for which Darby's Shropshire high-sulphur and high-silica coke pig iron was unsuitable. Thus, freed from any determined opposition from the established iron masters and landowners, Darby was able to consolidate his fledgling iron-foundry business at a time when the social and economic climate was ripe. Indeed, he was able to exploit his contacts in Bristol and capitalize on the rise of the new merchant class there, growing steadily wealthier from burgeoning colonialism (Cranstone 2001, 193). Thus the engine of the 'industrial revolution', the iron industry, was 'kick-started' by the profits of the colonialism and empire that it came to epitomise.

Other furnaces followed Coalbrookdale, such as Isaac Cookson's Little Clifton Furnace in Cumberland and Bryn Coch Furnace (near Neath). These businesses supplied cheap (relative to brass and copper) hollow-wares such as cauldrons for cooking and enabled them to take over the market for these. Such a change in the affordability of a fundamental class of artefact must have had potentially far reaching effects in diet and food culture that have yet to be researched. The coke-fuelled iron industry continued to innovate and expand providing many jobs for a new class of miner and industrial worker, and the quality and quantity of iron needed to produce the machines and structures on which the further development of globalized capitalism depended.

A corresponding change in the 18th century was from the finery, using charcoal to convert charcoal-smelted pig iron, to the use of mineral fuel to convert coke-smelted pig. A period of experiment and innovation (probably only partially recorded by the historical sources) culminated first in the 'potting and stamping' process (briefly dominant in the later 18th century), and then in the puddling furnace, developed by Henry Cort, which became the standard means of conversion throughout the 19th century (Hayman 2004; Mott 1983; Evans 1993b). The archaeological and archaeometallurgical evidence for these processes has barely been studied. The 18th-century development of forge technology offers opportunities for innovative historical and cognitive archaeological investigation into the broader processes of invention, innovation and technological development (Newman *et al* 2001, 186–197; Cranstone 2004).

The archaeological evidence for the change to mineral fuel in the iron industry consists largely of distinctive residues, notably sulphur-rich slag, and the higher sulphur content of the product. There is however a far wider change, namely in the location of the industry, abandoning traditional areas of coppice woodland and valleys whose water power had been harnessed to power furnace and forge bellows and forge hammers. The late-18th and 19th-century ironworks were sited on the coalfields, to assure supplies of coke, and of coal for steam blowing and rolling-mill engines. The industrial map of Britain was therefore profoundly altered, and the landscape archaeology of the industry reflects this. Former charcoal-using iron districts lost population, woods were made over to long-growth timber, and mill sites were abandoned. This gives rise to a paradox whereby the archaeology of the charcoal-iron industry is more accessible, through lack of subsequent development, than that of its coke-using successor, renewed and developed over the 19th and 20th centuries. So rapid and radical was this development, and so sudden the late-20th-century decline, that the archaeological record is poor, and the investigation of former ironworks sites difficult yet desirable.

### Pre-Bessemer steel making

The field evidence for post-medieval steel making, prior to the mid-19th-century development of bulk production associated with the Bessemer Converter and the Thomas-Siemens-Martin open-hearth process (1984), has only recently begun to complement Barraclough's epic archive-based study. The cementation process was developed shortly before 1600 on the continent, and spread to Britain early in the 17th century. Archaeological evidence for two 17th-century cementation furnaces has recently been recorded at the Upper Forge, Coalbrookdale (Belford and Ross 2007). Other early cementation steelworks were located in Birmingham, Bristol, the Sheffield area, Stourbridge and Wolverhampton. The North East and the West Midlands were both major steel-producing areas until the 1740s, but only the excavation of the cementation furnace at Derwentcote, Co Durham, has explored the north-east trade (Cranstone 1997; Belford and Ross 2007; Figs 86 and 87). The work of ARCUS at the Riverside site in Sheffield has provided evidence for a late-18th-century cementation furnace of atypical plan. In the middle of the 18th century Huntsman developed the crucible process, which melted cementation steel in refractory crucibles to produce homogeneous ingots (Barraclough 1984; Belford and Ross 2004). From the second half of the 18th century Sheffield became the most important centre of high-quality steel production in England.

*Figure 86: The early-18th-century cementation furnace at Derwentcote, Co Durham, with attached working buildings.*

*Figure 87: The interior of the cone of the cementation furnace at Derwentcote showing many internal flues (square holes) rising from the firing chamber beneath.*

## Bulk steel making: Bessemer, open hearth and electric arc

The cementation and crucible processes provided steel in small quantities for specialist applications where quality control was vital. There is a close relationship between steel makers using these methods and the makers of high-quality goods such as cutlery and edge-tools, and of the precision cutting equipment essential for an advanced engineering industry. Cementation and crucible steel, however, could not be produced in the quantities needed, for example by railways, for rails, axles and wheels, or by ship-builders. Until the third quarter of the 19th century these users relied on wrought and cast iron, whose performance and cost were a brake on innovation. In the 1850s and 1860s the time was right for innovatory production of bulk steel, and the inventions of Bessemer (the Bessemer Converter), Gilchrist and Thomas (the 'basic Bessemer' process which allowed bulk steel to be made from phosphoric pig iron), and Siemens (the open-hearth furnace) led to a rapid rise in the output of steels which were cheap enough to replace wrought iron, quite apart from their improved performance. These developments marked the start of the decline in wrought-iron production, which closed many puddling-furnace plants by 1914.

The increased demand for steel in the 19th century and the limitations of existing steel production provided an impetus for further advances in technology, and the increased production capacity that resulted led to new applications for steel; exemplified by the casting of large steel artefacts by Vickers and Sons from the 1850s. The first large castings produced by Vickers were steel church bells, and these quickly became a substantial part of Vickers' business (Fig 88). Although the acoustics of steel bells are inferior to that of traditional bronze bells, the novelty of the material appealed to the Victorians, and over 3000 steel bells were produced between 1855 and 1860. The company also cast steel railway wheels, pistons and railway crossings, facilitating the rapid expansion of the railway industry in Britain and abroad (Mackenzie pers comm). The economic motive was always key to innovation, leading Edward Vickers and his sons to experiment to find alternatives to the cementation process of steel production and thereby reduce production costs. A method of making cast steel directly from wrought iron had been patented by Mushet in 1800, but it was not a commercial success. William Vickers patented an alternative method using a mixture of cast iron and wrought iron in 1839. However, Barraclough's analysis of Vickers steel suggests that they were in actual fact infringing Mushet's patent for tungsten steel (Barraclough and Kerr 1976). Vickers then expanded their production of railway castings and began to look for new markets. This led to Vickers entering the arms business, using their expertise in large castings to produce large ingots that were forged into gun barrels. The increasing demand for armaments to feed the army of the Empire led to greater expansion, and in 1897 Vickers acquired an armaments company and became Vickers Sons and Maxim (Fig 89).

The growth of bulk steel production did not, however, signal the end of the earlier methods. The operators of cementation furnaces, it is true, found their

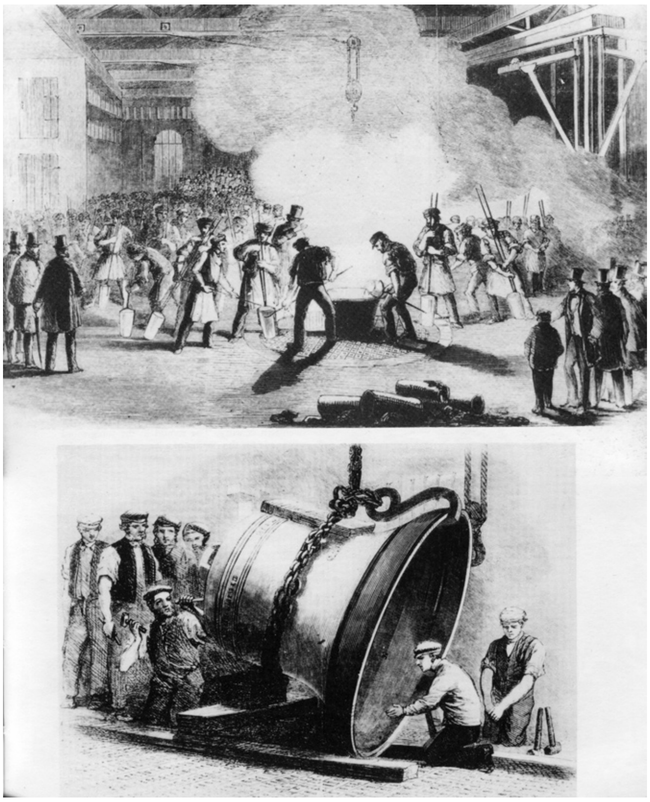

*Figure 88: Casting a bell weighing about 5 tons for the San Francisco fire station in 1860 at the Naylor, Vickers and Company works at Millsands in Sheffield. Barraclough 1976.*

product — blister steel — challenged by the best-quality open-hearth steels, but some edge-tool makers continued to use it, and it remained the feed-stock for the crucible furnaces. The long-term decline in use of cementation furnaces lasted until the second world war. Crucible steel, however, retained its place. Excellent quality control and the ability to make precisely-alloyed steels for the engineering industry meant that it remained a vital strategic resource through the 1914–18 war, and in Sheffield many crucible-steel furnaces survived in use to 1939 and beyond, and as disused structures up to the present. They were challenged from early in the 20th century by small electric furnaces, in which similar levels of quality could be achieved. It was these arc furnaces which were to develop into the large scrap-melting furnaces of the mid- and late-20th-century steelworks.

It might be argued that archaeological effort is misspent in the recording of the iron and steel industry of the period since *c*1850. It is true that the development of accurate urban mapping and the publication of information in professional journals may remove some of the uncertainties which beset the history of earlier industry. However, maps, even on such a scale as the 1:500 Ordnance Survey urban plans of the 1890s, are insufficient in their detail for certainty as to processes.

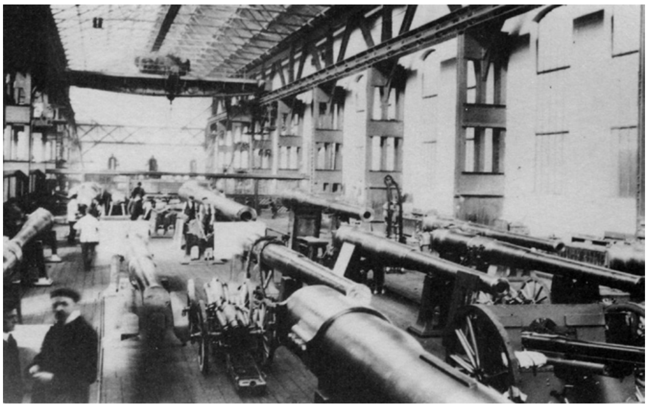

*Figure 89: The gun shop at Vickers' River Don works in Sheffield, c1900. Barraclough 1976.*

Journal papers, in this industry as in others (notably glass), can fail to give a picture of on-site experimentation and development which the archaeological record of a rapidly-changing industry can provide, through evidence of in-service structural modification and changing residues. Hence the significance of archaeological recording and scientific analysis during the redevelopment of now-redundant steel plants.

## 3.9: The archaeology of metals in the 20th century

The role of archaeology in the study of the 20th century is a developing, but still difficult and contentious, field. While important contributions to military archaeology and to standing buildings are now published and their role accepted within the profession, it is probably still true to say that a coherent archaeology of the 20th century has yet to develop. The archaeology of metals is no exception to this, despite some pioneering work; for example *Historical Metallurgy* Volume 19(1) was a special issue on alloys of the period 1900–1950. There are three major problems:

- The sheer wealth of the historical record, leading to a perception (however incorrect) that 'everything is [or can be] known from the documents', and that archaeology and archaeometallurgy therefore have nothing fundamental to contribute.
- The nature of many 20th-century industrial installations — increasingly prefabricated, and based on freestanding metal and/or concrete construction, therefore leaving far less, and less interpretable, field evidence than earlier constructions based on earth-fast masonry.
- 20th-century attitudes to site cleanliness, waste disposal, and 'contamination'. Unlike in earlier periods, process residues have rarely been deposited on-site in clearly-stratified deposits, and the below-ground

archaeology of many sites has been systematically destroyed by post-closure decontamination and reclamation.

The second and third of these problems are practical rather than fundamental. While many sites have indeed been destroyed, others have not, and in a holistic archaeology that includes buildings and artefacts as well as the traditional focus on excavation and excavated finds, the 'problems' are better seen as constructive challenges to develop and use appropriate methodologies. While site-based archaeology will undoubtedly have some valuable role to play, the archaeometallurgy of the 20th century may well centre on museum- and lab-based approaches.

The first problem is more fundamental. It is simply the essence of historical archaeology (in its broad topic sense) — of how to relate the material record of what people actually did, to the historical record of what they (or others) said they did. There will undoubtedly be circumstances in which a poorly-preserved archaeological record has little to add to rich and varied documentation. Conversely, even for the 20th century, there will be situations in which field archaeology and/or artefacts have much to add to a poorly-surviving historical record — and, even more interestingly, when the richness of both records allows detailed comparison of (for instance) modern scientific analyses and scientific understandings with the contemporary record of analyses and theoretical understandings. Archaeometallurgy has much to contribute to a holistic historical archaeology of the 20th century, and it is time that it began to do so on a systematic and regular basis.