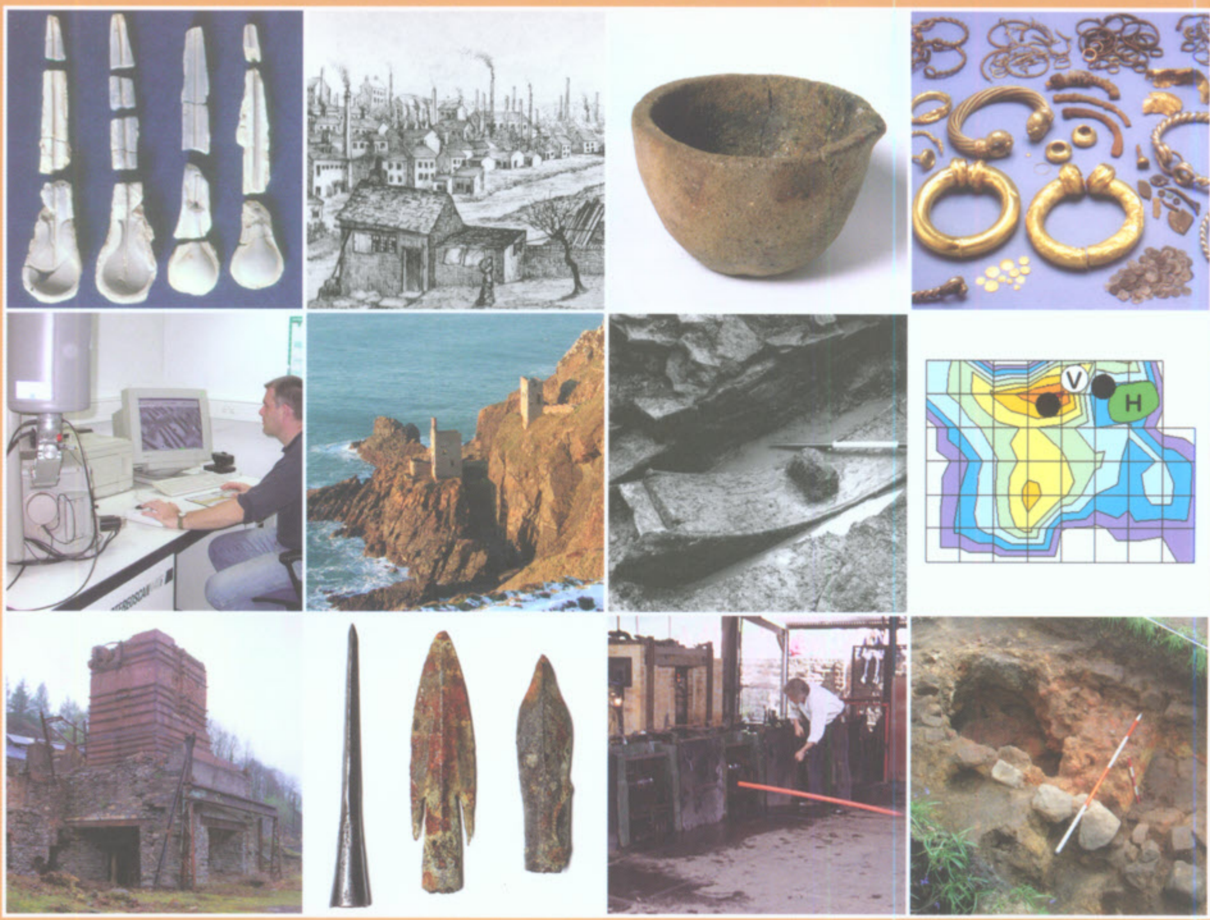
METALS AND METALWORKING

A research framework for archaeometallurgy



HMS Occasional Publication No 6

Cover images (from left, top, middle and bottom rows)

1 Mould fragments for casting late Roman spoons, from Castleford, Yorkshire. The fronts and backs were paired up and then assembled into a cone-shaped multiple mould, with the handles up, so 16 spoons were cast as once. Spoon length 150mm.

2 A view of the Sheaf valley, Sheffield in the mid 19th century showing many small workshops with their forge chimneys (see p.7).

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5 Scanning electron microscope in use. The screen shows a high-magnification image of the sample in the chamber to the left (see p.35).

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Metals and Metalworking

A research framework for archaeometallurgy

Compiled and edited by Justine Bayley, David Crossley and Matthew Ponting

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Metals & Metalworking: A research framework for archaeometallurgy

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SUMMARY

Metals and metalworking: A research framework for archaeometallurgy

The volume provides a research framework for archaeometallurgy in Britain, including a resource assessment, a research agenda and an outline research strategy. The first section identifies the nature of the resource. The evidence ranges in scale from landscapes and townscapes to sites and structures; it includes artefacts and residues from production as well as documentary sources. This section is particularly directed at curators and planners as it also deals with the management and protection of the resource, for which they have responsibility.

The second section, on methods in historical metallurgy, demonstrates that the subject goes beyond the work of the laboratory-based specialist, whose methods of examination and analysis are described. Also essential are the methods of field archaeology, landscape survey, geo-prospection and experimental archaeology, and the skills of metal-smiths and palaeo-environmentalists. The current pattern of development-led archaeology, in particular work on brown-field sites (which may be regarded as contaminated land), threatens the loss of sub-surface archaeological evidence for metal industries; appropriate methodological approaches to investigation, recording and sampling are discussed. The strengths and weaknesses of methods are examined, and areas for further development are outlined.

The third section summarises what is known about metalworking in the past, focusing on selected topics which illustrate either the considerable progress that has recently been made, or the need for further research. The examples include both ferrous and non-ferrous metalworking of all periods. 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. For the Iron Age, the focus is on the introduction of iron as an everyday metal, though copper alloys continued in use. The Roman period saw increasing use of metal and hence metalworking; the two examples given are the iron industry of the Weald, and the widespread adoption of brass as a common copper alloy. In the medieval period the lack of evidence for copper production is highlighted and the use of various copper alloys is discussed. Medieval methods of steel production are considered, as are later steel-making processes. After the medieval period there is a major change of scale, with the industrialisation of many metal industries. Relevant categories of documentary evidence are outlined, emphasising those which complement the archaeological record. An overview is presented of current knowledge of two metal industries important in post-medieval and modern Britain: lead production and the iron and steel industry. Archaeometallurgical studies can show how these industries, and the questions surrounding their development, are linked to changes in British society and the lives of its people.

Finally, the research agenda identifies major gaps in knowledge and suggests how they might best be filled. These comprise multi-period topics relating to methods in fieldwork and scientific examination, and other topics divided by period, from prehistoric to the present day. This section also outlines a strategy for promoting best practice in the discipline.

RÉSUMÉ

Métaux et métallurgie: un cadre de recherche pour l'archéométallurgie.

Ce volume propose un cadre de recherche pour l'archéométallurgie en Grande-Bretagne, présentant dans ce contexte une évaluation des ressources, un agenda de recherche, ainsi qu'un résumé de la stratégie de recherche établie. La première partie répertorie la nature des ressources : celles-ci sont présentes à différentes échelles et varient de paysages et scènes urbaines à des sites et structures archéologiques. Elles incluent également des artéfacts et des résidus de production ainsi que des sources documentaires. Cette section est tout particulièrement destinée aux archéologues et historiens locaux ainsi qu'aux principaux entrepreneurs impliqués dans des projets de développement et travaillant pour la commune ou tout autre autorité locale, puisqu'elle est aussi consacrée à la gestion et à la protection de ces ressources, pour lesquelles ils sont responsables.

La deuxième partie concerne les méthodes utilisées en métallurgie historique et montre que le thème abordé va plus loin que le travail d'un spécialiste, uniquement établi dans son laboratoire, dont les techniques d'investigation et d'analyse sont décrites. Les méthodes d'archéologie de terrain, de reconnaissance du paysage, de géo prospection et d'archéologie expérimentale, ainsi que les compétences des artisans du métal et des paléo environnementalistes sont tout aussi essentielles. La tendance actuelle de l'archéologie menée dans le cadre de projets de développement, en particulier les travaux sur des sites urbains à l'abandon (qui pourraient être considérés comme des terrains contaminés), menace d'entraîner la perte d'indices archéologiques liés à des industries métallurgiques, qui sont présents dans les sous-couches de surface ; différentes approches méthodologiques adaptées à l'investigation, l'archivage et l'échantillonnage dans ce contexte sont discutées. Les atouts et faiblesses de chaque méthode sont examinés et les domaines permettant de développer plus avant ces problématiques sont exposés.

La troisième partie résume les connaissances que nous avons du travail du métal comme il était réalisé dans le passé, mettant l'accent sur des thèmes bien définis, qui illustrent, soit le progrès considérable qui a été réalisé récemment, soit le besoin pour des recherches plus approfondies. Les exemples choisis comprennent aussi bien le travail du fer que les non ferreux de toutes les époques. La métallurgie la plus ancienne des îles britanniques date de l'âge du bronze et de l'âge du fer. Pour l'âge du bronze, l'emphase a été mise sur les travaux miniers en raison du nombre important de nouvelles données qui ont récemment été mises au jour. Concernant l'âge du fer, l'attention s'est plus particulièrement tournée vers l'introduction et l'usage du fer dans la vie de tous les jours, alors que les alliages de cuivre étaient encore utilisés. L'époque romaine voit une augmentation de l'utilisation des métaux et par conséquent du travail des métaux ; les deux exemples choisis pour cet ouvrage sont l'industrie du fer du Weald, et l'adoption très

The Historical Metallurgy Society

What it is and how to join

Origins

The Historical Metallurgy Society was established in 1962 to record and encourage the preservation of early blast furnaces in Britain. It quickly extended its scope and now covers all aspects of both ferrous and non-ferrous metallurgical history, from the earliest times to this century. It has an international membership of around 600, over a third of whom live abroad.

Publications

The Society publishes the results of recent research in its journal, Historical Metallurgy, which is produced annually in two parts. It also produces a Newsletter three times a year, which informs members of forthcoming conferences, other meetings and archaeo-metallurgical work in progress. The Society publishes the proceedings of some of the conferences it organizes and occasionally produces other publications which are offered to members at special prices.

Back numbers of Historical Metallurgy and indexes to it as well as other HMS publications are available from HMS Publication Sales, 22 Windley Crescent, Darley Abbey, Derby DE22 1BZ, UK.

Conferences

The Society holds an annual weekend Conference each September, and a day of lectures and visits at the AGM in the Spring. These meetings are held in different parts of the country so members have the opportunity to see sites of interest spread over a wide area. The Conference is always a mixture of lectures and guided visits to local metallurgical sites. It also provides an opportunity for members to give short talks about their own particular interests. Additional day and weekend meetings that are arranged from time to time are advertised to members in the Newsletter.

Joining

If you are interested in joining the Society, please write to the Membership Secretary; 17A Thorncote Road, Northill, Bedfordshire SG18 9AQ, UK. The annual subscription is £20.00 for individuals and institutions; there are reductions for members of the Institute of Materials, Minerals and Mining, and for full-time students. The subscription entitles you to receive the Journal, Newsletters and details of all activities that the Society organizes.

For further information see: **www.hist-met.org**

The Historical Metallurgy Society provides an international forum for research and the exchange of information about historical metallurgy. Founded in 1962, it covers all aspects of the history and technology of metals and associated materials from prehistory to the present. Our members' interests range from processes and production through economics to archaeology and conservation. The Society holds several conferences and meetings each year which showcase the latest research, and explore metallurgical landscapes and locations. It also takes an active rôle in the conservation of metallurgical sites.

Historical Metallurgy Society Occasional Publications

1 **Aspects of early metallurgy (1977)**
Edited by W Andrew Oddy
ISBN 978 095062 5409
Re-issued as British Museum Occasional Paper 17 (1980), ISBN 086159 0163

2 **Metals and the sea (1990)**
Edited by Janet Lang
ISBN 095062 5434

3 **Boles and smeltmills (1992)**
Edited by Lynn Willies and David Cranstone ISBN 095062 5442

4 **Mining before powder (1994)**
Edited by Trevor D Ford and Lynn Willies
ISBN 095062 5450
Issued jointly as Peak District Mines Historical Society Bulletin, Vol 12(3)

5 **The archaeology of mining and metallurgy in South-West Britain (1996)**
Edited by Philip Newman
No ISBN
Issued jointly as Peak District Mines Historical Society Bulletin, Vol 13(2)

6 **Metals and metalworking: a research framework for archaeometallurgy (2008)**
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INTRODUCTION

Knowledge of the sources, production and uses of metals is a central theme in the development of almost all societies and cultures, so understanding the history of metals and metalworking is a route to the heart of understanding our past. This history, which we call archaeometallurgy, is therefore a significant body of knowledge, and this volume is intended to aid the understanding of the subject and to demonstrate its place in the national research agenda for archaeology.

The need for archaeological research frameworks is widely accepted but the archaeometallurgical content of the emerging national and regional research frameworks (see section 4.5) has been uneven. There is thus a need for a research framework for metal production and use throughout Britain, spanning all regions and all periods, from the origins of metallurgy to the decline of the metal industries in the 20th century (Fig 1). The Historical Metallurgy Society has therefore produced this volume which provides a research assessment and an agenda for future work.

Figure 1: The blast furnaces at Stanton, Derbyshire, being demolished in 1976.

The current pattern of development-led archaeology places particular stress on the need to know more about our metallurgical past. In particular, the development of brown-field sites threatens the loss of important sub-surface evidence for the archaeology of industry. What is generally regarded as contaminated ground often preserves a significant archaeological record, which frequently relates to metal industries. This situation is fuelling an imperative to develop a new methodological approach to the investigation and recording of such sites. If archaeologists, curators, planners and policy-makers, often with little previous interest in metallurgy, are aware of the problems involved in securing a satisfactory record of metallurgical processes, then the information provided by structures, residues and artefacts can be effectively captured. This volume has been compiled to assist them.

What qualifies the Historical Metallurgy Society to undertake this work? The Society's membership draws on three areas of expertise and experience, the first two of which are familiar to archaeology. There are academic researchers and other specialist archaeometallurgists, many of them university-based or working within agencies such as English Heritage, but also including independent consultants. The second group are curatorial professionals, including those from museums who are responsible for the artefactual component of the record and those working with field-based agencies such as local authorities, who have responsibility for management and protection of sites. The third area of expertise is perhaps unique to the society, and comprises professional metallurgists who have spent their lives working within the metal industries. This group has specialist knowledge of more recent processes, which extends the influence of the society beyond that more usually represented within a specialist archaeological society and provides a continuum between past and present.

The volume has been divided into four parts, each viewing our metallurgical past from a different perspective. The first part deals with the resource. The evidence ranges from landscapes and sites to structures and townscapes. It also includes of moveable material, artefacts and the debris from production. These resources are recorded, inventoried and audited; they are studied and communicated to the wider community. This section is primarily directed at curators and planners who have responsibility for the management and protection of the resource.

The second part deals with methods in historical metallurgy. It has been included to demonstrate that the subject goes far beyond the work of the laboratory-based specialist, examining and analysing minute samples of metals and metallurgical debris with ever-increasing precision. The repertoire incorporates the skills of field archaeologists, landscape specialists, palaeo-environmentalists, those with geo-prospection skills, metal-smiths and those involved in experimental archaeology. With this range of skills, the tools available for the study of metallurgy are expanding. This section examines the strengths and weaknesses of our methods and flags those areas where further development is needed.

The third part reviews the present state of our knowledge. Given the scope of the subject, this cannot cover everything. The attempt here has been to select not only those subject areas about which we have a good degree of understanding but also those areas which highlight our lack of knowledge and the need for further research.

These three parts can be viewed as a resource assessment, providing an overview of current knowledge and practice. The final part builds on those that have gone before, and provides a research agenda that identifies major gaps in our knowledge and suggests how they might best be filled.

1 THE RESOURCE

Archaeometallurgy is the study of activities associated with the production and working of metals, which are found at most periods and cut across evidence for other contemporary activities. Evaluation and management of the resource is therefore complex, and intersects with many other areas of archaeological activity. The scale of the resource also varies from landscapes, through sites and features, down to individual scraps of waste, to artefacts and documentary records. Although some aspects of the resource are readily identifiable, for instance industrial complexes, others such as a pack-horse trail linking a mine to a smelter, or a metalworking hearth in an otherwise domestic site, may be less so. This part of the Research Framework discusses aspects of the nature of the resource, together with ways in which it may be engaged by the researcher and the manner in which the resource may be protected and managed for the future.

1.1 Geological background

The richness and diversity of the archaeometallurgical resource in Britain reflects the local geological resources that have been exploited over time, as well as the use of imported materials. The distribution of suitable metallic ores plays a dominant role in the location of primary smelting activities. The availability of fuel has also played a part in controlling and locating metallurgical activities, with the production of coal and coke from the Carboniferous coalfields having an especially strong influence in post-medieval times.

The complex pattern of resource generation through geological time leads to enormous variation in style of mineralization, which in turn means that exploitation of the resources often has particular, local features of technology, regulation or social context. Metalliferous geology thus provides both a backdrop to the discussions of the nature of the archaeometallurgical resource, and a context for viewing the variable nature of the resource: the landscapes of mineral extraction, primary metal smelting industries, secondary metal processing and industrial development of the coalfields.

Information on the nature, location and origin of metallic ores is included in recent syntheses of the geology of England and Wales (Brenchley and Rawson 2006) and Scotland (Trewin 2002). Detailed studies of almost all aspects of mineralization are presented by Pattrick and Polya (1993) while more specialized local information can be obtained from the sheet memoirs of the British Geological Survey and its predecessors. The Geological Survey was also responsible for a valuable series of *Special Reports on the Mineral Resources of Great Britain* between 1915 and 1945. Summaries of the distribution of the major groups of natural resources are presented in Figure 2.

1.2 Landscapes

Recognizing landscapes

The interpretation of metalliferous landscapes is a significant issue, despite the tendency for archaeometallurgy to be seen as primarily concerned with production sites and their output. In recent years there has been growing interest in the way in which such landscapes have evolved and developed. This interest has developed in response to threats posed by modern agricultural practices, and in part from development pressures on old industrial sites. In response to the rural threats, changes have been made to the funding support given to agriculture, with emphasis now being placed on protection and regeneration of past landscapes rather than on output. Some of these landscapes have been formed or influenced by metallurgical activities, even though they now give the appearance of being semi-wild and 'natural'. Obvious examples include the tin and copper districts of Cornwall and west Devon (www.cornish-mining.org.uk) or the lead-production landscapes of the Peak District (Barnatt and Penny 2004), but other, more subtle, evidence is contained in areas of woodland managed for charcoal fuel production, and in networks of routeways and settlements that link areas of mineral extraction with sites of primary and secondary production. In urban ('brown-field') areas, recognition of the need for evaluation under PPG 16 (1990) has come from an understanding of the evidence for past industrial, in many

Example: Metalliferous resources in Britain

The oldest significant areas of mineralization in Britain were generated between the Cambrian and the Devonian periods when northern Scotland and southern Britain lay on separate continents. Extensive and prolonged tectonic and igneous activity on the margins of these continents, together with metamorphic processes occurring during and after their eventual collision, led to a range of mineral deposits, which may collectively be referred to as 'Caledonian'. These include vein mineralization in SW and NW Wales, Cumbria and the Scottish Highlands. Some of the most significant are the volcanic-related polymetallic sulphide mineralization at Coed-y-Brenin and Parys Mountain. The latter deposit was exploited from prehistoric times onwards, although little is known about the earlier phases. The gold deposits of south and mid Wales also belong to this period. The sedimentary manganese ores of NW Wales are of Cambrian age. Late Caledonian igneous intrusions are associated with Cu-Mo-(Au) mineralization in northern Scotland, As-Sb-Au in the Southern Uplands and W-Sn-Mo-Li in the Lake District.

The next widespread phase of mineralization was during the Early Carboniferous. At this time large synsedimentary base metal deposits were formed in central Ireland, with smaller areas of Pb-Zn vein systems developing around the margins of the sedimentary basins in Britain. Early Carboniferous Pb-Zn deposits include many of those of the Central Welsh Mining District (although some here may be late Caledonian) and of the Bowland Basin. The Carboniferous period also saw the formation of Britain's coalfields which provide coal, and also synsedimentary blackband and claystone ironstones.

The large Cornubian batholith was intruded during the late Carboniferous–early Permian period. It is associated with the most intensely mineralized zone in Britain. This involves early W-Sn griesen-bordered veins, followed by the main stage with cassiterite (+Cu, As, Fe, Zn sulphide) veins. In some areas the late stage cross-course mineralization (Pb-Zn-Ag-Ba-F) may be due to the movement of low temperature brines from adjacent sedimentary basins. At a similar period Ag-Cu-Co-As-Ba vein mineralization occurred in the Midland Valley in Scotland, with minor base metal sulphide veins occurring elsewhere too.

In the subsequent Permian to Jurassic periods, there was widespread crustal extension across Britain associated with the opening of the Atlantic Ocean. This phase was accompanied by the development of two contrasting, but spatially-related forms of mineralization, iron oxide deposits (Bristol Channel Orefield, NE Wales, Cumbrian Orefield) and the 'Mississippi Valley-type' (MVT) deposits of Britain's major Pb-Zn orefields, including the N Pennines (Askrigg and Alston Blocks), S Pennines (Derbyshire), NE Wales (Halkyn-Minera), and Mendips (including its continuation in South Wales). Probably also related to this phase are the iron ores of N Devon and the Ba-Fe-Cu-Pb mineralization of the margin of the Cheshire Basin at Alderley Edge. These events are poorly dated, but where relationships are seen, the iron mineralization is earlier than the Pb-Zn. An even later stage is demonstrated by Britain's only copper-dolomite association deposit at the Great Orme, Llandudno, which post-dates the local MVT deposits and is therefore later Mesozoic-Tertiary.

The shallow shelf seas which covered much of Britain in the Mesozoic were responsible for the deposition of a wide variety of sedimentary ironstones. Most of the large deposits are ooidal ironstones of Early to Middle Jurassic Age (the Frodingham Ironstone, the Cleveland Ironstone, the ironstones of the Marlstone, the Rosedale Ironstone, the Rassay Ironstone, the Northampton Sands Ironstone and the Dogger Ironstones), with smaller examples continuing through the Late Jurassic into the Early Cretaceous (the Westbury Ironstone, the Abbotsbury Ironstone and the Claxby Ironstone). The Early Cretaceous is also important for development of sideritic claystone ironstones within the Weald of SE England. There are also various localities where oxidized iron-rich sediments, mainly originally glauconitic, have been worked from Early Cretaceous strata, including the Blackdown Hills, Seend and North Norfolk. With the exception of the claystone ironstones of the Weald, these Mesozoic ironstones are generally of low grade, but are very widespread and were worked in early times wherever superficial oxidation raised the grade of the ore. Tertiary sediments of SE England (*eg* in Surrey and Hampshire) also yield sedimentary iron ores of sufficient grade to have been worked in the past.

The most recent ore deposits are bog iron ores which accumulated in various parts of Britain in the Holocene. The former distribution of these deposits is largely unknown, and in many cases it is the recovery of archaeological evidence for iron smelting that is providing that evidence. The best-known areas of of bog ores are the uplands of North Wales, the wetlands of Humberside and E Yorkshire and the Highlands of Scotland.

Chemical symbols

Ag	silver	Cu	copper	Pb	lead
As	arsenic	F	fluorine	Sb	antimony
Au	gold	Fe	iron	Sn	tin
Ba	barium	Li	lithium	W	tungsten
Co	cobalt	Mo	molybdenum	Zn	zinc

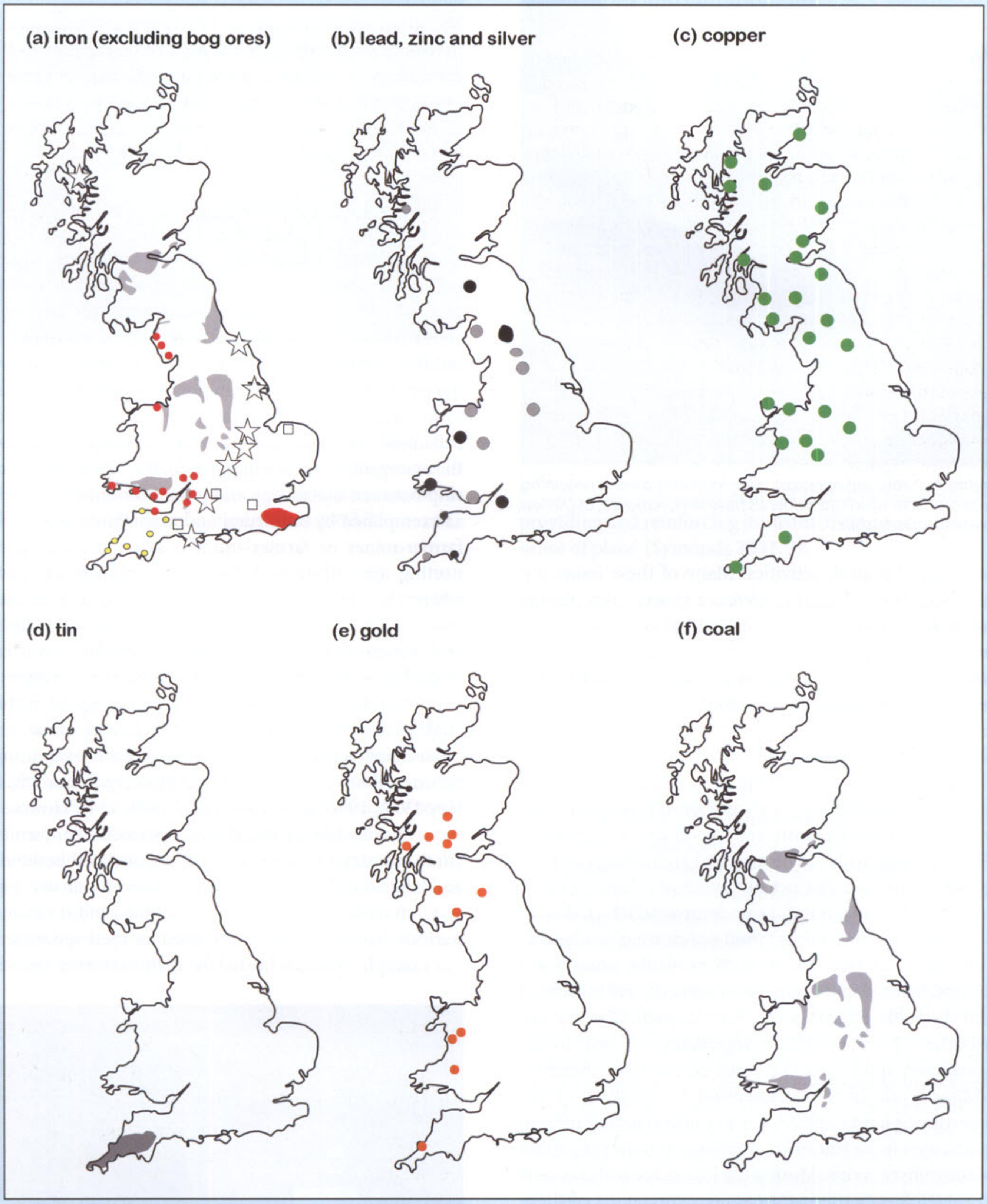

Figure 2: Maps showing the mineral deposits of the British Isles. a) Iron (excluding bog ores): grey tone = the Carboniferous coalfields, with claystone and blackband sedimentary ironstones; red = the Weald, Cretaceous claystone ironstones; yellow spots = oxide iron ores associated with the SW mineral province, including gossan and oxides after siderite; red spotsoxide iron ores associated with epigenetic mineralization on Mesozoic basin margins; stars = sedimentary ooidal ironstones of Mesozoic age; squares = other sedimentary ironstones of Mesozoic–Tertiary age. b) Lead, zinc and silver: areas indicate main lead-zinc orefields. Those in black also produced significant quantities of silver. c) Copper. d) Tin: working of alluvial tin deposits in SW England took place over a wider area than the distribution of the primary mineralization. e) Gold. f) Coal.

Figure 3: A rake (an opencast mine following a vein containing lead ore) from which the minerals have been removed, at Dirtlow, Castleton, Derbyshire.

cases metallurgical, activities. Many of these issues are discussed in the edited conference proceedings *Mining before powder* (Ford and Willies 1994) and *Mining and metallurgy in south-west Britain* (Newman 1996), which within their respective themes provide a benchmark for recent understanding of the subject.

Surface landscapes

The key to the understanding of landscapes shaped by metal industries is the inter-relationship between mining, primary production and secondary occupations. When dealing with the history and archaeology of mining there are two distinct but symbiotic landscapes to consider, the surface and the underground which should be treated as one. Underground ore-mining (see below) also leaves surface traces, such as shafts, adits, spoil dumps, haulage and drainage equipment, and industrial and domestic buildings (for lead in particular, the distribution of metal-tolerant vegetation can help locate overgrown spoil); underground fieldwork is therefore adding a valuable new dimension to the study of surface mining landscapes. A key to understanding mining landscapes is the role of local geology and the properties of the mineral veins. Most of the landscape features seen in metalliferous mining areas are expressions of these geological patterns (Fig 3). The relationship between the ore-field and smelting operations depended on markets, fuel supply and the availability of labour. In some cases, notably in the tin-districts of SW England, the operations were often adjacent. In the Pennines, lead smelters were often sited in the direction of market outlets, and adjacent to the coppice-woodlands or Coal Measures which produced the necessary fuel. Road networks assist the understanding of such patterns. By contrast, post-medieval smelting of the copper ores of SW England was overwhelmingly concentrated in south Wales, the ore being taken to the fuel and the smelted metal then being transported to markets.

In the West Midlands and Yorkshire, iron-mining and smelting thrived adjacent to settlements where land-shortage made employment in the secondary metal trades an attractive supplement or alternative to farming. In Sheffield and its surroundings, ore deposits, coppiced woodlands and water power served the iron industry, while upland agriculture was characterised by the need for industrial by-employment, which gave rise to secondary specialisms that in the end dominated and urbanised the local economy, and provided a base for the emergence of heavy metal industries. In the relationship between metallurgy and other economic activities, as exemplified by both rural and urban landscapes, the farmer-miner or farmer-smith is a key concept, connecting agriculture with industry, especially in areas where the agrarian resource was limited. The archaeological evidence for such activities is often indistinct and unexpected which frequently means that it is overlooked in watching briefs; further studies are required. Economic historians have made much progress in the study of this dual economy, in relation to both metal and other manufactures, partly with the object of examining theories about proto-industrialization (*eg* Thirsk 1961; Hey 1972; 1990; Rowlands 1975; 1989, 114). However, the considerable archaeological potential of former rural-industrial buildings and the associated residues and land boundaries await identification and survey (Fig 4). Craft workshops existed in many areas, and at various periods, beyond districts renowned for their specialism. For example Tyneside hosted the manufacturing centres

Figure 4: Farmhouse with attached smithy (second building from the right) at Dungworth, near Sheffield, Yorkshire.

Figure 5: Remains of 18th-century blast furnaces at the World Heritage Site at Blaenavon, Gwent, South Wales.

of the Crowley and Hawkes families in the 18th and 19th centuries (Flinn 1962; Evans 1993a), and the fringes of the Forest of Dean had significant numbers of smiths at the end of the medieval period (Evans 1993a).

Research into the metal industries of the 18th century and later has concentrated on large units (Fig 5), the blast-furnaces and forges, and rolling mills together with factory-units, rather than the small craft-based workshops. However, the identification of small workshops and the crafts that were practised within them is important in recreating the landscape of the past (Fig 6). The study of the standing remains is one method, where such evidence survives. Additional information can be retrieved by excavation (and by the application of some of the methodologies discussed in Part 2), though often the residues of small craft processes are limited and difficult to retrieve and understand. Routine sampling of soils from sites that may have been the location of small craft workshops can reveal the nature of the craft; see the adjacent example.

Figure 6: View of the Sheaf Valley, Sheffield, in the mid-19th century showing many small workshops with their forge chimneys.

Townscapes and communities

The separation of town and country is relatively recent, characterised by the urbanization of the Industrial Revolution, as is the distinction between the industrial and the agricultural workforce. In urban districts, landscape evidence relating to industries producing and working metal in the last two hundred years is often still quite evident. In Sheffield there has been a growth of interest in the city's industrial past, where items such as cutlery, silver-ware and silver plate, engineers' tools, pins and needles and agricultural implements were made. These industries declined through the 20th century, but their importance was realized, and an attempt was launched in 2001 to encourage the re-use, rather than demolition, of their buildings (Wray *et al* 2001). An English Heritage press release at the time stated: 'Humble workshops as well as the great integrated works buildings played a crucial role in the metals trades. The surviving buildings are a powerful symbol of Sheffield's industrial past. Equally, they are components of the city's regeneration, providing and reinforcing its distinctiveness and unique sense of place' (Symonds 2002, 3).

The Jewellery Quarter in Birmingham is a similar entity with different industries working next to each other in tenement workshops (Fig 7). The inter-relations between crafts in such environments have been the subject of study (Cattell *et al* 2002). These were arguably more complex than in Sheffield, as both ferrous and non-ferrous trades worked in close proximity and a wider range of goods

Example: Making fish hooks in Kings Lynn

Excavation of what seemed to be 13th- and 14th-century workshops on Norfolk Street, Kings Lynn revealed a rubbish pit containing evidence for small-scale iron-working, the complete contents of which were subjected to wet-sieving. This is a fairly new approach to dealing with metalliferous residues and involved washing the soil through a 1mm mesh sieve, a process that was thought by some to be too damaging for the iron (Cowgill 2003). Initial examination produced some fascinating insights into the occupation of the workshop's inhabitants. Iron wire was being made by drawing strips of annealed metal cut from sheet through a steel draw plate. The wire was then made into fish-hooks, by first splaying the end of a length, forming a barb from the splay, then bending the wire into the hook shape and finally splaying the other end (ibid). The sequence and likely speed of this process was recreated from careful study of the waste with the co-operation of a skilled blacksmith. The range of fish-hook sizes recovered has also allowed comparison with the fish-bones retrieved and has fed into a study of medieval fishing and the coastal economy in Kings Lynn.

Example: Evidence for urban metal industries

In Sheffield the existing evidence has been categorized; similar headings would be applicable in other industrial cities:

- Standing remains: *eg* small workshops (often joined to domestic structures), large cutlery and steel works, cementation and crucible furnaces (rare), water-powered sites (for grinding and forging), water management features (leats, wheel pits etc); housing adjacent to these industrial sites. These are mainly of the 18th–20th centuries. Walls may contain materials such as grindstones and 'crozzle'—the clay crust from cementation chests.
- Buried remains (often well-preserved below later structures): Cementation and crucible furnaces, building foundations, water-powered features, waterlogged timbers (*eg* tilt hammers), grinding hulls, artefacts (representing various stages of production), residues and palaeo-environmental evidence. Some features (*eg* deep wheel pits, grinding troughs, water channels) act as catchment zones for artefacts and residues.
- Archives and/or collections from companies: trade catalogues, tools, finished and unfinished artefacts. For example, the 18th–19th century Fairbank collection of finished maps, notebooks and survey books. Old photographs and other records. The Hawley collection in Sheffield University has sought to salvage and bring together much of this sort of evidence from the Sheffield region (www.shef.ac.uk/hawley), but initiatives of this type are rare.
- Oral history.
- Working craftsmen; there is an extremely limited number of craftsmen continuing traditional working practices which all badly need documenting.

Steelmaking continues, although much of Sheffield's output now is 'speciality' steel. There has been a shift in the pattern of production in recent years that itself needs documenting whilst the information still exists.

Figure 7: A tenement workshop in the Birmingham Jewellery Quarter.

was manufactured (Belford 2006). As well as jewellery, Birmingham was also highly regarded for the manufacture of 'toys', a term which covered small articles including buttons and buckles (rather than children's toys, in the modern sense). Such articles required a range of inputs, from glassmakers and enamel workers as well as the metal trades. A number of trades developed out of this, including silverware, jewellery, and the production of pen-nibs, coins and medals. Birmingham was also important as a source of tools of all kinds. Except for some production during the Civil War, the origins of the Birmingham gun trade (making muskets and pistols) probably lie in the 18th century. Some aspects of production were purely manual, but water mills were used to produce the strips that were forged into gun-barrels, and then to bore out and grind off the barrels. Other components were produced in domestic workshops. During the 19th century the industry was centralized in factories, and it also branched out into making tubes (such as gas pipes), bicycles and machine tools. The wide range of metalworking skills in the region was exploited with the advent of new industries. For example, component manufacture for the motor vehicle and aircraft industries in the 20th century developed out of the skills gained in the mechanization of the 19th-century gun trade. Many 17th, 18th and 19th-century industries—and the lives of those that worked within them—have remained little-studied archaeologically. Such explorations require a holistic approach that examines the wider landscape of houses, pubs, shops and streets, as well as the workshops themselves (Belford 2001; 2003; 2006).

In the 19th century the Black Country, outside Birmingham, possessed many examples of urban landscapes characterized by small workshops. At Cradley Heath there were around 900 chain-makers' shops, most very small-scale family enterprises (Belford 2006). Despite the small scale of production, Cradley Heath produced most of the chain used in Britain and its overseas territories during the 19th century. The industry remained dominated by hand forging, and by a tightly-knit and closely-demarcated workforce. Several small concerns might join forces for a particularly large order, but independence was valued and the industry never developed the tenement workshops that became a feature of the 19th-century Sheffield trades (*ibid*). Such approaches to the social aspects of metalworking can also be used to inform the interpretation of the archaeometallurgy of more distant periods (see Part 3).

Below-ground features

The commonly-held view that certain forms of mining are primitive, and must therefore be evidence of

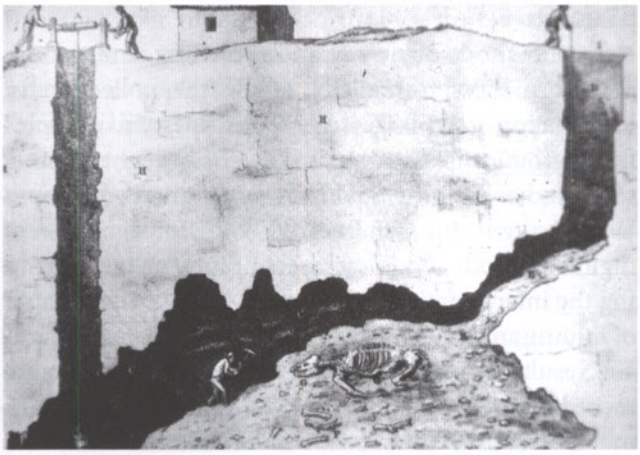

Figure 8: Drawing of Dream Mine, Wirksworth, Derbyshire, showing two shafts, the one to the left with a windlass. After Buckland 1823.

early workings, is an idea that can be challenged. For example, the presence of a line of small shafts has traditionally been taken as indicating early mining (Raistrick 1975). However, when extracting ore from shallow deposits, this was the most appropriate technology. Such features represent the presence of an economic ore-body near the surface. Early miners were likely to have found these deposits attractive, but in locations such as Grassington Moor, Yorkshire documentary evidence suggests that shallow mining did not commence until the mid 18th century (Gill 1993). In contrast, in the 17th century, some mines in Swaledale, Yorkshire were working in the Main Limestone at depths of over 200ft (60m) at a time when the use of gunpowder for blasting rock was unusual (Raistrick 1982). This, and other evidence, indicates that the rock-breaking technology of the medieval miner did not preclude deep mining. The main technical obstacle to working at depth in earlier periods was that of mine drainage. However, social factors were just as important. In areas where traditional mining law prescribed the allocation of 'meers' (short lengths along a vein) to different partnerships of miners, extraction by lines of small shafts was almost inevitable. But in the minority of mining areas, such as Bere Alston, Devon, where mining developed under Crown control, deep mines with long adits, centralized water-powered pumping and long surface leat systems to supply the water, developed in the medieval period (Claughton 1994; 1996).

The extensive nature of many underground mining remains demands consideration analogous to research into surface landscapes, and the basic techniques of archaeology—survey, excavation, analysis, experiment, conjecture and reconstruction—can all be applied underground. Mines comprise complex three-

Figure 9: The sub-surface of a lead-mining landscape at Gunnerside Gill, North Yorkshire. This engine house is on Sir Francis Level 240ft below the valley (Fig 35). Two Davey hydraulic engines were installed in 1880: one (centre left) worked the pumps (two large vertical pipes) and another (behind camera viewpoint) the winding gear. One cage is suspended just below floor level.

dimensional structures within which are individual sites or features (Fig 8). Three-dimensional computer modelling of underground spaces is a valuable tool for interpretation. Surveys of workings have produced valuable evidence of changes in ore-mining methods. Examples are the change from fire-setting to the use of explosives, the development of drainage-adits (soughs) together with mechanical and hydraulic drainage devices (Fig 9), horizontal and vertical haulage systems, provision for ventilation, and methods of ore-selection below ground, minimizing the quantities of material brought to the surface.

It is often suggested that metal mining destroys its own past; and modern mining certainly can totally obliterate earlier evidence. In some areas, notably the Pennine lead-fields, ore-dressing wastes were reprocessed and previously uneconomic ores were smelted as new technologies developed; this has been a feature of mining for (at least) several centuries. However, even where more-recent mining has been extensive, destruction of earlier workings is often far from total. For example,

Figure 10: A small-scale 17th- and 18th-century mining landscape at Bonsal Moor, Derbyshire. The upcast (spoil) around the mine shafts dominates the view.

at Alderley Edge, Cheshire, careful archaeological recording was able to disentangle the remaining profiles of Bronze Age shafts from wholesale post-medieval slitting of the vein along which they had been sunk (Timberlake and Prag 2005).

Mining archaeology is defining site components and attempting to place them in a chronological framework. Documentary records of plant and machinery on mining sites are helping to show when technological changes occurred and, therefore, broadly date the related features. This works well for the 18th and 19th centuries but for earlier mining characterization is more difficult, because there are few detailed records and because 17th-century miners were still using medieval methods (Fig 10). To ensure that the recording of underground sites is carried out to adequate standards, the National Association of Mining History Organisations (NAMHO) has a descriptive specification for underground survey which aims to be equivalent to those of English Heritage for surveys of field monuments and standing buildings (Roe 2002). Its use ensures that reports on underground sites will correspond with local and national Historic Environment Records.

1.3 Recording metallurgical evidence

Both survey and excavation can provide information about metallurgical sites. Some are primary production sites where ores were mined or smelted to produce metal, and a wide range of features and structures may be found. However, it is often only the technological debris that survives, but its collection and study can usually identify the processes being carried out.

Sites

Newer methods of survey and recording, and the use of information technology, allow the collection of information from large-scale landscapes and complex underground sites, which can then be brought together with studies of individual features to produce comprehensive site studies (*eg* Roe 2000). The introduction of digital methods is adding layers of information, changing the interpretation and understanding of landscapes of mining and metallurgy, both above and below ground. The results of such site and landscape surveys require recording as sensitive areas in county Historic Environment Records (HERs) or Sites and Monuments Records (SMRs). This may best be undertaken as specific programmes of HER enhancement (see section 1.6). Such recording of data facilitates the long-term preservation of a range of metallurgical sites and sites of metallurgical interest, over the full range of time-periods, site types, regional traditions, and types of industry. This aim has been partly achieved by the Monuments Protection Programme (MPP) (Fairclough 1996, 3–4 and 15; Stocker 1995), by its successor Strategy for the Historic Industrial Environment Reports (SHIERS) and by Scheduling and Listing a selection of the most significant sites (see section 1.6).

It is especially important that all metallurgically-important sites whose preservation cannot be guaranteed, or which are under active threat of destruction, are recorded. Such records should be published promptly (except in cases where this might itself expose the site to threat), and the documentation appropriately archived. Curatorial archaeologists should be encouraged to make full use of planning procedures to preserve important sites. Additionally, efforts should be made to encourage the adequate publication of developer-funded work rather than confining results to 'grey literature'. While this is of very variable quality, the reports are likely to include important historical and field information. Mechanisms for wider dissemination and synthesis are much-needed, perhaps on the lines developed by Bradley (2006) for prehistory. Excavation should be carried out only as part of the response to regional or national research strategies or when there is a threat through development. In either case adequate resources of both funding and expertise, for work in the field and particularly for post-excavation study, must be made available.

A high priority for preservation and/or intensive site-recording in advance of destruction should be attached to sites whose historical importance rests on their association with key innovations, and which may therefore offer unique opportunities to investigate the processes of innovation archaeologically. Similar considerations apply to sites where specific processes are known to have been used but their archaeological manifestations are not yet well characterized. It is hoped that examples of good practice quoted here will encourage a general improvement in the quality of work carried out.

Evidence for metal production

The production evidence for the prehistoric through to the medieval period is inevitably scant, but does exist; most comes to light through excavation. Furnaces and other structures were frequently insubstantial so usually the only indicators of early metal production are residues. Specialist expertise can help to identify what little evidence may survive, so working with an archaeometallurgist will often lead to the retrieval of a more complete sample of the available production evidence (see sections 2.2 and 2.3) than just retaining readily identifiable metallurgical material for post-excavation processing. Collaborative working is crucial for the full understanding of the archaeometallurgical resource, especially that of earlier periods. The very wide type- and date-range of non-powered iron-smelting sites remains incompletely understood and so the survey and excavation of those with the possibility of such production evidence is a priority (see Part 3). Copper, tin and lead production sites for the earlier periods are extremely rare, thus the identification of any such operation would be of importance (see section 3.1). In particular the identification and excavation of Roman and early medieval non-ferrous metal production sites is a priority.

The later medieval period has more substantial production evidence, and smelting and forging sites can be identified from the historical record. Early blast-furnace sites (*c*1490–1560 AD; Figs 12 and 13) are a high priority for study and preservation as are copper-smelting sites of the 16th and 17th centuries, the period of Crown encouragement of copper extraction. The medieval and post-medieval 'blowing house' tin smelter is relatively common in south-west England, although few have been excavated. However, the tin industry is of international importance and therefore justifies a high level of preservation. Later medieval lead smelting is a topic of developing interest, and further research into technical improvements should be encouraged.

The later developments in iron smelting, especially the post-medieval blast-furnace in the period of adoption of mineral fuel, warrant further study, so it is a priority to identify and preserve sites where production evidence

Example: Metal industries in Cornwall

Archaeologists working in Cornwall potentially have the evidence for a metal industry spanning more than two millennia on over 2000 (and probably many more) sites. Some are exceptionally well-documented or survive as upstanding buildings or earthworks (Fig 11); others have been identified only from aerial survey, chance finds, excavation or field survey. Over nearly thirty years, the resources available to professional archaeologists have provided a massive data base with which to work. Emergent research frameworks and contextual information has allowed targeting of attention to mineral processing activities as part of developer-led excavation, where opportunities for more leisurely data-gathering are available, and evidence can be accurately dated and analysed within a secure, wider context. Such excavations have produced a wide range of evidence which is helping to refine a local research agenda. Tin, copper and iron slags have come from a large number of sites; fragments of cassiterite and haematite from prehistoric settlements well away from any known lodes, and stone weights, ore-grinding mortars, smithing hearth bottoms and hammer scale from sometimes unexpected sites. Evidence for secondary iron and, possibly, copper-working has come from Trevelgue Head promontory fort (which may have been exploiting a local iron lode) (Nowakowski forthcoming) and Romano-Cornish iron-working has been identified at Little Quoit Farm near Goss Moor (Lawson-Jones 2003). Secondary metalworking has also been found at Tremough, Reawla (Appleton-Fox 1992) and Trethurgy (Quinnell 2004) Iron Age enclosures and, most interesting of all, a late prehistoric defended enclosure at Killigrew Round seems to have been wholly devoted to metallurgical activities. In a context where secondary gold-working appears to be the norm rather than the exception in late prehistory, professional archaeologists in Cornwall now make provision in their project designs for methodologies designed to detect and analyse such evidence.

Figure 11: The Crowns engine house, Botallack mine, Cornwall, is set at the foot of a cliff on an outcrop of a rich tin and copper lode. This mine was worked from at least the 16th century.

Figure 12: Chingley blast furnace, Kent, under excavation, showing the bellows area in the foreground and the furnace hearth beyond.

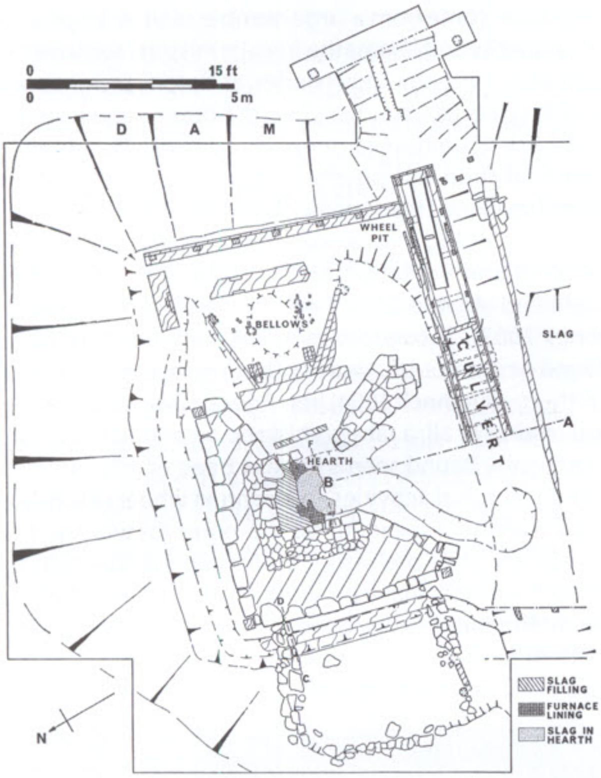

Figure 13: Plan of Chingley blast furnace with bellows area at the top and the wheel pit to the right, discharging into the culverted tail race.

is likely to exist. Similarly, the development of conversion forges (which turn cast iron into 'wrought' iron) is incompletely understood, excavated evidence having come only from two charcoal-fuelled Wealden examples. Archaeological investigation and preservation of 17th- and 18th-century finery-forge sites is badly needed. In addition, scientific research is needed, particularly on forges of the late 18th century that used the 'potting and stamping' process, on early puddling furnaces, and on those with balling furnaces for recycling scrap (King 2003, 58–66) (see section 3.8).

Technological debris

Technological debris comprises a crucial part of the available resource. This falls into five broad groups: raw materials, structural evidence, process evidence such as crucibles and moulds, waste products and the metal itself (which is discussed further in section 1.4). Often it is only the process-residues that survive to contribute to the archaeological record.

Raw materials

The geological identification, size, size-distribution, shape, and mineralogical composition of mining wastes can yield information on the technology of both underground mining and surface processing. On smelting sites ore can occur as raw fragments, as roasted ore pieces and as small roasted ore fines. Charcoal is not necessarily found in abundance on smelting sites, as it was too valuable a material to waste. Samples, especially from features, are potentially important not only for dating but to identify the species used and as an indication of woodland management by coppicing. Coal and coke were not used for smelting until the post-medieval period.

Structural materials

Clay was used in the construction of furnaces and once fired it can be important for the identification of sites by geophysics, and for their archaeomagnetic dating (see section 2.2). The processes carried out can sometimes be identified, particularly when slags etc adhere to the clay. Stone, brick and tile were also used in furnace structures. Examples are the distinctive clay tiles found on some Roman sites (Fig 60), and firebricks associated with post-medieval cementation steel furnaces. The high temperature in a furnace can vitrify clay, giving it a glassy surface, but all furnace and hearth structures will show some evidence of some degree of heating.

Crucibles and moulds

Crucibles and moulds are non-recyclable so are probably the best and most recognizable and abundant archaeological indicators of non-ferrous metalworking. Ceramic crucibles used for metal-melting are usually reduced-fired (grey or black) as metals have to be melted under reducing conditions to stop them being oxidised and lost into the crucible slag (Fig 14). As they are used at high temperatures, crucibles become vitrified and small quantities of the metal being melted may be chemically or physically trapped. Visual examination, with the naked eye or under low magnification (x10–x30), can give some idea of the metal being melted. Some vessels identified as crucibles in the course of excavations may

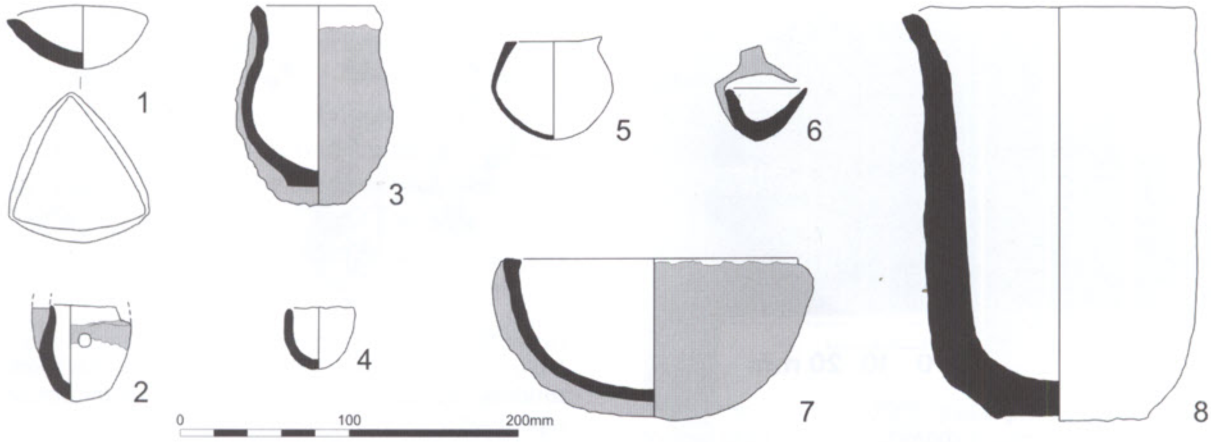

Figure 14: Drawings of common crucible forms dating from Iron Age to the post-medieval periods. 1: Iron Age, 2-3: Roman, 4-6: early medieval, 7: later medieval, 8: post-medieval. The grey tone represents added clay, serving either as lids (2 and 6) or extra outer layers (3 and 7).

actually have been used for processes other than metal melting (Bayley *et al* 2001).

Molten metal was cast, either direct into objects, or into small ingots. The latter could be hammered to produce rods, wire or sheet, which was in turn made into objects. Ingot moulds were usually made of stone, though some are brick or tile with shapes cut into them. Moulds for small objects were usually made of fired clay though stone and metal moulds are known.

Slags

Slags are formed during the smelting and working of metals. Iron slags of various types are the most frequently found, usually dumped in negative features such as pits and ditches. If a large accumulation of slag is found in the base of a furnace, it is possible that the smelt failed and the furnace had been abandoned. Copper-, lead-, tin- and iron-smelting slags can be sparse, due to re-smelting, but can lead to the discovery of furnaces and other related structures (Fig 15). The excavation of slag deposits can provide stratigraphic information, allowing the documentation of technological change when sequences of slags are analysed in the laboratory. The presence of dateable material within a slag-heap, such as diagnostic pottery or charcoal for radiocarbon dating, can allow site chronologies to be related to technological changes and developments (see section 3.3).

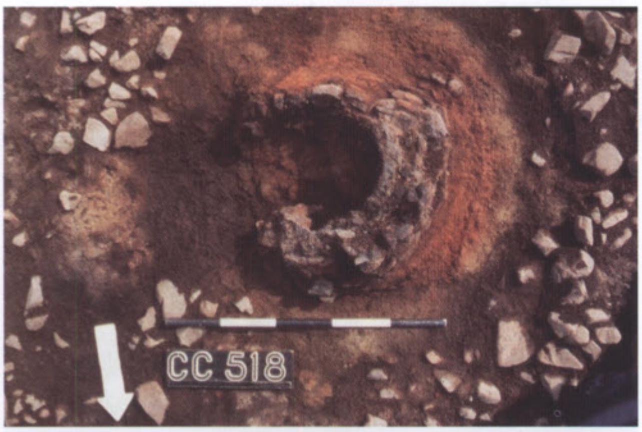

Figure 15: Base of excavated Iron Age bloomery furnace at Crawcwellt West, Gwynedd. The red-burnt clay shows the walls were originally ~200mm thick. Scale bar 0.5m.

The amount of slag which can be expected at a primary production (smelting) site varies considerably with the period. With prehistoric examples even a few kilograms can be significant. Deposits at Roman and medieval iron-smelting sites can vary widely, up to thousands of tonnes. Slags are not datable in themselves, but consideration of the types which occur (Figs 16 and 17) and their quantities may give some indication of the period. With prehistoric iron slags there can be difficulty in distinguishing smelting from smithing residues. However, in the Roman period and later, smelting slags are more readily distinguished, with tap-slags from bloomeries and glassy blast-furnace slags being characteristic. Routine examination of slags aids the accurate identification of site function (Fig 18) and can potentially provide the basis for a better understanding of questions raised in Part 3. A combination of visual examination and scientific analysis can also indicate the variability within a slag assemblage, and hence inform decisions about the discard or dispersal of some of the material — often a welcome relief to museum professionals with over-full stores (SMA 1997, 29).

Where there were large quantities of slag, they were often removed from the site. Many early slags contained significant quantities of metal so they were re-smelted as technologies developed. Slag could also be re-used as hardcore in areas lacking good supplies of local stone, and large quantities were used as ballast under railway tracks.

Figure 16: Tap slag, showing its characteristic flow-form surface structure.

Figure 17: Blast-furnace slags are usually glassy in appearance and can range in colour from blue/green through to grey/brown. They were often re-used as hardcore and so can be found in small pieces far away from furnace sites.

Metals

Smelting normally produces ingots of metal, sometimes called pigs, that were cast direct from the furnace. As iron could not be melted in early furnaces, the end-product of smelts was a 'bloom'—effectively a sponge of metallic iron full of slag—which was taken from the furnace and hammered to compact it and squeeze out the slag, producing forgeable bars. Late and post-medieval blast furnaces produced liquid iron that was cast into ingots, like other metals, or direct into large objects such as guns. For more information on metals, see section 1.4, below.

1.4 Artefacts

Especially for the early periods, often the only evidence of a particular technology that survives is the end product—the artefact itself (Fig 19). Archaeometallurgy has therefore traditionally reconstructed technologies

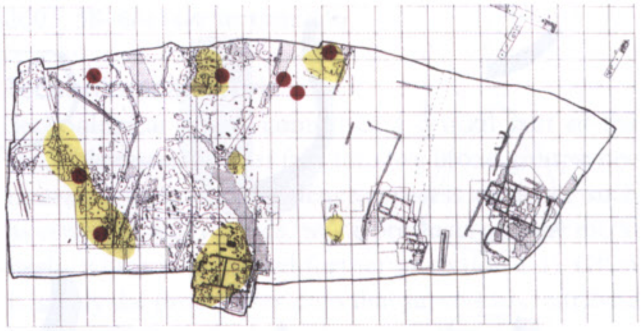

Figure 18: Plan of excavated features at the Roman site at Shepton Mallet, Somerset, where both iron smelting (yellow shading) and smithing (red spots) were taking place. Note the partial spatial separation between the two activities.

from artefacts through laboratory analysis.

Analysis and study

Investigation of artefacts can vary from visual examination, through low-power binocular microscopy and radiography to metallography and full-blown chemical and/or isotopic analysis. There are various techniques available to analyse artefacts and these are discussed in section 2.4. The results of analyses are only as good as the sampling strategy allows them to be (see section 2.3), and with artefacts this can sometimes be as important as the analysis itself. Analysis of metal artefacts and other technological debris can inform on a great many issues:

- Smelting technology: chemical and microscopic analysis can indicate ore type, the efficiency and nature of the smelting process, furnace parameters, whether fluxes were used, etc (Craddock 1995, 135–144).
- Fabrication technology and treatments that modify the properties of the metal: radiography can inform on macro-fabrication and metallography on micro-fabrication. This is especially true for ferrous metals as heat treatments can alter their physical properties, which can be very informative about an artefact's place in the culture that produced it (see section

Figure 19: Hoard of complete and fragmentary precious-metal Iron Age torcs from Snettisham, Norfolk.

2.4). Detailed study of chemical composition can also provide information on workshop and industry organization.

- Material culture: technological choices made when producing artefacts can reveal culturally specific strategies and how these relate to ideas of ethnicity and belonging (see sections 3.3, 3.4 and 3.5).
- Trade and exchange: chemical and isotopic analysis in particular can provide information about artefacts' origins, important in discussing their circulation and exchange (see sections 3.1 and 3.4)
- Economic and fiscal policies: chemical analysis of coinage can aid understanding. For example, two coins of the same size and weight may appear to have the same intrinsic value, but only analysis can tell if the alloy and therefore the value is the same.

Despite all these possibilities, artefactual analysis is still relatively rare and certainly not as routine as other types of archaeological recording and investigation. Photography, drawing and weighing are all standard ways of characterizing artefacts yet composition and fabrication history are deemed relatively unimportant. Indeed, until recently many museums displayed all objects made of a copper-based alloy as 'bronze' regardless of alloy type; yet we now know that alloy type can be an important differentiating criterion (see sections 3.4 and 3.5).

A way forward

Museum collections can be unrepresentative of metalwork in use at any particular time, as they tend to concentrate on the best-quality and most aesthetically-pleasing items. Even some modern acquisition policies can be accused of bias towards artefacts which are of interest to curators, reflect collecting fashions, or which attract visitors and headlines. However, the attempt to preserve all the finds from excavations means that local museums often store excavated archives which contain representative, everyday metalwork. Additionally, under the Portable Antiquities Scheme many museums have Finds Liaison Officers attached to them who can be sources of information and access to recently-discovered metal artefacts (see section 1.6). Museum curators are often keen to have their holdings used for research, as this helps justify the maintenance of the collection as a resource.

Analyses of metal artefacts need to be conducted on a sufficiently large scale to be representative; one or two analyses are not sufficient to characterize manufacturing practices, an artefact type or culture group (Bayley and Butcher 2004) (Fig 20). The statistical examination and investigation of analytical data is also now regarded as a necessity. A useful overview of such approaches with a comprehensive bibliography is provided by Baxter and Buck (2000). However, before any analyses are contemplated, there should be an explicit research question to which the results have the potential to contribute, if not to answer.

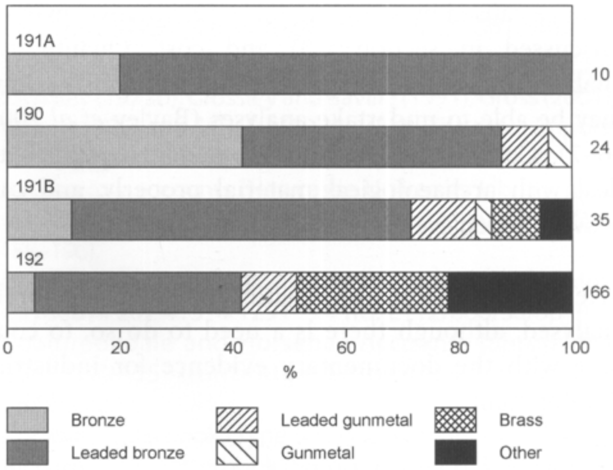

Figure 20: Frequency plot of alloys used to make different types of late-Roman crossbow brooches. The early examples (191A) are mainly leaded bronzes while the latest (192) have only a minority of leaded bronzes but many brasses and other lead-free alloys, many of which were mercury gilded.

The counter-argument is that in an ideal world a proportion of metal artefacts from all excavations should be routinely analysed alongside any production refuse. It may be that the analysis of a fibula and a couple of fragments of copper-alloy sheet from a single site are of little inherent interest or value in themselves, but when analyses of metal finds from several sites of a particular type are brought together, patterns and trends can begin to be identified and discussed (*eg* Bayley and Butcher 2004). If this sort of approach is to be adopted, it would be desirable for all developer-funded projects to have funding for analysis of metal-related finds routinely written in.

If a 'future-proof' database of analyses were to be compiled, an acceptable quality bench-mark for analytical data would have to be set up. At present most analyses are directed at answering specific questions, which can be at the expense of providing data of the consistency and quality required for a national archive. It may seem sensible that where an analysis is to be undertaken it is as full as possible, even if a low-level qualitative analysis would answer immediate questions, but in the real world resources are limited so compromises usually have to be made.

The arguments against such a policy are the risk of damage caused by sampling for a quantitative analysis (discussed in section 2.3) and cost. Quantitative analyses are relatively expensive, but some institutions may be able to undertake analyses (Bayley *et al* 2001, 26–7). Commercial analysts are seldom equipped to deal with archaeological material properly, and can provide expensive disasters through ignorance.

Artefacts from the post-medieval period are rarely analysed, although there is a need to do so, to compare with the documentary evidence for industrial development.

1.5 Documentary resources

Recently-produced documents may summarize a variety of information on metalworking in particular areas. Much of this is 'grey literature' which is not fully published, but it will complement and often update the information contained in books and journal articles, as well as that to be found in the variety of documentary sources discussed below.

The historical records of the post-medieval iron and steel industries are used as an example, but archive sources are also available for the working of other metals. Records of many types exist for the lead industry (*eg* Kiernan 1989, Raistrick 1973; 1975), for copper and brass (*eg* Harris 1964, Day 1973, Morton 1985) and for silver extraction. For the latter, the records of the English Crown are a major source; Claughton (2003) has synthesized the documentary evidence for silver production between 1066 and 1500.

Example: 18th/19th-century knife manufacture in Sheffield

Analysis of finds from ARCUS excavations at the Town Wheel cutlery workshop, Sheffield, was undertaken by Rod Mackenzie of Sheffield University. Three blister steel bars provide independent evidence for 18th- and early 19th- century steel-production technology and allowed research into the characteristics of the material. They show the wide range of steels produced at Marshall's Millsands Steelworks, which was only about 100m from the excavated workshop, from lower carbon steels typically used in cheap cutlery to high carbon steels for specific applications.

The two knives were selected for analysis as they dated to the period when Marshall established his steel works at the site. Analysis has shown them to be made of blister steel (see section 3.8). Figure 21 shows at least seven different layers of steel in the blade which originates from the separate bars of blister steel that were forged into a single piece known as shear steel. Cleaner blister steel bars appear to have been selected for the outside and centre of the shear steel as these regions would have formed the exterior and cutting edges of the blade. The use of single-shear steel suggests that this knife would have been of reasonably good quality. In contrast, Figure 22 shows a much higher abundance of inclusions (dark spots) in the metal. Although the blade appears to be a well-finished object it has been 'cobbled together' from separate pieces of steel of varying carbon contents, suggesting that it was made from recycled scrap blades. In the 18th century, steel was a valuable commodity, purchased by weight, and would have been reused rather than discarded. The makers of both objects are identifiable from their stamps. The higher-quality blade was made by an experienced cutler, while the lower-quality one was either made by a less experienced cutler from poorly re-cycled metal, possibly someone only recently apprenticed, or may be an example of lower-quality cutlery.

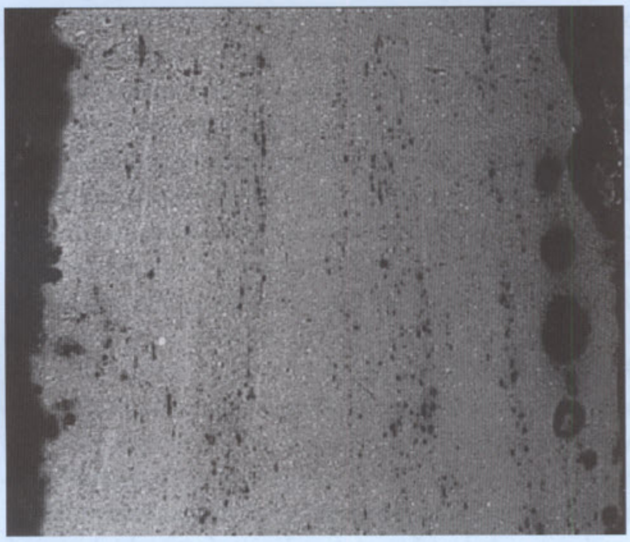

Figure 21: Section through knife blade showing seven layers in the shear steel. Image width ~1mm.

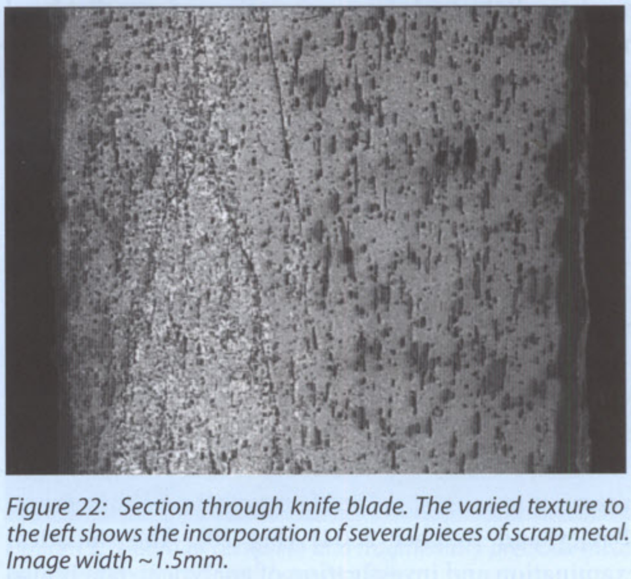

Figure 22: Section through knife blade. The varied texture to the left shows the incorporation of several pieces of scrap metal. Image width ~1.5mm.

Lists of ironworks

Although only giving site-names and outputs, the 18th-century lists of ironworks are a significant source. Those compiled in *c*1716, 1718, 1736 and 1749 were published by Hulme (1928) and evaluated by King (1996) and Evans (1993a). The data for furnaces operating between 1660 and 1980 have been systematically collated by Riden (1992; 1993) and Riden and Owen (1995). Forges have received much less attention and a 1790s list in Birmingham Archives (B&W MII/5/12) appears to be the last survey of them until the later 19th century. Recent research by King (2003) includes a systematic gazetteer of forges which provides an invaluable basis for further work.

Commercial records

Compared with some commercial activities, the surviving records derived from ironmasters are relatively plentiful, but nevertheless far from comprehensive. They are particularly scarce for the period before the middle of the 17th century. However, records of the sales and purchases of one works can provide information on the business of contemporaries. Most surviving records consist of accounts, leases, supply agreements and correspondence, and result from ironmasters or their descendants becoming members of the landed gentry, but a few have remained in the hands of successor firms.

Estate records

Where the internal records of an ironworks do not survive, information about the ownership of the business can be derived from the estate records of its landlord (Fig 23). Obvious sources in this connection are leases. These may not only provide for the letting of a furnace or forge, but often also the provision by the landlord of cordwood (for charcoal) and mining rights for iron ore. In addition to the deeds themselves, details of leases can sometimes be found copied into lease-books, or abstracted in estate surveys, in terriers (lists of land-parcels) written on (or prepared to go with) maps. These records generally do not say much about an ironmaster's business, but do show that the ironworks was in operation and who owned it. Somewhat less useful (but still valuable) are the landlord's own title deeds (including settlements and mortgages), which have a brief description of his property, often naming his tenants.

Other financial records

Land Tax Assessments, which between 1780 and 1832 were lodged with the Clerk of the Peace, are therefore among Quarter Sessions Records in County Record Offices. These survive for many but not all counties. For

Example: Ironworks records up to the mid 18th century

Published ironworks records include those edited by Crossley (1975b), Crossley and Saville (1991), Gross (2001), Riden (1985) and Schafer (1978; 1990). The most important ironworks records in manuscript include:

Backbarrow accounts (Newcastle University Library, misc ms 32; Lancs RO, DDMc 30/1-9; Barrow in Furness RO, z 186–196).

Boycott & Co accounts (National Library of Wales, Cilybebyll 202 413–4 1291–5; PRO, E112/880/Salop 9).

Coalbrookdale and Horsehay Accounts (Shrops RO, 6001/329–35; Ironbridge Gorge Museum Library, CBD59.82.5).

Cookson letterbook (Tyne & Wear Archives 1512/5571).

Richard Ford's letterbook (Shrops RO, 6001.3190).

The Foley collection (Herefs RO, E12).

Forest of Dean administrative records (PRO, various classes including E178; SP 18/130/146ff' SP18/156B; E178/6080; LR6).

Knight ironworks accounts (Worcs RO, 899:31 BA 10470; Herefs RO, T74).

William Lewis's The Chemical and Mineral History of Iron (Cardiff Library ms 3.250).

Letterbook of Robert Morgan of Carmarthen (National Library of Wales, Griffith E Owen 162).

Staveley Ironworks Records, which also cover ironworks at Sheffield (Sheffield Archives, SIR).

The Spencer-Stanhope Collections (Sheffield Archives and Bradford Archives, SpSt).

Tredegar Park collection (National Library of Wales, Tredegar Park 76; Tredegar mss & documents 136).

Diary and letterbook of John Watts 1715 (Sheffield Archives MD 3483).

Weale mss (Science Museum Library ms 371/1–4).

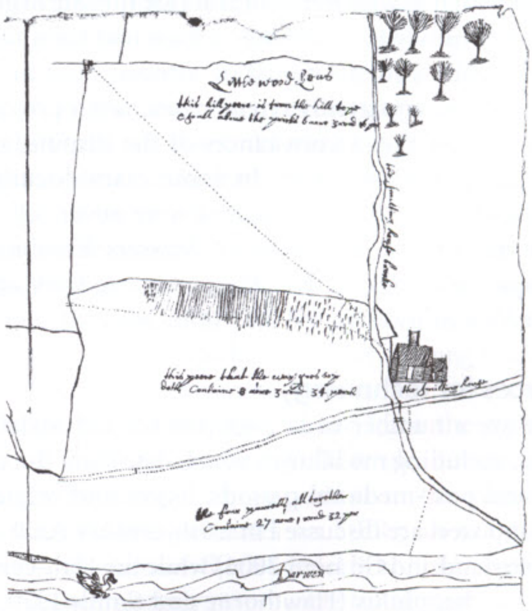

Figure 23: Sketch, probably from the mid-17th century, showing Little Rowsley lead-smelting mill on the Smelting House Brook that flowed west into the River Derwent, Derbyshire (bottom), and the woodland (top) that provided fuel for the smelter (Chatsworth Map H304/43).

some areas there are further copies of the assessments, which have been deposited in Record Offices by Land Tax Commissioners. For parts of Sussex these go back to the 1690s. The amount of tax payable did not vary after 1780, and only rarely changed before that. This enables the ownership and occupation of each property to be followed from year to year. Rating records (in parish deposits) may be used in a similar way if they survive.

Litigation

Much valuable information can be obtained from the records of litigation in the equity courts, preserved in the National Archives (formerly the Public Record Office). These are the Courts of Chancery and Exchequer, and, before the Civil War, the Courts of Requests and Star Chamber. The listing of many of these records is still far from satisfactory. Most classes were originally only listed by the plaintiff's name although in some cases there is a calendar that specifies the subject matter of the claim. If so, a place-name index may have been prepared from this, but there are hardly any subject indices. Work is in progress to enable the National Archives lists, calendars and other finding aids to be searched on-line. Until this work is completed, discovering relevant documents is likely to remain difficult unless the names of individuals are known from other sources. Disputes were of many kinds, but perhaps most valuable are those between the partners in an ironworks. These often list all the works owned by the firm, and may have accounts attached to pleadings. However, many actions were concerned with less-significant matters, such as whether a contract for the sale of goods had been fulfilled, or whether a loan had been repaid. The statements (depositions) of witnesses can be valuable, even in apparently trivial cases, often providing statements of the circumstances of the dispute, some with topographical asides. In some cases documents lodged with the court as evidence were never collected. These are known as Chancery Masters Exhibits, an example being the early-19th-century ledgers of the Ebbw Vale ironworks (PRO, C 114/124–127).

Sources for technology

There are a number of key sources for industrial processes, including metallurgy, which date from the medieval and post-medieval periods. Types and origins of iron and steel are discussed in a 9th-century Arab treatise (Hoyland and Gilmour 2006) while the 12th-century tract by Theophilus (Hawthorne and Smith 1979) is a valuable early source, as are the 16th-century books by Biringuccio (Smith and Gnudi 1943) and Agricola (Hoover and Hoover 1950; Fig 24) which have later equivalents, notably Diderot's *Encyclopedie* (Gillispie 1959) for the 18th century, Rees' *Cyclopedia* (Cossons 1972) and various editions of Ure's *Dictionary* (*eg* Ure 1843) for the 19th century. However, at the practical level, knowledge of processes was generally transmitted from generation to generation by the apprenticeship system, under which a master agreed with the parent of a young man to teach him his trade. This was largely done by demonstration, rather than by the pupil reading a description. Hence contemporary descriptions of metallurgical or other processes are rare. Some new processes were patented, and by the middle of the 18th century the grant of a patent was followed by the enrolment of a specification. These are valuable as far as they go, but do not indicate whether the process was viable, either in technological or economic terms. The economics of a process can be deduced from ironworks accounts, but that does not indicate how it was carried out. For that it is often necessary to rely on what visitors described. Their observations are widely scattered in diaries and journals. Some visitors had little understanding of the processes and their descriptions are less valuable. However, of particular value are the journals of Swedish travellers, who (coming from a country whose main export was iron) were particularly interested in the processes. A recently published example is *Angerstein's Diary* (Berg and Berg 2001; Fig 26). The same applies to certain French visitors, who came late in the 18th century expressly for industrial espionage. The translation and publication of their diaries would add significantly to our knowledge.

Figure 24: Water-powered stamp mill crushing ore in Germany in the 16th century from Agricola's De Re Metallica. *After Hoover and Hoover 1950.*

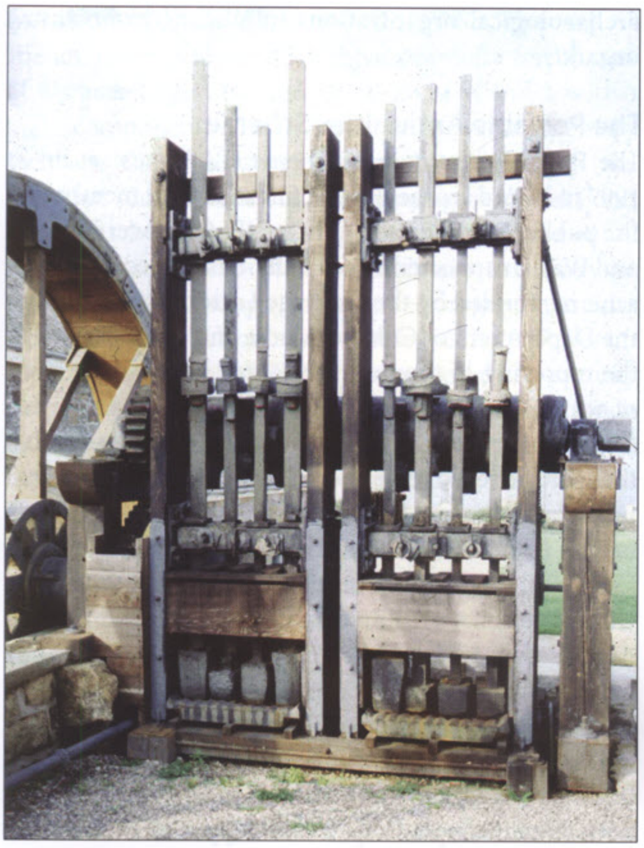

Figure 25: 20th-century ore stamps from Zennor, Cornwall. Compare with Figure 24 and note how little has changed in 400 years.

1.6 Managing the resource

Statutory protection of sites

The Monuments Protection Programme was set up by English Heritage in 1986 to review and evaluate England's archaeological resource. Although some metallurgical sites and buildings had been Scheduled or Listed, it was acknowledged that their representation was inadequate. Industrial monuments were therefore used to test the methodology, and the outcome was the production of a series of documents. These reports were not formally published but copies were deposited with the NMRC at Swindon and in relevant HERs (see below); it is now planned to make the information in them available on the English Heritage website (www.english-heritage.org.uk). For each industry there was a Step 1 report which included a breakdown of the component features of the industry, including a glossary of terms and the likely date-ranges of each component. These were based mainly on published studies with limited reference to field archaeology. This, however, fitted with the project aim of establishing what is there (Stocker 1995), but was not always able to say what it meant. Later, Step 3 reports were compiled which presented lists of sites that were regarded as representative of the different features and developmental stages of the industries; these were

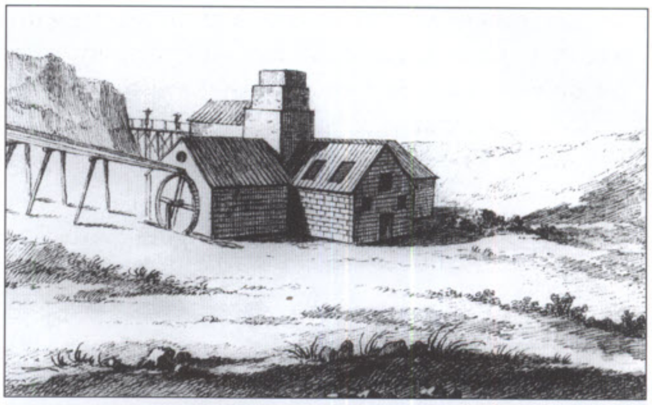

Figure 26: Sketch of Maryport blast furnace, Cumbria, from Angerstein's diary. After Berg and Berg 2001.

graded according to their importance and desirability for statutory protection.

Although for some industries specific recommendations for statutory protection were made, not all of these have so far been followed through. The outcome of the current Heritage Protection Review (www.english-heritage.org.uk/server/show/nav.8380) will be a faster, more open and unified system that should ensure increased protection for these English sites; it is to be hoped that similar systematic protection will be introduced in Wales and Scotland.

Historic Environment Records

An integrated heritage database, the Historic Environment Record (HER), covering archaeological sites and monuments is maintained by most local authorities in Britain and comprises a sites and monuments record (SMR) and a historic buildings record (HBR). These are publicly available resources that are supposed to be the repository for the archaeological resource within a region. Most HERs have been built-up since computerisation in the 1980s, but older records still have a substantial paper component. In most cases, new information usually comes into the SMR through the planning process. Some HERs such as those in the Lake District and Norfolk, which has a strong tradition of good relations with metal detectorists, now record individual finds. Data also comes from the Portable Antiquities Scheme (see below). The role of individuals seems to be particularly important in the recording of archaeometallurgical sites on HERs; an example is the work of Michael Davies-Shiel who, over some 30 years, has been largely responsible for around 250 iron-working sites being recorded on the Lake District HER (Fig 27). Some HERs are perceived as primarily a tool in the planning process and not specifically an archaeological resource, any archaeological benefit being a

Figure 27: Two linear slag tips at Crowdundle Beck, Cumbria; the left-hand one is being eroded by the beck. This bloomery site was identified by Davies-Shiel and probably dates to the 17th century.

spin-off. Such attitudes can lead to an incomplete and biased record for archaeology as a whole, and especially for archaeometallurgy which is often poorly understood by the archaeologists themselves.

A positive example is the Lake District National Parks Authority which, in collaboration with the National Trust, has recently undertaken a programme of HER enhancement with particular reference to iron-working sites. The results are quite outstanding and have led to the geophysical survey of over 35 bloomery sites dating from the 13th to the 16th centuries (Hodgson pers comm). There is a general need to expand the scope and quality of HERs, and to raise their profile as research resources. Further progress is needed on converting paper-based systems to a digital format.

The development of digital resources for archaeology is expanding greatly. Alongside local HERs there are now national resources, many of them hosted by, or accessible via, the Archaeology Data Service (ADS; ads.ahds.ac.uk). It preserves digital data in the long term and makes available digital resources such as those listed on HEIRNET (Historic Environment Information Resources Network) or included in the ADS catalogue, ArchSearch. It also gives access to data from projects such as OASIS (Online AccesS to the Index of archaeological investigationS), which provides an online index to archaeological grey literature produced as a result of large-scale developer funded fieldwork. The Scottish Royal Commission's website (www.rcahms.gov.uk/search.html) gives access to their digital archives, including CANMORE and Pastmap, which contain information on archaeological sites and monuments. Similar information for England is accessible through Pastscape (www.pastscape.org), while CARN (The Core Archaeological Recods iNdex) provides an index to information held by archaeological organizations in Wales (carn.rcahmw.org.uk/).

The Portable Antiquities Scheme

The Portable Antiquities Scheme (PAS) was set up in 1997 to record archaeological finds made by members of the public. Finds Liaison Officers (FLOs) cover England and Wales, supported by centrally-based specialists. The scheme, funded by the Heritage Lottery Fund through the Department of Culture, Media and Sport, has led to the reporting of thousands of objects every year, most of which would otherwise have remained unrecorded (Fig 28). A recent annual report makes the point that there are believed to be about 10–15,000 metal-detector users operating in England and Wales and they may find as many as 400,000 archaeological (metal) objects in a year. The PAS is committed to feeding the data it gathers to local HERs, which should in time provide databases for research.

Before the advent of the PAS, some classes of object were almost unknown, due to either a lack of recording facilities or a lack of knowledge as to what they were, or both. One example is the small copper or bronze bars and blanks used during the 3rd and 4th centuries AD to produce unofficial coinage in Roman Britain. Their increasing numbers have made metallurgical analysis on a significant scale possible, which has begun to answer questions about the methods of production of these coins and their alloy composition (see section 2.6). With recording taking place across the whole of England and Wales (www.finds.org.uk) and the recent extension of the Treasure laws to include prehistoric base metal hoards, new opportunities for archaeometallurgical research have opened up.

Figure 28: Metal-detectorists collected this later 3rd century copper-alloy waste from the manufacture of Romano-British coinage, and reported it through the Portable Antiquities Scheme.

Curation of archives

The archaeometallurgical archive normally forms part of a much larger archaeological archive and has two main components: the material and the documentary archives. These are derived from the site record (the materials and records collected during fieldwork) and the research archive resulting from analysis and study. It is, of course, important to maintain this body of material intact, though museums' storage constraints may make some selection inevitable (SMA 1997; Perrin 2002, 9–10; Brown 2007). Surplus material can usefully be placed in teaching or reference collections, such as the Hawley Collection of tools at Sheffield (www.shef.ac.uk/hawley), or can be offered to the National Slag Collection at Ironbridge (www.ironbridge.org.uk/about_us/ironbridge_archaeology/research). This collection can be consulted free of charge, by prior appointment, although deposition of items with the collection may be subject to a small fee to cover storage materials and administration costs. The development of a searchable database of metallurgical samples and related analytical data is under way.

There are basic minimum requirements for creation, transfer and accessioning of archives to recipient museums (Owen 1995), which apply equally to metallurgical material. In some cases, county archive services and archaeological contracting units have drawn up recommendations for standards of deposition and archiving, following the recommendations of the Museums and Galleries Commission (MGC 1992). The material archive may contain ore, fuel, furnace remains, metallic products and waste materials as well as prepared samples removed from them. The fragility and storage requirements of the materials will vary so packaging and handling must be appropriate.

Minimum standards for storage include adequate protective packaging and suitable environmental conditions for both the material archive and the documentary archive; specific requirements for long-term storage have been set out (Walker 1990; MGC 1992). It is common practice to keep samples, such as prepared specimens of metal from artefacts, with the material archive (Davis and Starley 2002; Fig 29). Other types of samples may include polished and mounted pieces of slag or other waste products, thin sections of ceramics for petrological analysis, samples of corrosion products or process residues, and samples for scientific dating. The documentary archive may include paper records, plans and drawings, photographic negatives and prints, as well as electronic media. Methods of documentary archiving are likely to develop towards electronic systems. The active curation and access arrangements for these will require further consideration (Richards and Robinson 2001).

Figure 29: Cabinet containing polished metallurgical samples made between 1863 and 1865 by Henry Clifton Sorby, the pioneer Sheffield metallographer. Now in the collections of the South Yorkshire Industrial History Society.

Current threats

The archaeometallurgical resource faces the same threats as the rest of archaeology: coastal erosion, climate change, and development pressures such as road and house building. In addition, there are extra pressures: those due to continuing exploitation of mineral resources which remove superficial layers, together with evidence for earlier mining, to gain access to deeper deposits; and those caused by the current drive to re-develop brown-field sites and clean up contaminated land. These latter activities have proportionally more effect on archaeometallurgy as many brown-field sites were previously occupied by heavy (metallurgical) industries, and much of the contamination is the result of wastes from those industries — so remediation effectively removes or destroys the archaeology we want to investigate (Payne 2004; see also section 2.3).

To these external threats we sadly have to add the cavalier ways in which past excavators and museums dealt with metallurgical debris. The situation is now better, thanks to increasing awareness in the archaeological community and the provision of guidelines such as those concerning archaeological archives (*eg* Owen 1995; SMA 1997). However, until the archaeological community learns to appreciate the contribution that metallurgical finds can make, they will continue to be vulnerable to second-class treatment, especially when projects are under-resourced.

2 METHODS IN HISTORICAL METALLURGY

2.1 Introduction

Much early archaeometallurgical research originated from a desire to understand the technical abilities of our ancestors, but within a modern materials-science framework. Such an approach is acceptable for documenting the history of metallurgy, but scientific characterization is only a beginning. It is also necessary to understand how contemporaries saw the processes and products. Questions about why metals were made or fashioned in particular ways need to be asked and addressed within the appropriate cultural and economic frameworks. A combination of technological ability, social constraint, and fashion and cultural mores inform all societies' approaches to metallurgy, and will leave their mark on the way ores and metals were processed and how artefacts were made. The archaeometallurgist has the task not only of characterizing these processes, but of placing them in a wider context. In the past, metals were a product of the landscape, alongside crops, livestock, timber, stone or clay. Metal production, particularly in rural communities, was often a part-time occupation, seasonal or cyclical, rather than practised by the distinct and regulated trades which were to emerge, notably in towns, from the Middle Ages onwards. Archaeometallurgy is becoming a more comprehensive sub-discipline of archaeology as the importance of metalworking in cultural, social and economic change, and vice versa, is appreciated and understood. It is towards an understanding of such relationships, from the prehistoric to the post-medieval, that much current research is directed. The development of historical archaeology in the United States has been particularly influential, with its awareness of the importance of social context in technological studies.

The context

Archaeology today is very much concerned with people and how they lived, using information from both fieldwork and archive sources to reconstruct past lives. In the same way, archaeometallurgy is concerned with those who made and used metal, studying artefacts, residues and documentary sources to understand not only the processes but the people behind them.

Most studies of the changes in industrial society in the 16th–19th centuries have been conducted by economic and social historians depending mainly on written evidence, and on occasion marked by a failure to understand the technologies involved. These studies tend to focus on the activities of entrepreneurs and landowners, rather than of the artisans and labourers who worked for them; the activities of the latter are much less-well documented. Accordingly, archaeology complements archive-based historical studies and will often illuminate the lives of ordinary working people and show how their lives were affected by technological advance, in ways that are not possible through documentary evidence. Similarly, the products and residues discussed in Part 1 can be viewed as the 'voice' of the artisan and labourer.

A related issue is the loss of skills from industrial sectors now or recently in decline, but which represent the end of long traditions of metalworking. The concentration of much of the UK's steel industry in a few very large automated works, and the loss of related trades such as rolling, forging and smithing has resulted in depletion of the skills base. Many recently-retired workers will have trained on plant that originated in the 19th century, and could trace its origins back to the beginnings of industrialization. The foundry, forge and rolling mill at the Ironbridge Gorge Museum, for example, continues to maintain a tradition of hand-rolling of wrought iron (Fig 30), but the day-to-day experience of those who spent a lifetime working in the metal trades is being lost — and with it a vital source of information for those exploring sites of the more recent past.

2.2 Fieldwork methods

Numerous landscape surveys encounter archaeometallurgical evidence, whether residues found during field-walking or sample evaluations, or indications from archive references. The study of the latter (see section 1.4) can provide a valuable source of information for the later periods, setting metallurgical activities within

Figure 30: Red-hot wrought iron being rolled at the re-erected rolling mill at Blists Hill, Ironbridge. Traditional metal-working skills are being preserved as 'living history'.

a landscape and social context. The involvement of an archaeometallurgist from the start of field projects is important, enabling the interpretation of documentary or previous field evidence for metal production during the planning stages of a project, being available to identify features or finds during survey, and providing contact with experts on the specific type of process, structure, residue or artefact. Recent developments in landscape archaeometallurgy show the potential of integrated approaches. An example is the Exmoor Iron Project which has a strong archaeometallurgical underpinning but includes the survey of landscapes to investigate features such as woodland management systems used to produce charcoal for iron smelting.

Fieldwalking

Fieldwalking is an established, even universal archaeological survey technique, providing information about settlement patterns over extensive landscapes (Haselgrove *et al* 1985, Macready and Thompson 1985). Its potential to address specifically archaeometallurgical questions has been demonstrated by work in the Weald and in south Lincolnshire, contributing to the understanding of the Roman and medieval iron industries of these regions (see section 3.3).

Fieldwalking for archaeometallurgical evidence requires some training in the identification of slags, the most common diagnostic find. Although some slags can be hard to identify, volunteer field walkers have achieved worthwhile results. In cases where there is good contrast between natural soil colour and the dark grey or black of iron-working slag it can sometimes be possible to identify slag scatters in plough-soil from some distance. In Lincolnshire, for example, slag scatters have been identified from a car. Aerial survey may enable slag scatters to be identified over large areas that can then be further investigated on the ground. The ground cover of a landscape is an important factor, and South Lincolnshire lends itself to this approach by being largely under arable cultivation. Fields set aside or fallow one year will come under cultivation in rotation, so a picture can be built up over time. Following fieldwalking in 10m by 50m transects, the sites identified can then be subject to geophysical survey.

In Lincolnshire, fieldwalking for slags has dispelled the notion that much of the county has no ores suitable for bloomery iron smelting. During the winter of 1994, the Castle Bytham Fieldwalking Project identified four slag scatters varying in size from 10m to over 100m in diameter, and two further scatters with no foci. The majority of excavated iron-working sites have been found within or close to settlement sites, but this initial survey has shown that many iron-working sites were located on isolated hillsides and far from known settlements (Cowgill pers comm). The apparent lack of iron smelting in this and other areas may simply reflect the lack of observation and survey.

Geophysics and archaeomagnetic dating

Resistivity, magnetometry and ground penetrating radar have considerable potential in the study of early metalworking sites. There is a large body of literature on such geophysical methods (*eg* Gaffney, Gater and Ovenden 2002) while the English Heritage geophysics guidelines (English Heritage 1995) and the HMS datasheet on geophysical techniques (McDonnell 1995) provide an overview of the practicalities of applying geophysics to metallurgical sites. Magnetic susceptibility studies undertaken during excavation allow analysis of iron-working areas, particularly smithies, because hammerscale is highly magnetic (Bayley *et al* 2001, fig 5).

Whilst more research needs to be done on the application of geophysical prospection to metalworking sites, magnetic survey methods are potentially useful, both prior to excavation and to define the nature and extent of a site without excavation. There remain many problems to overcome, especially with the survey of excavated furnace structures. There has been caution over commitment of geophysical survey resources to some sites, due to igneous geology, steep topography, or disturbance by later working, cases where targeted fieldwalking can produce good results. However, geophysics can be successful in unpromising terrain, and the development of methods is to be encouraged.

As part of a long-term project by the Lake District National Park and the National Trust, 27 bloomery sites

Example: How magnetometer surveys can date furnaces

Peter Crew has developed methods for detailed magnetometer surveys on iron-working sites (Fig 31). He conducted a fluxgate gradiometer survey at Crawcwellt in NW Wales, that showed three anomalies that were initially interpreted as slag dumps. One of these was re-surveyed using a grid with half-meter spacings, revealing two possible furnaces. On excavation they proved to be furnaces within a sequence of stake-walled buildings (Crew *et al* 2003). Pushing the technique further showed that the anomalies were dipoles so the direction of total magnetism was visible, which in turn allowed the estimation of a date range, although this is highly problematic. Later developments in magnetometer technology led to another re-survey at even higher resolutions (between 50 and 100mm grid size). Two surveys were conducted, the first on the excavated and defined furnace and the second after removal of the furnace lining and furnace bottom. The second survey gives a background signal that can then be subtracted from the overall signal to provide much cleaner residual maps (Crew 2002; Fig 32). This allowed mathematical modelling of the data using multiple dipoles which gave more reliable results, and an indication of the contribution of the different furnace materials to the overall magnetic signature. The procedure gave a last firing date for one of the furnaces of 50 BC. The other furnace gave less precise readings, but nevertheless provided a date range of between 100 and 400 BC (Crew *et al* 2003). The medieval site of Gelli Goch was also re-surveyed (Fig 31) and modelling came up with a date of around AD 1350, again consistent with the historical data.

Figure 31: Magnetometer survey at Geli Goch, Gwynedd using a 4m-square frame at a sensor height of 320mm. To the right of the furnace is the working pit, with the last run of tap slag still in situ.

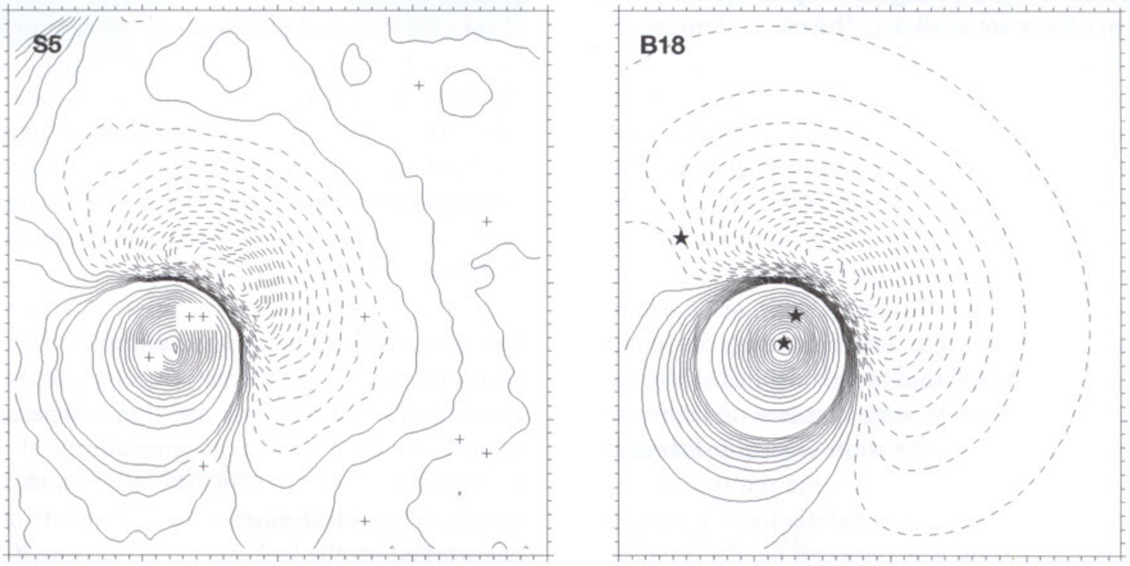

Figure 32: Left: High-resolution magnetometer survey results for a 4m square containing a furnace at Crawcwellt. Right: Calculated map of multiple dipoles (stars mark the centre of each dipole) which closely models the survey, allowing the direction of the calculated dipoles to be used to estimate the date of last firing. Positive contours solid at 100nT, negative contours dashed at 10nT. After Crew 2002.

in Cumbria have now been subjected to high-resolution survey (Crew 2002, 180). This approach is useful for any site where there is a burnt feature of simple shape, including hearths, ore-roasting and charcoal-burning areas, as well as furnaces. The aim is to build a magnetic typology to enable the identification of un-excavated sites and lead to the recognition of technological, chronological and regional patterns. The surveying of un-excavated sites is yet to yield data of sufficient quality to allow accurate dating because of the interferences caused by overlying slag and other deposits. Of the 27 Cumbrian sites surveyed, eight magnetometer survey maps had dipolar signals that were clean enough to provide dates. A radiocarbon dating programme is currently under way to compare with the magnetic dates and the results will enable further refinements of the method and establish the limitations of the technique as a dating tool (Crew 2002).

Conventional archaeomagnetic dating of fired clay structures is a well-established technique. It relies on the orientation of the magnetic minerals within the clay becoming aligned with the direction of the earth's magnetic field when they are heated. Its precision is better at some periods than others as it relies on matching measured values to a calibration curve which does not change in a regular way (English Heritage 2006, fig 14). However, the magnetic remanence can be distorted if the structure was near to ferrous material such as smelting slag as it cooled, and this will affect the date obtained.

Environmental and geochemical survey

Environmental techniques can also be used on metallurgical sites. Recent and ongoing work in Coalbrookdale, for example, is exploring the stratified sediments in pools created as part of the water-power system on a variety of ironmaking sites. Events in the environmental record can be linked to historical developments in technology — for example changing levels of pollution, or a reduction in coppiced woodland associated with the emergence of mineral-fuel technologies.

Geochemical survey is being developed to study the field evidence for metalworking. The method measures the heavy metals deposited in the environment, typically down-wind from a smelting furnace or downstream from a mine or ore-dressing site (Wager *et al* 2002). This information can identify, map and interpret areas and the features within such zones where metalworking was occurring. Geochemical survey works in a spatial dimension (analogous to geophysics) and on an intra-site basis (Doonan 2002), or on a landscape scale; pollution from lead smelting can cover significant areas and be found in peat deposits (Mighall *et al* 2004) and stream-silts some distance downstream from the source of contamination (Hudson-Edwards *et al* 1999). The technique requires the removal of soil samples and their subsequent analysis for the concentrations of heavy metals. The data can be displayed on

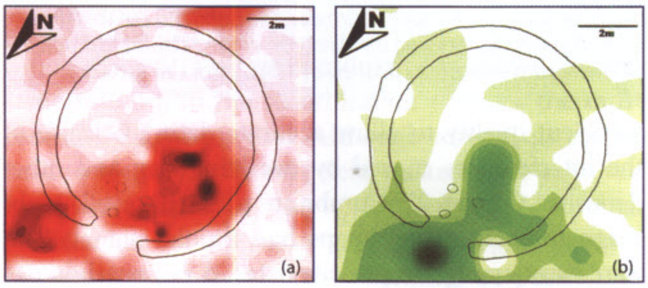

Figure 33: Schematic plan of an Iron Age round house at Billown, Isle of Man, overlaid with areas of enhanced magnetic susceptibility (a), and geochemical survey results for copper (b), showing that metalworking activities were restricted to the NW part of the structure.

a spatial mapping system (GIS) that has data-analysis capabilities, or simply plotted on plans of archaeological features (Fig 33).

Geochemical survey can provide information that is not otherwise available but it is best used in conjunction with other techniques as interpretation is not always straightforward. The combination of geochemical survey with geophysical (magnetometer) survey has been fruitful, with the geochemical surveys defining the metalworking areas and the processes occurring, and the geophysics identifying the furnaces and hearths.

Excavation

Much of the excavation carried out in Britain today is development rather than research led, so the aims have to be decided, often quickly, at the site-assessment and evaluation stages. It is therefore important that those carrying out initial desk-top assessments should be aware of archaeometallurgical indications provided by past field and archive work, and that those performing site evaluations should be able to identify characteristic residues. Archaeological units tendering for such work need to arrange for specialist back-up at the outset, and also to train staff in the basics of residue-identification, for example by using the 'Slag Days' organized by English Heritage's Technology team and its Regional Science Advisers. It is important that curatorial archaeologists in local authority planning departments are also aware of the need for specialist expertise when developing briefs for tenders for developer-funded work on brown-field metallurgical sites.

The scarcity of archaeometallurgists in university archaeology departments means that research excavations that are run by these departments are seldom focused on archaeometallurgical questions. Exceptions do occur (Fig 34), often with significant results. Gerry McDonnell of the University of Bradford has worked on the late-medieval iron-smelting sites at Rievaulx, N Yorkshire, and has joined forces with the Huddersfield Archaeology Society to excavate a medieval iron-smelting site at Myers Wood, W Yorkshire, with funding from the Heritage Lottery Fund. Individuals, within and beyond the university sector have built up expertise which is available to developer-funded work: examples are Simon Timberlake (prehistoric copper mining), Peter Crew (Iron Age to medieval iron smelting), David Cranstone (medieval and later ironworking), David Crossley (post-medieval iron smelting) and Martin Roe (mining landscapes, especially underground). Non-professional groups, the Wealden Iron Research Group being an excellent

Figure 34: Iron-smelting furnace 137 at Stanley Grange, Derbyshire, after the removal of superficial material and the fill of the slag-tapping pits. Scale bars 1m and 0.3m. After Challis 2002.

example, have also developed expertise sufficient to advise on developer-funded projects.

The three metalworking processes most likely to be encountered by archaeologists during any excavation, are iron smelting, iron smithing and secondary non-ferrous metalworking. The components of these site types are shown in Table 1. Additionally, in certain geological areas the smelting of non-ferrous metals, particularly lead, tin and copper, may be encountered.

Table 1: Finds associated with common metalworking processes

Iron smelting
ore and ore processing
fuel, including charcoal platforms or coke-ovens
furnace remains and furnace debris (Figs 15 and 56)
water-supply earthworks (later medieval onwards)
slags (Figs 16 and 17)
Iron smithing
fuel (charcoal or mineral coal)
hearths and hearth lining
water-supply earthworks (later medieval onwards)
slags, including hammerscale
scrap metal
anvil bases/sockets
Secondary non-ferrous metalworking
fuel (charcoal or mineral coal)
hearths and hearth lining
crucibles, moulds and slags/residues (Figs 14, 67, 70, 75 and 76)
scrap metal (Fig 28)

Some metalworking sites have associated structures; there are great advantages in smithing and casting indoors, because the temperature of the metal, gauged by its colour, is more easily determined in subdued light. There is as yet little evidence for the roofing of medieval or earlier smelting furnaces, but it is clear that casting from the post-medieval blast furnaces took place within roofed buildings. The provision of dry-storage areas for raw materials is known in the medieval Wealden iron industry (Money 1971) and post-medieval charcoal and ore-storage barns survive in the Lake District (Bowden 2000) and elsewhere.

Where developer-funded excavation has revealed metalworking or metal-production evidence, the results have been variable, but integration between field and laboratory work is becoming more common. Developer-funded excavations by ARCUS at the Riverside site in Sheffield provided a picture of a late-18th-century cementation steel furnace of unusual design, the residues from which were examined by Rod Mackenzie in the University of Sheffield. Rescue excavations in Exeter that encountered a post-medieval bronze foundry (Blaylock 2000) were accompanied by a study of mould fragments, and analyses by David Dungworth. Evidence for medieval iron smelting was found (by Trent and Peak Archaeology) at Stanley Grange, Derbyshire, during excavations prior to opencast coal extraction (Challis 2002; Fig 34). Eight furnaces were excavated, but the investigation was limited to the area under threat so a complete understanding of the site was not possible. The developer did not fund scientific analysis of slags, but despite this analyses were undertaken at Nottingham University after the site was destroyed.

2.3 Sampling

Sampling strategies can exist on a number of different levels: selecting sites within a landscape, sampling material from field-walking, sampling excavated residues (slag heaps, smithing floors etc) within a site, selecting sub-samples of residues for analysis so the data will reflect the composition of all the material, selecting artefacts from excavated assemblages to provide similarly representative data and, finally, selecting areas on an artefact to sample for chemical or isotopic analysis.

Landscapes

Information from wider investigations of landscape change is important in the identification and sampling of archaeometallurgical sites. For example, changes in woodland cover from the prehistoric to the post-medieval have been significant in determining the location and intensity of mineral exploitation. For the medieval and post-medieval periods, documentary references to metalworking, especially ironworking (see section 1.5), enable investigation of ownership and tenure (Cranstone 2001). Metal production may have been stimulated by technological considerations, but could also be fostered or constrained by local factors such as vested interests in charcoal production, or the ownership of the rivers which provided water power for furnaces or forges. Documentary evidence suggests that at the end of the Middle Ages many water-powered bloomeries were associated with pre-Dissolution monastic landholdings; post-medieval blast-furnaces tended to be set up by (or lay on the estates of) major secular landowners and the Crown (Cranstone 2001, 187). The distribution of different categories of site within a landscape can be instructive; they can lie within large estates, or in areas of small freeholder settlement such as the West Midlands, which is a complex palimpsest of mining, metalworking, transport and housing developments without wide-scale estate planning and development (Belford 2006).

One approach is to sample a landscape by setting up transects across different environmental zones to compare distributions across moorlands, enclosed land and across different estates. It is also important to sample across the full spectrum of site-types of all periods; for iron, both forging- and smithing- sites as well as those involved with smelting must be included. With the advent of affordable GPS (Global Positioning System) receivers, which can record the position of features to within 5m or less, it is possible to make a rapid record of the distribution of features in complex landscapes (Fig 35). The accuracy of the data recorded governs the end use of the information, but even the least accurate GPS systems are valuable for recording patterns of distribution of features. This information can be used to identify chronology by demonstrating how the landscape is zoned, which suggests the sequence in which features and activities appeared. GPS surveys define the distribution of landscape components, but there is still a need to produce detailed surveys of individual features in order to understand their characteristics.

Sites and residues

Strategies for the sampling and retrieval of residues and other material during excavation are discussed by McDonnell and Starley (2002) and by Bayley *et al* (2001). Metalworking residues may be recovered from buildings or areas in which metalworking was practised (primary deposits), but are also recovered from where debris has been dumped in middens, pits and ditches, or used for surfacing trackways etc (secondary deposits).

Figure 35: Gunnerside Gill, North Yorkshire: the surface of a lead mining landscape. Virtually the whole surface on both sides of the valley and on the high moorland beyond is occupied by a palimpsest of hushes, shafts, levels, ore-dressing floors, and their associated waste tips, water supplies and transport networks.

In primary deposits, metalworking structures (furnaces, hearths, and pits) may be encountered, and the distribution of residues such as hammerscale or runs of slag in or around a building can be crucial in identifying and separating different activities. Characterization of these residues provides information on methods, raw materials and equipment used. The excavation of areas where metalworking has been carried out will require gridding and careful sampling, both of hand-recovered material and of soil samples for micro-residues, such as hammerscale, a by-product of iron-smithing. Three-dimensional recording of bulk finds such as slags is not usually feasible, but crucibles, scrap metal etc should be treated as registered finds.

Secondary deposits include materials that are contemporary with, or later than, the metalworking activity that produced them. Recording of the residues may indicate the direction from which the material was dumped. Soil samples should be taken for recovery of micro-residues. Where the fills of hearths or furnaces are dumped, the complete range of debris may be present. If very large features, *eg* extensive boundary ditches, are only sectioned, then dumps of material may be partially recovered or missed altogether. Detailed geophysical survey may identify the extent of such deposits.

A further refinement to consider when dealing with soil samples is to use flotation and wet sieving to maximise the recovery of hammerscale, charcoal

Example: Hammerscale distribution in a smithy

Two iron-working workshops were excavated at the Roman site at Westhawk Farm, near Ashford, Kent. In one of them an occupation layer survived that contained extremely high concentrations (up to 90wt%) of hammerscale (Paynter 2007a), which in some areas was consolidated into a thick layer known as smithing pan: this demonstrates that smithing took place in this section of the structure. The occupation spread within this area was sampled at 0.5m intervals across a grid. In this instance only the area of the floor visibly rich in hammerscale was sampled, rather than the entire occupation surface of the structure plus a small area outside, as is generally recommended. The results show that the limits of the deposit were estimated accurately, however, so no data was lost. The samples were sieved to remove particles greater than 3mm in size, and then processed using a magnet to separate the magnetic hammerscale and heavily fired clay fragments from the remaining residue (Mills and McDonnell 1992). The magnetic fraction present was expressed as a weight percent of the total. A plot of hammerscale concentration (Fig 36) across the sampling grid shows the change in concentration from low levels (pale) to high ones (dark). The highest concentrations were in the NW half of the workshop suggesting that an anvil was situated in this area, although it has left no diagnostic mark, and that a hearth was also nearby. The features in this area included a small pit containing a large upright jar and an adjacent sub-rectangular feature with a flat base, almost vertical sides, fire-reddened edges and a charcoal-rich fill. The large pot may have held water for use by the smith and the sub-rectangular feature may be the remains of a ground-level smithing hearth. The trough in the hammerscale deposit, elongated towards the east and west, may be a result of individuals treading the deposit across the floor as they left the area towards the eastern corner.

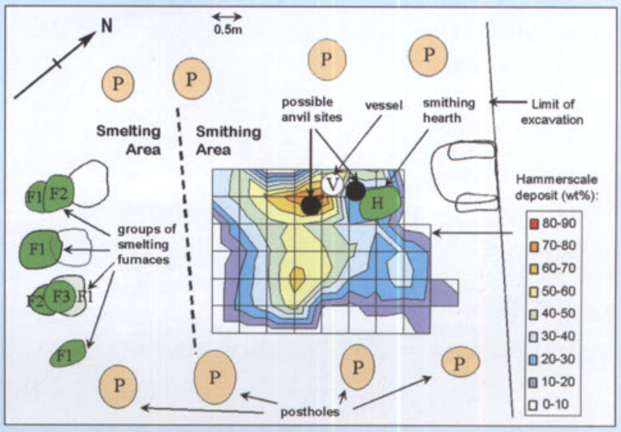

Figure 36: Plot of hammerscale distribution in workshop R at Westhawk Farm, Kent, in relation to other features. Soil samples were collected on a grid and the hammerscale extracted; warmer tones show increased hammerscale concentrations. After Paynter 2007a.

and other metallurgical residues — though its cost-effectiveness on a range of site types has still to be demonstrated. Check beforehand for any fragile material, such as mould fragments, that may not survive flotation. Weighed samples are then washed using a flotation sieve with a 0.5mm mesh and an internal wet-sieve of 1mm for the residue; both the flot and residue are dried. The residues are re-floated to ensure the efficient recovery of charred material and are then sieved through 10mm and 1mm meshes and sorted by eye. If a magnet is run through the finer residues (<10mm) it will remove the magnetic portion including hammerscale. This process retains not only hammerscale and other metalliferous material, but also charcoal and ore fragments and environmental material that form the archaeological context of the craft or industry under investigation, and provide the evidence to enable a more complete reconstruction of the site. This process will often find hammerscale deposits not identified during normal sampling and processing, and so provide information on site activities that would otherwise be missed (Cowgill pers comm). The proportions of plate hammerscale to spheroidal hammerscale can be used to understand the nature of the iron-working operations on a site, the assumption being that spheroidal hammerscale is formed during primary smithing of blooms or during high-temperature welding operations. As a result, plate scale, formed during forging, is generally more heavily represented than spheroidal scale on sites where iron was worked rather than produced (Unglik 1991).

Brown-field sites

The 'urban renaissance' has found a clear expression in many British cities. Recent government planning guidance (PPS3 2006) advocates the use of brown-field sites for housing developments and is encouraging the re-development of inner city land formerly in industrial use. Such land can contain significant additions to the archaeological record of post-medieval development. However, archaeological considerations can take second place to the need for economic regeneration as well as perceived issues of contamination (Belford 2006). There is often considerable archaeometallurgical potential in such sites. Frequently such activity will have been on a small scale, often in association with non-metallurgical industries. In Sheffield, for example, there were close relationships between the cutlery and bone industries (Symonds 2002). In the West Midlands, both ferrous and non-ferrous trades were closely interlinked, and different stages of production of different materials were often located in close proximity (Belford 2006).

Figure 37: Buildings at Jessops Brightside steelworks, Sheffield, set into large-scale metalworking waste (dark soil consisting of ash, crucible waste, cinders and slag). Scale bar 2m.

Archaeological work on brown-field sites requires a flexibility of approach that is not always anticipated, in order to do justice to the archaeology of the large-scale changes of the Industrial Revolution and later (Fig 37). The scale of archaeological evidence for 19th- and 20th-century industrial structures is often underestimated. To grasp such scale requires area-excavation rather than evaluation trenches. A particular problem is the need for sampling strategies for brown-field metalworking sites. Some archaeology units have begun to develop fieldwork strategies together with sampling and collection policies; examples of these approaches are given by Dungworth and Paynter (2006). These are based on:

- broad and rapid characterization of deposits and areas from physical and cartographic evidence: this is important in assessing the potential of the site prior to targeted evaluation/excavation.
- the scale/volume of residues: later industrial sites will often have extremely large volumes of residues.
- movement of residues around sites: residues were often used as make-up material for later construction work.
- movement of ground-water and contamination may affect chemical and other analysis. There may also be health and safety implications.
- re-use/recycling of many residues for other processes: this can confuse archaeological interpretations. For example in the iron industry, castings, forgings, slags and other residues were often re-used in smelting or foundry processes and in the pre-Bessemer steel industry refractory materials were re-used, both in crucible furnaces, crucibles themselves, and in the cementation process.

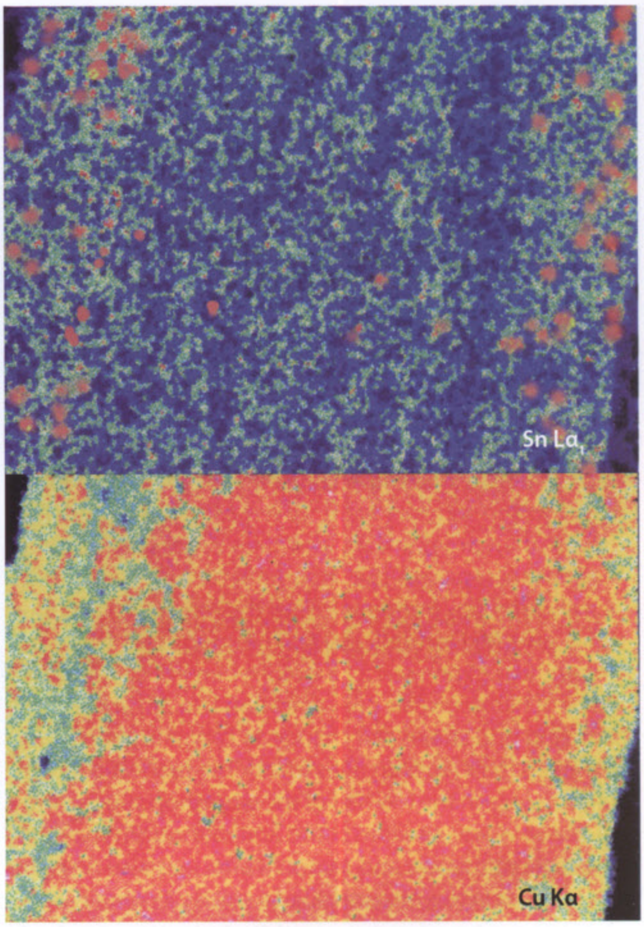

Figure 38: Elemental maps of tin (upper) and copper (lower) in a cross-section of a prehistoric bronze sheet. The warmer colours (yellow and red) indicate high levels of each element. It is easy to see that there are areas of tin enrichment towards the surfaces of the section that also correspond to areas of lower copper concentration. A surface analysis gave a result of 19% tin whereas a bulk analysis of an interior area revealed the correct tin content as 8%.

Artefacts

Before selecting artefacts from excavated assemblages for analysis (see section 2.4), it is essential to set the archaeological question(s) that it is hoped the analyses will answer. In the past there has been a tendency for 'interesting' or unusual artefacts to be selected. However, if the aim is to get an overview of the variety and proportions of different metals and alloys used at a particular site or period, a representative sample should cover all categories of artefact (including nondescript fragments and off-cuts, especially when dealing with workshop assemblages). Recent analytical programmes overlooked. Even when its preservation is not good, information relating to compostion, structure and quality can be obtained from finished objects and metal stock. This data can also inform about smithing and smelting processes, especially when linked to analyses of ironworking slags.

Production debris can be found in large amounts during archaeological excavations, but it is not always fully appreciated exactly how much information can be extracted from such un-prepossessing material. The English Heritage guidelines for archaeometallurgy (Bayley et al 2001) provide a good overview of the different categories of material that can appear and the sort of information that they can provide when studied by specialists. The Historical Metallurgy Society has produced a series of datasheets for different categories of waste material that provide a brief introduction and are available without charge from the HMS website (hist-met.org/datasheets.html).

Analytical techniques

Many analytical techniques have applications in archaeometallurgy (see Table 2 and Pollard *et al* 2007). Much university-based archaeometallurgy in Britain is conducted within archaeology departments using well-established techniques. The application of new techniques is to be welcomed but the time and cost of analyses need to be balanced against the research outcomes. Where chemical composition is determined it is important that reference materials are analysed at the same time; where possible these should have compositions close to those of the archaeological samples.

X-radiography

Radiography is a technique more associated with conservation than with archaeometallurgy (Fig 39). However, it is a tool with considerable power for understanding fabrication techniques (Figs 40 and 41), and is a necessary precursor to sampling iron objects. It is now routine for all excavated iron objects to be radiographed, but not so usual for non-ferrous objects, unless embedded within a soil-block. However, its benefits are beginning to be appreciated with excavated coins sometimes being radiographed to enable a first-stage identification and to allow prioritization of cleaning and conservation time (Jones 1998). Both Lang and Middleton (1997) and Fell *et al* (2006) present some useful examples of

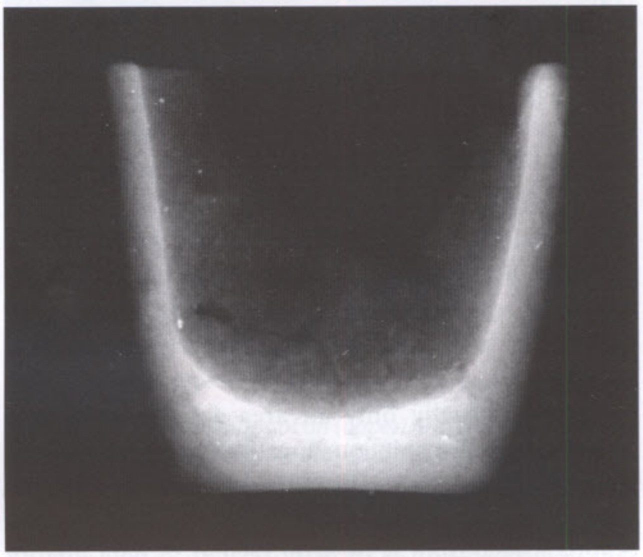

Figure 39: X-radiograph of a post-medieval crucible in section, with the metal-rich slag on the inside surface showing as bright zones, and metal droplets as white spots, especially in the thickness of the base.

Table 2: Commonly-used analytical techniques

Analytical technique	Information produced	Sample size	Cost	Availability
Radiography	macrostructure; fabrication	entire object	moderate	common
Optical microscopy	microstructure; guide to composition and heat-treatment	requires a small cut sample (a few millimetres minimum)	low	common
XRF-ED/WD	composition (bulk analysis of major and minor elements; trace if WD)	whole object or cut or drilled sample	moderate (ED) high (WD)	common rare
AAS/ICP-AES	composition (bulk analysis of major, minor and trace elements)	cut or drilled sample (~20mg) dissolved in acids	moderate	scarce
XRD	identification of compounds (crystalline solids only)	very small powdered sample or small flat sample if metallic	moderate	common
SEM-EDS	surface topography; microstructure; composition (bulk- and micro-analysis of major, minor and trace elements)	usually a small cut sample or fragment (mounted in a block), but can examine small whole objects	moderate	common
EPMA/PIXE/SIMS	microstructure; composition (bulk- and micro-analysis of major, minor and trace elements)	usually a small cut sample or fragment (mounted in a block), but can examine small whole objects	high	rare
ICP-MS	composition (bulk analysis of major, minor, trace and ultra-trace elements) and isotopic abundance	cut or drilled sample (~10mg) dissolved in acids or can use laser ablation which is almost non-destructive	high	rare
TIMS	isotopic abundance	cut or drilled sample dissolved in acids	high	rare

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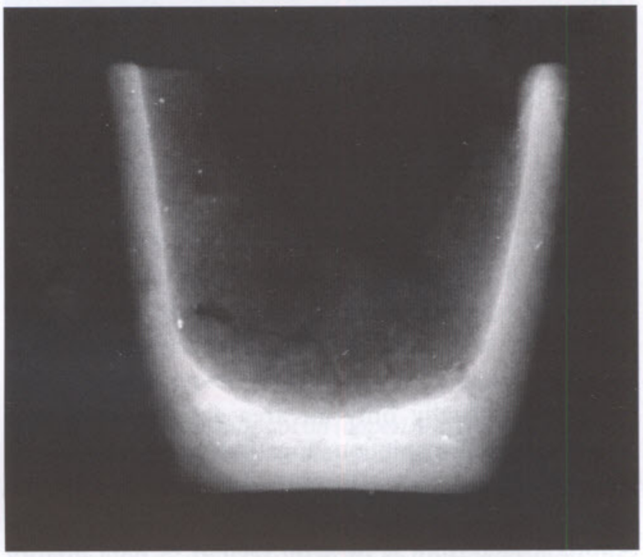

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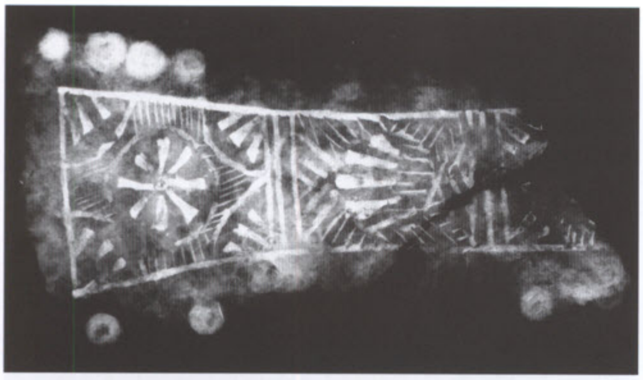

Figure 40: X-radiograph of a Roman dagger sheath plate made of iron and decorated with tin (which shows as brighter lines). The round rivet heads are also tinned. Both metals are totally mineralized but X-radiography provides a simple and non-destructive method of investigation. Length 105mm.

how radiography can aid characterization of an object and add to our understanding of both its technology and cultural context.

Microscopy

Low-magnification microscopy (x10–x30) is an almost essential precursor to any detailed study or analysis, and an experienced user can identify many finds and materials without further work. Traditional metallography (optical microscopy of polished sections of metal objects) was used extensively in the early days of archaeometallurgy (*eg* Allen *et al* 1970; Coghlan 1975; 1977). More recently it has taken second place to scanning electron microscopy and instrumental chemical analysis for everything except iron and steel, the metals that can be best understood through study of their microstructures (see Examples 8 and 9). The equipment is relatively inexpensive but metallography is very labour-intensive, which increases costs.

Metallography shows whether an object was cast or forged (wrought), what types of iron or steel were used, whether it has a composite structure and what treatments (such as hardening) it underwent during and after manufacture. An understanding of how metals' physical properties were manipulated can reveal much about how metals were used and valued in a society. Non-ferrous metallography has great potential for addressing issues of manufacturing and production, such as identifying those artefacts that were cast in metal, rather than clay or stone, moulds.

Chemical analysis

Elemental analysis was seen as the way to address questions of metal source by characterising metals according to compositional profile, and matching this to either objects of known origin or metal ores from known mines. However, as knowledge of the chemistry of metals and their smelting and refining processes increased, it became clear that any chemical fingerprint in an ore became irreversibly altered during smelting, and that subsequent refining, mixing and re-cycling introduced further changes. Recent work suggests the composition of iron slags is related to that of the ores smelted (Paynter 2006). As slag inclusions are found in many iron objects, they can potentially be linked to

Example: X-radiography can reveal metallographic structures non-destructively

Roman blades in the later Empire seem to be of poorer quality than earlier ones, possibly reflecting the change from small scale workshop fabrication by skilled craftsmen (recorded on contemporary monuments) to large imperial fabricae churning out weaponry of mediocre quality in large amounts to fill quotas set by the Imperial bureaucracy (Lang 1988). An even more profound contrast is seen when comparing Saxon and Roman products; the term bespoke has been applied to Saxon blades, suggesting small craft workshops took great care to produce items of particularly high quality — as metallography demonstrates (Tylecote and Gilmour 1986; Fig 41).

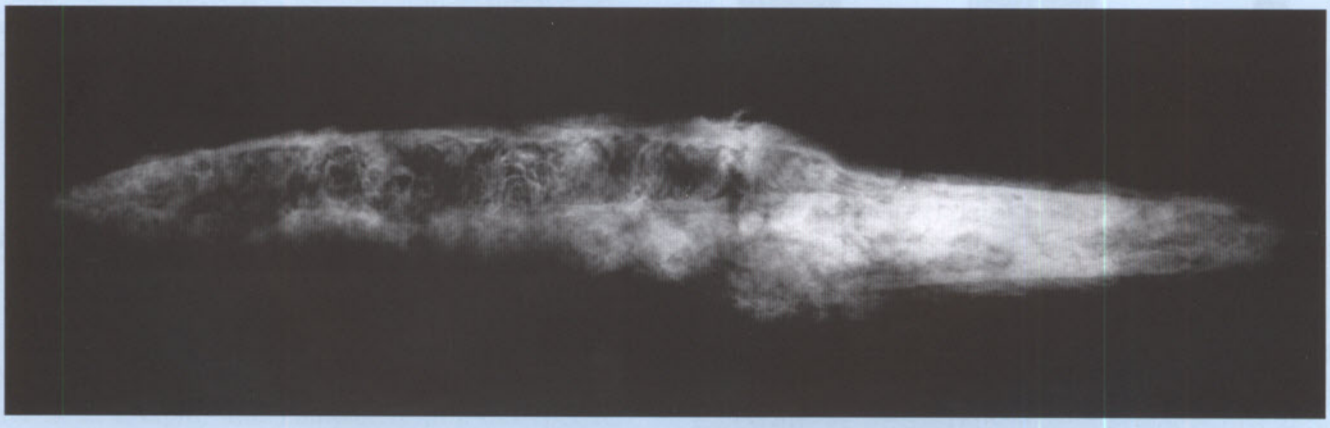

Figure 41: X-radiograph of early-medieval knife with pattern-welding visible in the back of the blade. Length 178mm.

Example: Metallography of medieval arrows

St Briavels in Gloucestershire produced 25,000 quarrel (crossbow bolt) heads in 1256 (Pounds 1990, 109) and records indicate that it was understood that they needed to be specially hardened, but that this was not always the case:

'I woulde wyshe that the head makers of Englande shoulde make their sheaf arrowe heades more harder poynted then they be: for I my selfe haue sene of late suche heades set upo sheafe Arrowes, as ye officers yf they had sene them woulde not have bene content wyth all.' (Ascham 1545, 20).

Metallography has shown that smiths selected high quality and expensive steel for prestige objects such as armour and weapons and also, though sparingly, for some everyday objects like knife blades. Such expense was not undertaken for mundane ironwork, such as building fittings or fixtures (Starley 1999). Is it possible that arrowheads, produced in tens of thousands, were manufactured with high levels of craftsmanship, using expensive high-grade metal? Such arrows (Fig 42) would have been used against armoured rather then soft targets so metallography can distinguish war heads from those made for peacetime activities. The examination of 30 arrowheads (Starley 2000) showed that heavy quarrel points were made of soft iron (Fig 43), the greater mass of the head determining its destructive power. One of the two bodkin point arrowheads examined did contain some steel, but this was unhardened, so would have given little advantage. In contrast three-quarters of the compact winged and socketed arrowheads were much more sophisticated metallurgically, being of composite construction with iron socket and steel point and wings, quenched and tempered to provide optimum penetrating properties (Fig 44).

Figure 42: Three medieval arrowheads: left: bodkin point, Type 7; centre: compact winged and socketed, Type 16; right: Type 10. Typology after London Museum 1967.

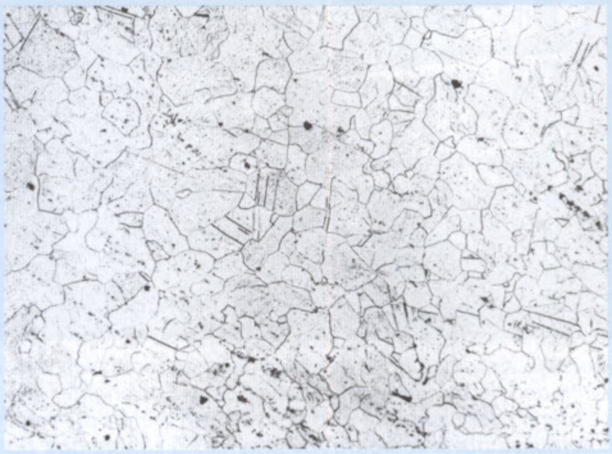

Figure 43: Micrograph of pure ferritic iron. Image width 1mm.

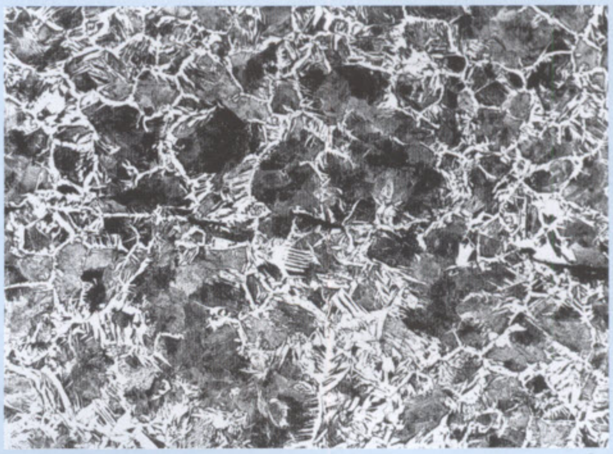

Figure 44: Micrograph of unhardened steel containing 0.7% carbon. Image width 1mm.

The bodkin point originates in the 11th century, where the main defence was mail (Jessop 1996). This narrow, tapered, head would have been devastating against mail, with its ability to pass through coarse mail and burst apart the finer links. Compact winged and socketed arrowheads only appear from the 14th century. This coincides with increasing amounts of plate armour being worn on the battlefield. By the time of Agincourt (1415) a knight (if not the common soldier) was virtually entirely cased in plate armour. Even so, with an estimated 7,000 archers firing up to 100,000 arrows each minute, survival was a matter of statistical probability. Metallurgy suggests that from the 14th century onwards considerable resources were committed to producing 'high tech' projectiles that aimed to counter the improvements in armour and to maintain the effectiveness of the archer.

Figure 45: Inductively-coupled plasma atomic emission spectrometer.

Figure 46: Scanning electron microscope in use. The main screen shows an image of the sample in the chamber to the left, at high magnification, while the screen to the right displays the results of EDS analysis.

an ore type and thus to a geographical area (Paynter 2006; Hedges and Salter 1979). Today most archaeometallurgists are informed by both archaeology and metallurgy, and produce important results for archaeologists and historians. For example, recent work on Bronze Age metalwork has shown how elemental analysis relates to archaeological groupings, and that certain elemental combinations can be shown to relate to specific ore types or metalworking horizons (Northover 1999a, and see section 3.1). Lead isotope ratios (see below) can be used in conjunction with elemental data to further refine the groupings (Rohl and Needham 1998; Needham 2002). The application of such approaches to the non-ferrous metalwork of later periods needs serious consideration.

Many analytical techniques can provide information on chemical composition (Table 2). X-ray fluorescence (XRF) can be used in two rather different ways. The first is as a rapid, and completely non-destructive, method of determining the approximate (qualitative) composition of the surface of an object or sample, such as identifying an alloy or a surface plating on an object, or the nature of a metal melted in a crucible. It can also be used for bulk quantitative analysis of prepared samples. Much early chemical analysis was done using emission or atomic absorption spectroscopy (AAS) though inductively-coupled plasma atomic emission spectroscopy (ICP-AES) is now the preferred technique for both metals and other materials (Fig 45). The new technique is much quicker, more stable and, for many important elements, more sensitive. A greater range of elements is also measurable, including important ones for archaeometallurgy, such as sulphur and phosphorus. Micro-beam techniques such as SEM/EDS are now commonly used to determine chemical composition (see below). X-ray diffraction (XRD) can identify the crystalline compounds, rather than elements, present in a sample.

Micro-beam techniques

Scanning electron microscopy (SEM), usually with an energy dispersive analysis system (EDS) is a very versatile imaging and micro-analysis technique which is becoming increasingly common in archaeological studies (Fig 46). This technique is particularly well suited to archaeological material, especially process residues, as it relates composition to structure, and allows the chemical analysis of particular areas or phases, as well as providing bulk compositions.

Other microbeam techniques (EPMA, PIXE, SIMS) are increasingly powerful tools for interpreting the microstructure and hence the history of many classes of artefact and residue. However, it is not always clear that the benefits of using such techniques outweigh the high costs. Sometimes it is just another way of doing something that is already possible with existing (and more affordable) technology, though EPMA is essential for determining trace elements present in iron.

Isotopic analysis

The ratios of the three main isotopes of lead, Pb204, Pb206 and Pb208, depend on the geological age of the lead ore and are not affected by smelting or any subsequent refining (but are affected by mixing during the course of re-cycling). For metal not heavily re-cycled this potentially offers a way of tracing metals containing even traces of lead to their geological source (Fig 47). This, for all practical purposes, means that only early prehistoric (Bronze Age) metalwork or newly-smelted metal (ingots) are suitable. Despite many successes, especially in Mediterranean archaeology, this technique is not the panacea it originally appeared, par-

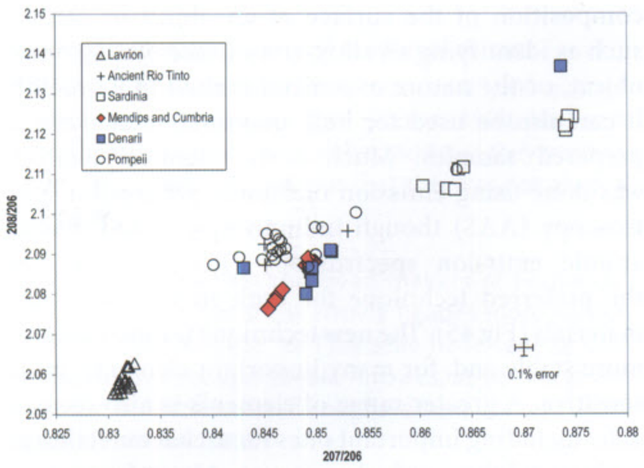

Figure 47: Lead-isotope plot of data from Mendip lead (red lozenges) and Roman silver denarii (blue squares) superimposed on data from other ore fields.

ticularly in Britain where many lead sources have similar geological ages. Further problems have been raised by recent research that has shown that lead isotope ratios can vary even within the same ore body, especially between near-surface deposits (those used in antiquity) and deep deposits (those remaining today) and some aspects of the statistical basis for matching artefact to source through lead isotope analyses have also been questioned (Budd *et al* 1993). Despite these problems, lead isotope analyses can identify multiple sources of metal even if the individual origins cannot be unambiguously identified.

Lead isotope abundances are normally measured using thermal ionisation mass spectrometry (TIMS) or inductively-coupled plasma mass spectroscopy (ICP-MS). A new development is the application of laser ablation mass spectrometry (LAMS) for lead isotope analysis of ancient coins using small drilled samples; its potential for in situ analysis of lead inclusions needs to be investigated. Certainly the precision of the lead isotope results produced by LAMS is an order of magnitude greater than for conventional TIMS (Ponting *et al* 2003).

Dating techniques

Techniques for dating archaeometallurgical remains can be quite specific, due to the nature of the material, but most of those regularly used also have more general archaeological applications. Radiocarbon dating can be applied to charcoal associated with metalworking evidence as has recently been demonstrated at Sherracombe Ford, Exmoor (Juleff 2000). Additionally, charcoal embedded in slag can sometimes be the only dating evidence, as was the case at the iron-working site at Welham Bridge (Halkon and Millett 1999, 80–81).

Pioneering work on the C-14 dating of iron was conducted in the 1960s (van der Merwe 1969) but was found to be impracticable because of the very large samples required to extract a dateable amount of carbon (1g of carbon, *ie* 20–1000g of iron). Further developments in the early 1990s used accelerator mass spectrometry (AMS) to measure the isotopes which substantially reduced the required sample weight (<100μg). Tests conducted on museum artefacts with dates already established by traditional methods proved very successful (Possnert and Wetterholm 1995) but no further application of this potentially useful technique has been published, though further research is underway. If successful, it may lead to the more routine application of this technique.

The possibility of dating of metallurgical sites through the use of relict magnetisation of burnt clay structures has been discussed above (see section 2.2).

Thermoluminescence dating (TL) is a technique particularly suited to the dating of fired clay, and as such could be of value to archaeometallurgy. However, no British metallurgical ceramics have yet been dated by TL.

2.5 Experimental archaeology

There is potential for experimental archaeology to address important questions in archaeometallurgy: by accurately replicating a process archaeological interpretations can be confirmed. The principles for archaeological process-replication set out by John Coles 30 years ago apply as much now as they ever did (Coles 1973, 15–18; 1979, 46–48). Much of the work to date has concentrated on metal smelting, notably the work of Tylecote on iron (Tylecote *et al* 1971) and crucible smelting of copper (Tylecote 1974), Merkel (1990) and Zwicker on early copper smelting (Zwicker *et al* 1992), Crew's work on iron smelting in Britain (Crew 1991; Crew and Salter 1991), and various papers in the volume edited by Craddock and Hughes (1992).

Merkel's work took the excavated archaeological evidence, and used this to reconstruct the smelting regime at Timna, including replicating the slags produced and estimating the actual furnace charges used. Unfortunately, there is as yet insufficient archaeological evidence for early copper smelting in Britain for specific experimentation to be possible, despite the recent discoveries at Great Orme (see section 3.1). However, experimentation would seem to be important for medieval and early modern lead smelting where excavation of known bole and ore-hearth sites could produce sufficient evidence. Experimental lead smelting would face environmental and health considerations.

Crew's experiments have investigated many aspects of early iron smelting, especially the utilization of specific ore types and the products of smelting (*eg* Crew and Salter 1993; Serneels and Crew 1997). Much of this has been aimed at providing comparative data for the interpretation and quantification of excavated iron-working debris. A series of experiments exploring the smelting of bog-iron ores during the Iron Age was conducted in furnaces based on excavated evidence; these provided an understanding of iron smelting on that particular site. Crew's work investigated the whole iron production process and included bloom-smithing experiments to estimate the amount of labour required, and the efficiency of the process (Fig 48). For one experiment using bog iron ore, it was estimated that about 100kg of charcoal were used to produce one kilogram of fully-smithed iron in a non-tapping furnace of the type used in prehistoric Britain (Crew 1991). The conclusions demonstrate the large investment of time and manpower, and notably the quantity of charcoal, that early smelting of bog ore required and therefore allow us a more informed discussion about the nature of Iron Age society in North Wales and the role of metallurgy within it.

Such experimental work remains crucial to our understanding of early and historic metal production, because only through such direct experience can we appreciate the degree of material and social investment in metalworking. Crew's work is particularly important in this respect because it looks at a specific smelting regime. General, non-specific, metal smelting experimentation has served merely to demonstrate the possibility of smelting using 'primitive' technologies, but it does not answer specific archaeological questions. To do this, it is necessary to gain an insight into particular smelting operations for which reliable archaeological evidence exists.

Experimentation with non-ferrous metals has lagged behind the work on iron and, while some good work has been done, a coherent research programme of experimental casting of copper-alloys, based on archaeological evidence and using authentic materials, is still required. Although similar things have been done in the past, these have often cut corners over authenticity; using oil-sand moulds, modern alloys and electric or gas furnaces. The emphasis has been on producing something that looks right rather than something that

Figure 48: Experimental iron smelting at Plas Tan y Bwlch, North Wales.

was made by the correct method. There exist numerous excavated moulds, including several dozen matrices for palstaves and socketed axes and around 40 clay moulds for the mid to late Bronze Age (Needham pers comm). These provide a good basis for the study of mould manufacture and for setting out a programme of experimental work on their use. One of the few published accounts of using stone moulds is the casting of an oxhide ingot of pure copper into a replica limestone mould based on an excavated example of Bronze Age date with clear signs of intense heat from Ras Ibn Hani in Syria (Craddock *et al* 1997). The research revealed the importance of the careful selection of the stone used and the practicalities of casting, especially the fact that any artefact produced (such as flat axes) would have needed extensive working by hammering because of porosity. This underlines the importance of metallography in understanding the cooling and subsequent working history of an artefact. It was also shown that it would have been impossible to have cast objects with any surface detail in such moulds because the surface of the limestone mould would decompose at casting temperatures (*ibid*, 6).

Metallographic data from experimental casting experiments and also subsequent experiments in the fabrication of copper-alloy artefacts needs to be expanded, quantified and codified. Ultimately, the aim of this should be to create a body of metallographic data that can be used in similar ways to (and in conjunction with) the body of compositional data, in order to draw general technical and archaeological conclusions about metal objects. Such information would be crucial in addressing such questions as the condition the object was in when it was deposited, possibly showing whether the metal was specially prepared for burial.

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

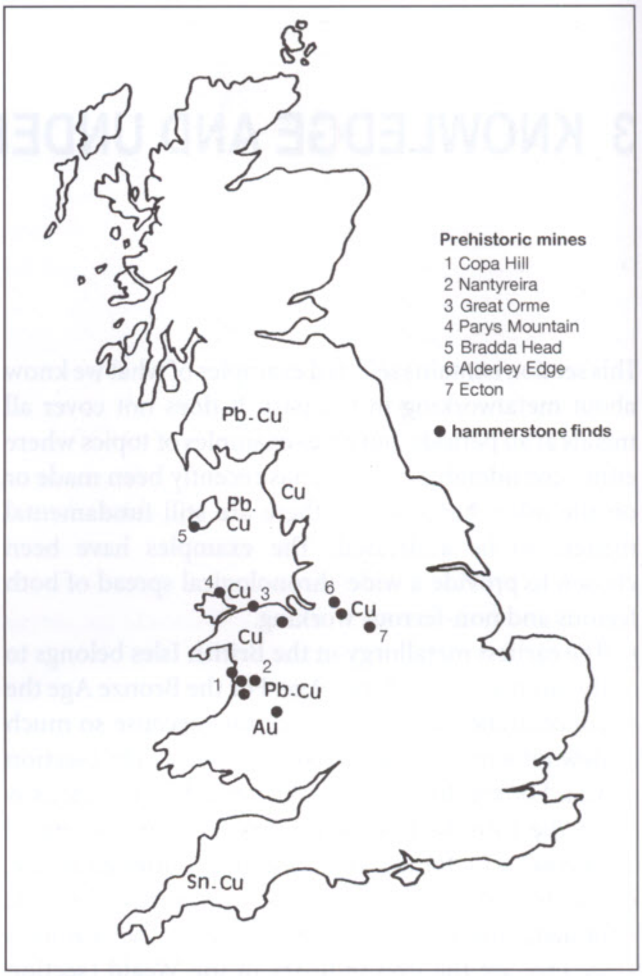

Figure 50: Map showing finds of stone hammers, and known British prehistoric mining sites in relation to ore-bodies.

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.

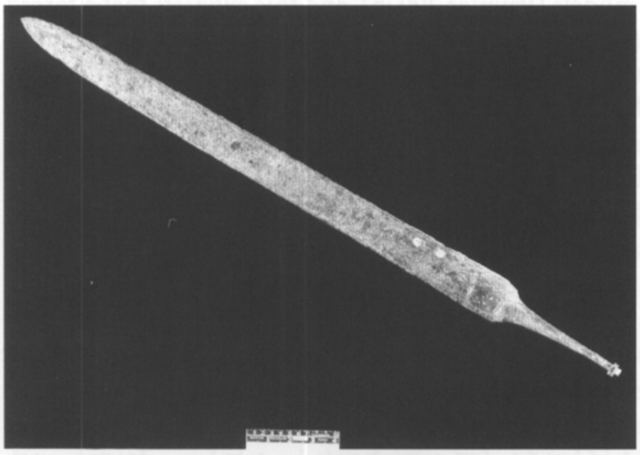

Figure 54: Iron Age sword with brass appliqués from Isleworth, Middlesex. Length 750mm.

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.

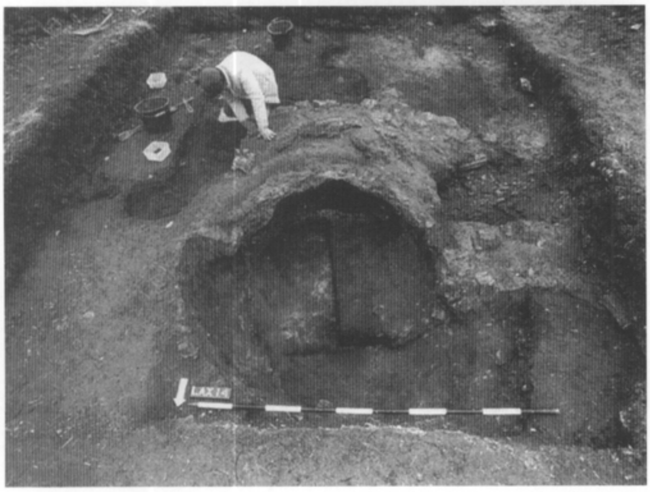

Figure 56: Roman furnace at Laxton, Northamptonshire. The basal slags have been removed and the lower deposit of ore fines sectioned. The right hand side of the furnace has been damaged by a recent pit. After Crew 1998b.

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

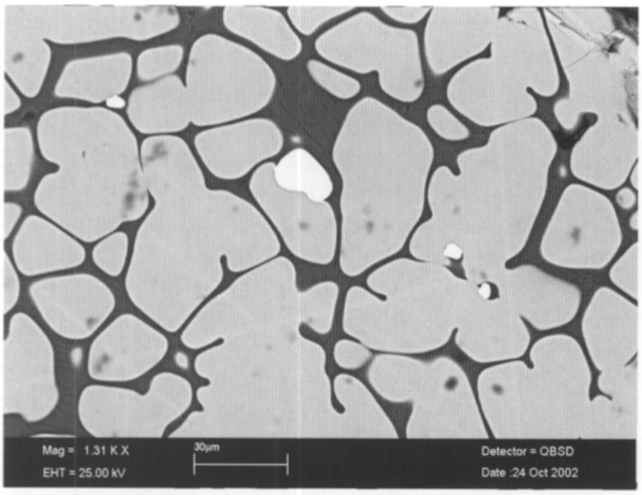

Figure 57: Backscattered SEM image of Late Iron Age/Roman iron slag (slag cake) showing metallic iron (white) and wüstite (iron oxide, light grey) in a dark glassy matrix.

(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

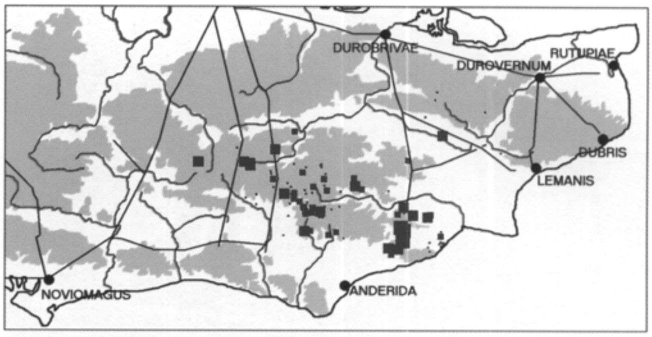

Figure 58: Map showing the location of Roman iron-smelting sites in the Weald. The four sizes of red squares represent sites with over 10,000m³ of iron slag, 1,000–10,000m³, 100–1,000m³, and under 100m³ of iron slag respectively.

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.*

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.

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.

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

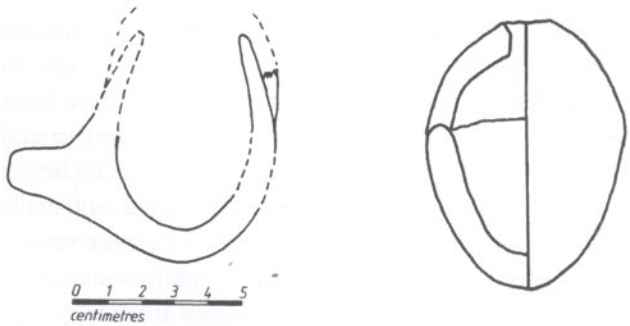

Figure 61: Early Roman brass-making crucibles from Culver Street, Colchester, Essex (left), and Palace Street, Canterbury, Kent (right). After Bayley 1984.

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

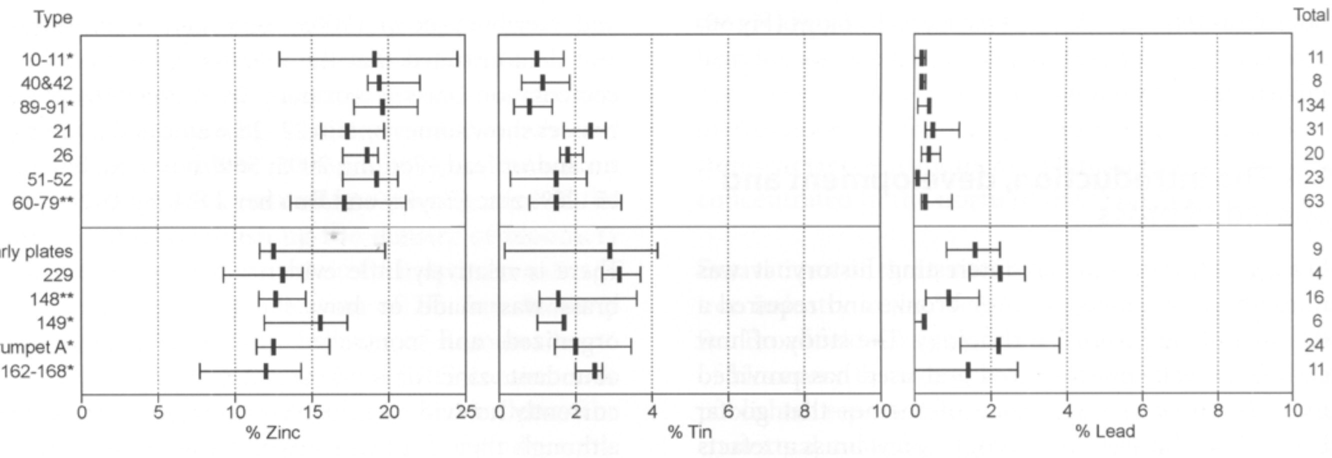

Figure 62: Graph showing alloy composition of different of 1st-century brass brooch types. After Bayley and Butcher 2004.

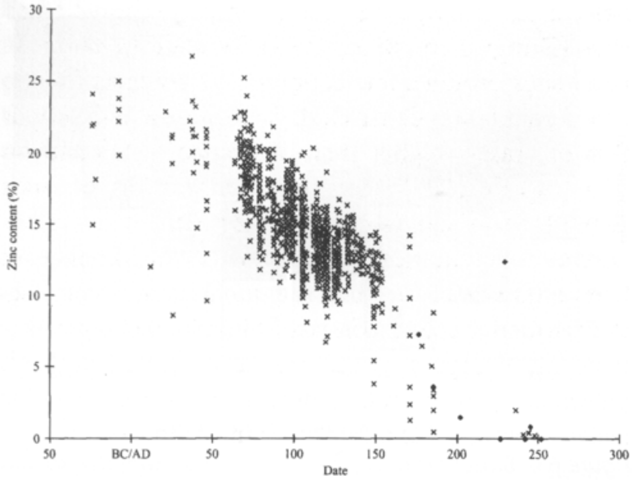

Figure 63: The zinc content of Roman brass coins dropped steadily from the 1st century AD onwards. After Dungworth 1996b.

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

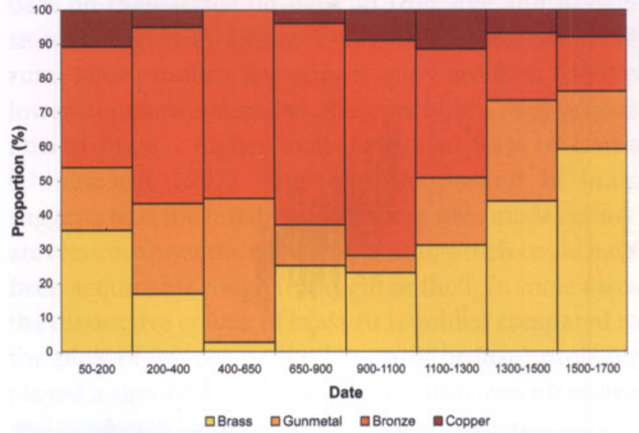

Figure 65: Bar-chart of copper alloys in use from the Roman conquest to the Industrial Revolution. Based on data from Dungworth 1997 and Blades 1995.

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 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.

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.

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

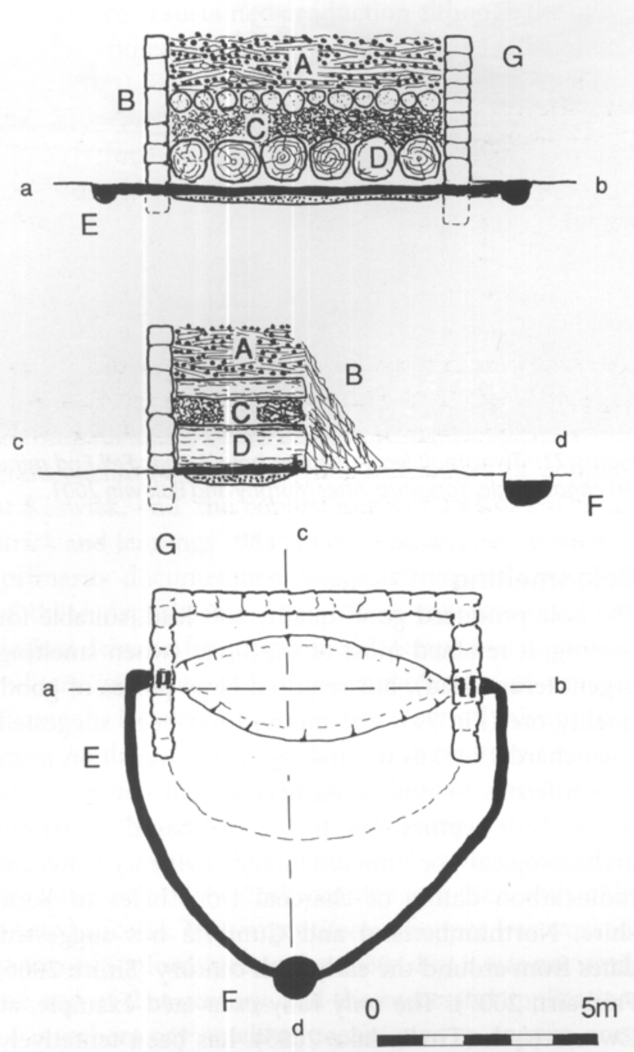

Figure 72: Reconstruction of a Derbyshire 16th-century lead-smelting bole. In the stone enclosure (G) were placed wood (shankerds B and blocks D), with blackwork (part-smelted ore C), beneath ore and small wood (A). The smelted lead flowed by channels (E) to a mould (F). After Kiernan 1989.

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.

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.

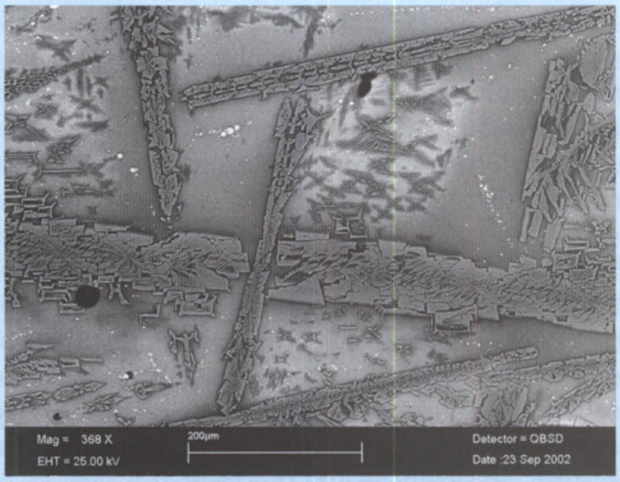

Figure 73: Backscattered SEM image of lead-smelting slag from the earlier (16th century) deposits at Combe Martin, Devon. The dendrites are olivine and the bright droplets are sulphides of lead, copper, iron and zinc in a glassy matrix.

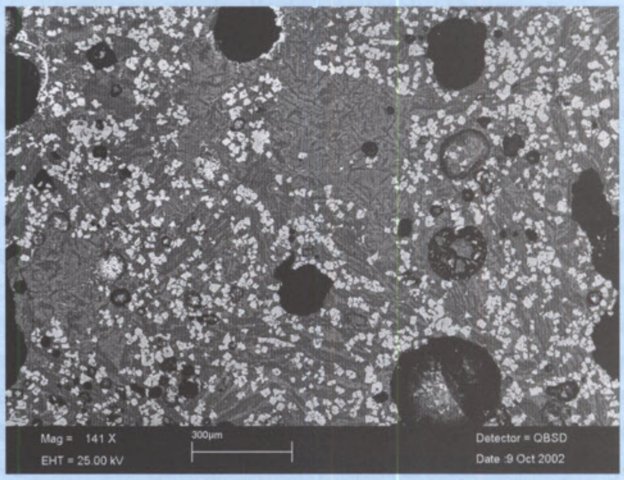

Figure 74: Backscattered SEM image of lead smelting slag from the 19th-century deposits at Combe Martin, Devon. The bright phase is spinel (hercynite), the dark needle-like crystals are corundum (Al_2O_3) and the mid-grey phase is anorthite ($CaAl_2Si_2O_8$)

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.

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.

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.

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

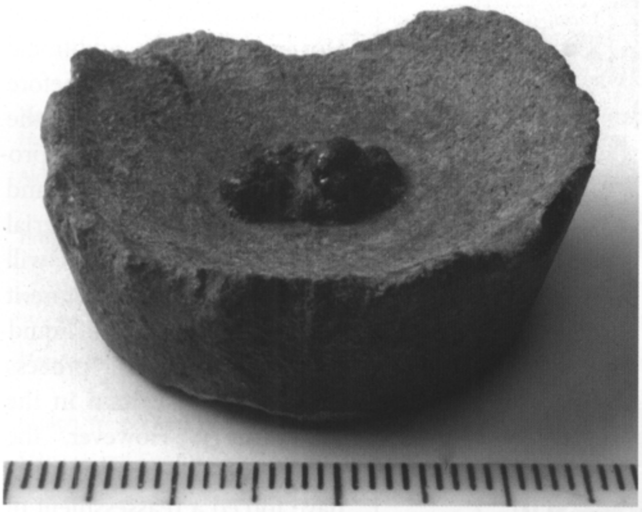

Figure 76: A bone ash cupel from Cripplegate, London, with the silver that was assayed in it still in position. Scale in mm.

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

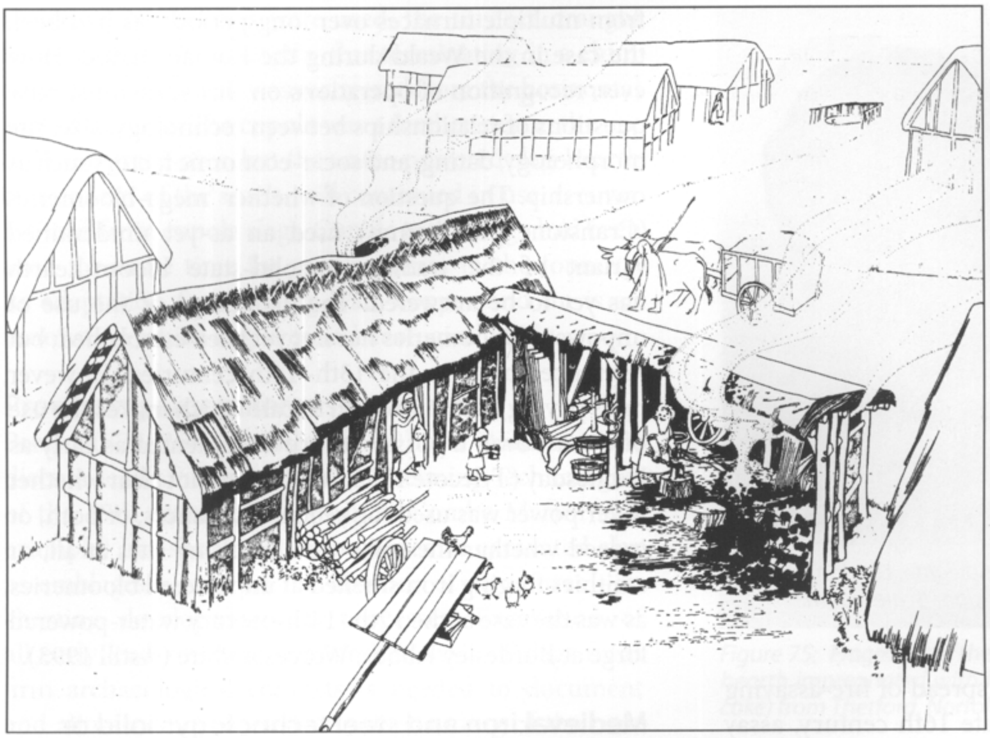

Figure 77: Reconstruction of the blacksmith's forge on Site 31 at Hamwic (Saxon Southampton), Hampshire. After Mack et al *2000.*

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.

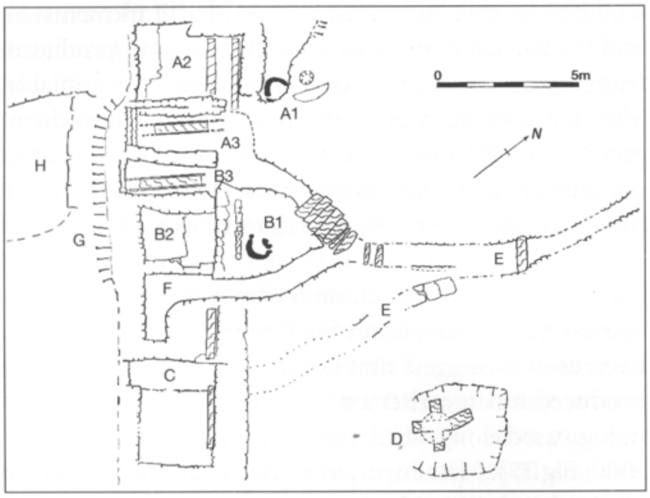

Figure 78: Rockley, Yorkshire. Plan showing the bloomery furnace (A1), bellows house (A2) and water-wheel (A3). The string hearth (B1) for reheating blooms also had bellows (B2) driven by a water-wheel (B3). The purpose of the third wheel-pit (C) is uncertain, being too far from the anvil (D) to be likely 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	c1474–1495	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	c1500–c1640	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

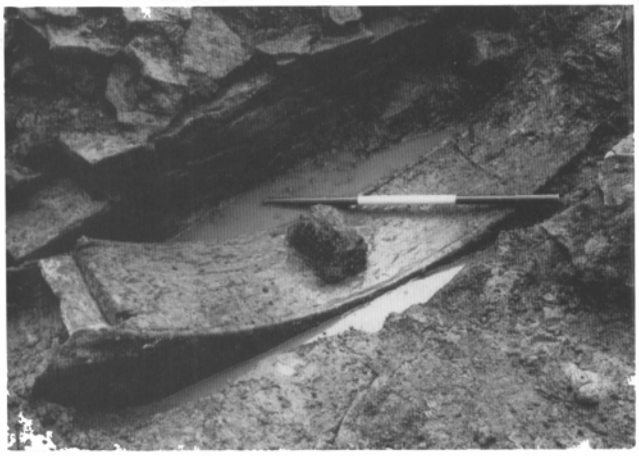

Figure 79: Part of a water-wheel in position in a wheel pit at Rockley, Yorkshire.

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.

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

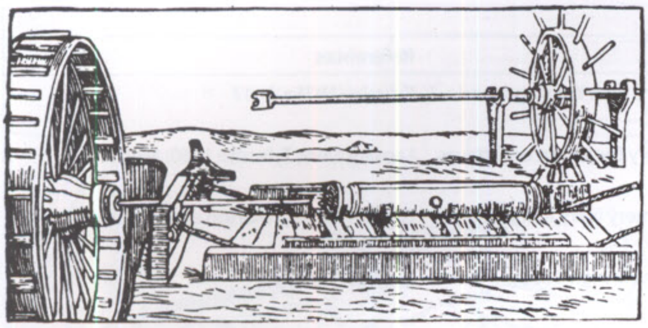

Figure 80: 16th-century gun founding: an illustration from Biringuccio's Pirotechnia *showing how castings were bored.*

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.

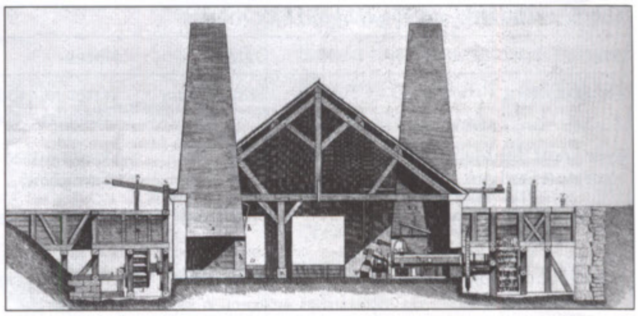

Figure 82: Drawing of a French conversion forge showing a finery hearth (left) and water-powered forge hammer and chafery hearth (right). After Diderot (Gillispie 1959). This can be compared with Figure 83.

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

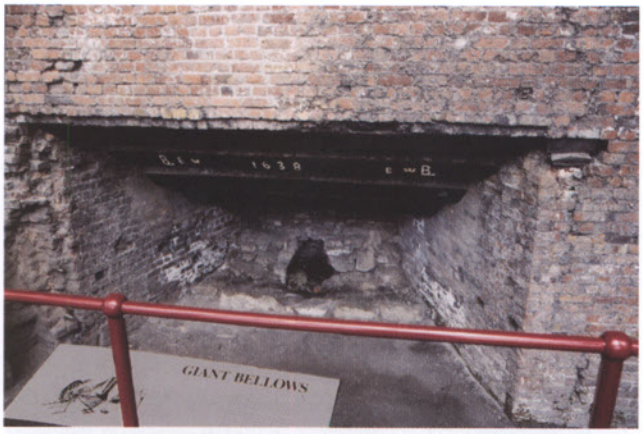

Figure 84: The bellows arch of Abraham Darby's furnace at Coalbrookdale, Shropshire.

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.

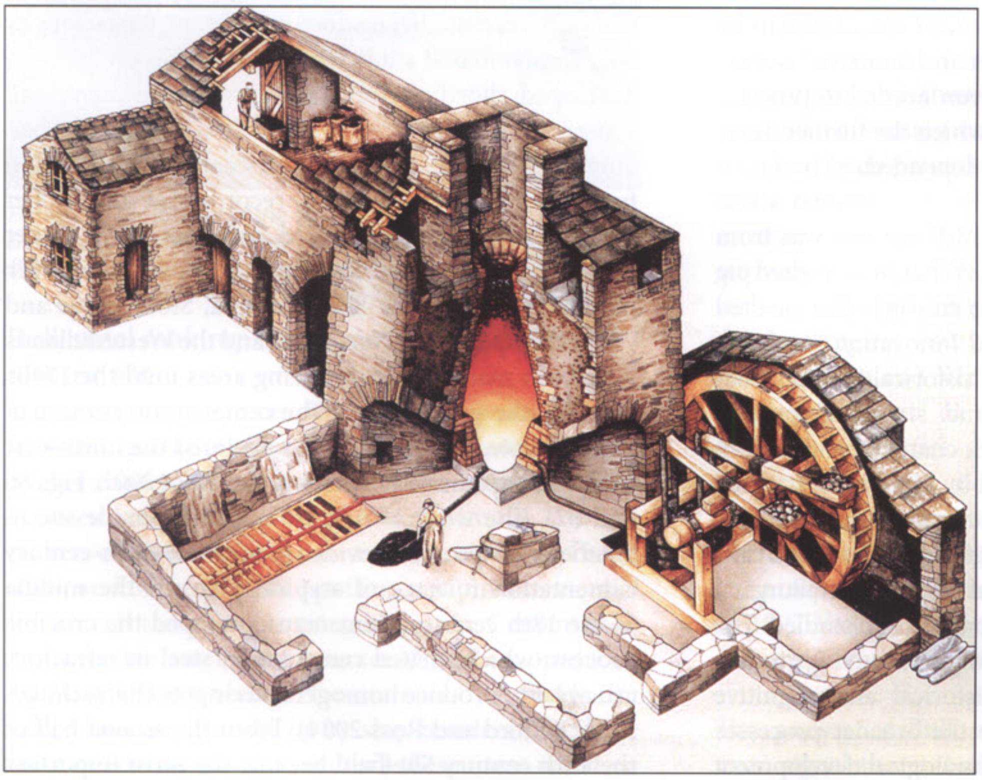

Figure 85: Reconstruction of the charcoal-fuelled blast furnace at Duddon, Cumbria, built in 1736.

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.

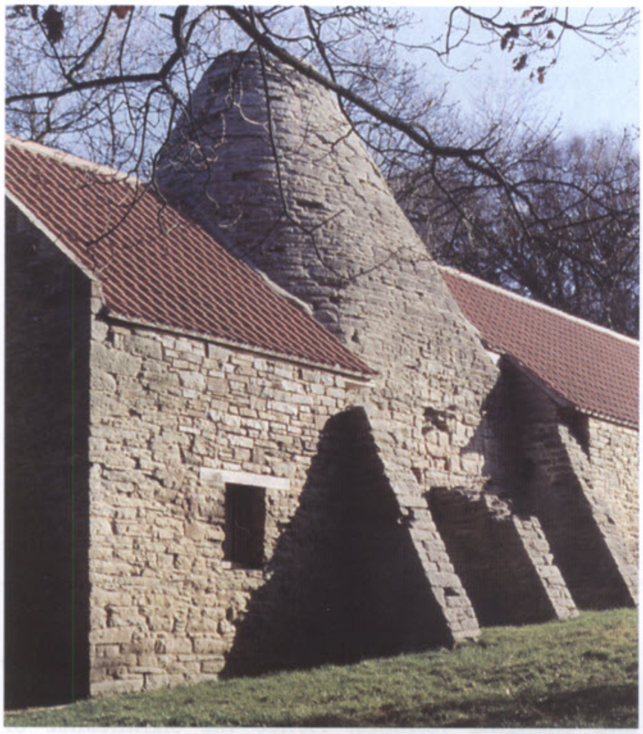

Figure 86: The early-18th-century cementation furnace at Derwentcote, Co Durham, with attached working buildings.

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

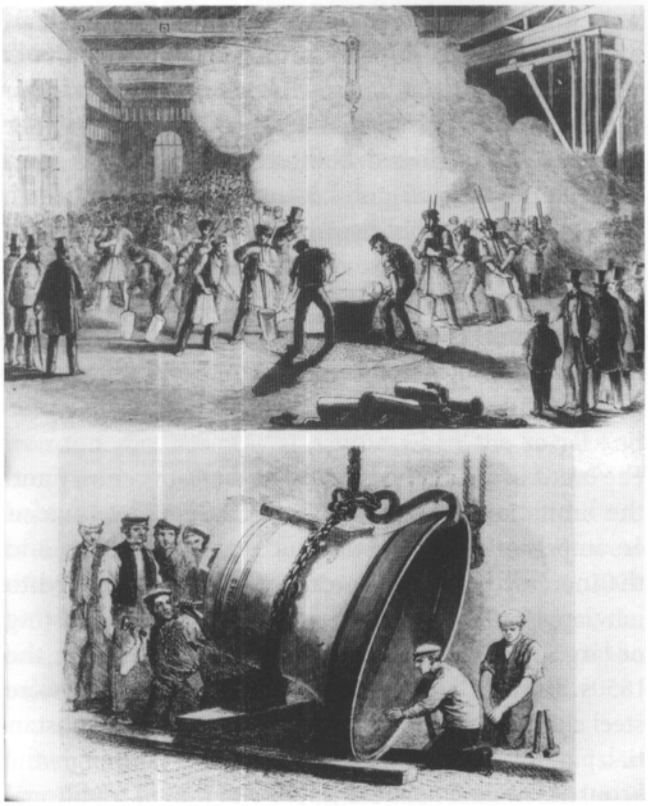

Figure 88: Casting a bell weighing about 5 tons for the San Francisco fire station in 1860 at the Naylor, Vickers and Company works at Millsands in Sheffield. Barraclough 1976.

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 mis-spent 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.

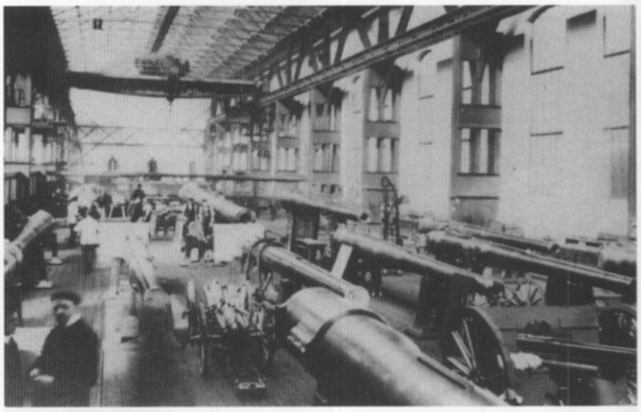

Figure 89: The gun shop at Vickers' River Don works in Sheffield, c1900. Barraclough 1976.

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.

4 CONCLUSIONS AND AGENDA

4.1 Conclusions

The preceding parts of this document have described the resource, the approaches to investigation, and given some case studies of how archaeometallurgical data can be used within broader archaeological or historical contexts. The examples above should alert archaeologists at all levels within the profession to the potential of using the archaeometallurgical resource more fully in pursuit of the past and its people.

Because of the nature of the archaeometallurgical resource, good interaction between archaeometallurgists and other heritage professionals is needed — and this should result in a fuller understanding of the contribution of metals and metalworking to the lives of past peoples. In only a relatively small number of projects will metallurgy drive the activity; in a much larger number the archaeometallurgical component of a project may be perceived as tangential to the main undertaking, but may none the less have the potential both to enhance understanding of the immediate project and also feed into broader issues of the past use of metals. Such potential will only be realised through the full integration of archaeometallurgical investigations within all stages of projects; in particular archaeometallurgists should be involved throughout and not solely as post-excavation specialists.

This document has been able to look at this particular aspect of human history in more detail than in the regional and period-based archaeological research frameworks. It must be remembered however that this agenda is also very wide ranging, with enormous temporal and geographical diversity. Realization of the potential of archaeometallurgy must involve close dialogue between technical specialists and those engaged in investigating broader social context. The need for such a dialogue is not unique to archaeometallurgy, but is common to the application of scientific approaches within archaeology.

The future of archaeometallurgy lies, therefore, in a more synthetic approach to all archaeology at all levels. It also needs archaeometallurgists to have better communication with the rest of their profession, both field archaeologists and other specialists. The realization that archaeometallurgists can and do work with sites and landscapes as much as laboratory studies, and that context and proximity are as crucial as chemistry and structure, are important developments in this discipline. Many of the topics identified in this research agenda are technical ones, but access to the landscapes, sites and artefacts that can and will provide the material on which work is needed will only come through collaborative working. We hope our colleagues across the archaeological community will agree with many of the priorities identified below, and will work with us to achieve some of the goals we have identified.

4.2 A research agenda for archaeometallurgy in Britain

The identification of priority areas for research involves both consideration of multi-period issues and those which apply to particular periods of the past. The following list is therefore divided along these lines, facilitating comparison and integration with the Regional Archaeological Frameworks whilst also identifying over-arching themes. In Scotland a more limited review has been undertaken (Hunter *et al* 2006), and its priorities, mainly for non-ferrous metals before AD 1100, should be considered alongside those given below. There are also many other topics where new knowledge would be welcome, so opportunities should be grasped when they offer themselves.

Multi-period themes

- Develop holistic approaches to the description and interpretation of landscapes associated with metallurgical activity. Mining, ore beneficiation, smelting, fuel supply, transport, metalworking, associated industries (*eg* ceramics), metal artefact production and distribution may all occur, situated within complex social and geographical contexts which may be largely unrelated to metallurgy.

- Consider the environmental setting and implications of metalworking. This may include heavy metals and other traces in peat profiles and alluvial sediments, as well as conventional pollen analysis.
- Undertake elemental and isotopic analyses of groups of metalwork with regard to artefact style, date and geographical distribution. Much pioneering work has already been undertaken on Bronze Age copper alloys, but this needs extension to other materials and periods.
- Broaden archaeometallurgical understanding through the identification and investigation of sites with unusual or innovative processes, and sites where the archaeometallurgical residues of poorly-understood processes may be investigated.
- Further investigate the radiocarbon dating of iron.
- Revolutionize our knowledge by identifying at least one early production site for each of the major non-ferrous metals, and preferably one from each relevant region (see Fig 2).
- Set alongside cognitive approaches to the archaeology of metals, that look at the mind-set and understanding of the past metalworker, modern scientific investigation of what was going on.
- Develop research approaches to the processes of invention, innovation, and technological progress, as exemplified by metals.
- Consider metalworking techniques and practice in Britain in relation to continental Europe. Differences as well as similarities are important; existing assumptions on the direction of any influence should be critically examined. For the post-medieval period look beyond Europe.
- Consider relationships between metalworking traditions in England, Scotland and Wales without assuming a uniform pan-British tradition.
- Investigate the relationships between metalworking and other pyro-technologies such as glassmaking.

Prehistoric topics

- Develop techniques to identify prehistoric mines in the absence of stone hammers and, more generally, to date ancient mine workings.
- Seek evidence for prehistoric lead mining, particularly in the Mendips, mid Wales and Derbyshire.
- Reasons should be sought for the fluctuations in prehistoric use of gold.
- Identify the mechanisms that brought brass to Britain in the later Iron Age; analyses of finds from well-dated contexts may assist in this. The spread and development of the use of brass require clarification.
- Investigate the relationships between site types, the types of artefacts manufactured and the techniques used, particularly for bronze-working in the Iron Age.
- Investigate and date the beginning of iron technology in Britain.

Roman topics

- Investigate whether specific alloys were selected for different types of objects or different methods of manufacture, and whether date or place of manufacture affected the alloys used.
- Identify where the raw materials for making Roman copper alloys came from.
- Establish whether brass production and use retains its strong administrative/military link throughout the Roman period.
- Investigate regional patterns of copper alloy use and their changes through time in non-Romanised parts of the British Isles.
- Clarify the nature, status and sources of the industries working in lead, tin, pewter and silver.

Early medieval topics

- Clarify the role of brass in the early medieval period: the case for discontinuity or decline.
- Investigate the nature of primary metal production in post-Roman societies.
- Investigate continuity versus replacement for iron technology and production in the early medieval period, particularly comparing different areas of the British Isles.
- Develop provenancing tools to clarify the nature of trade in metals both within the British Isles and with external areas.
- Further investigate the nature and production of early medieval steel.

High medieval topics

- Look for evidence of copper production and use; attempt to bridge the medieval gap
- Document the changing technologies of lead and silver production throughout the medieval period
- Investigate medieval steel — did it come from bloomeries or from alternative technologies?
- Investigate the early spread of industries associated with iron into the coalfields.
- Investigate the range of ironmaking in the later Middle Ages in relation to both continental developments and to patterns of secular and monastic control and capital.

Post-medieval topics

Synthetic accounts of historical metallurgy are usually structured round known individuals, places and processes. However, in a startlingly high proportion of cases there is currently no physical evidence for key developments which drove and responded to the Industrial Revolution, so the comparison of data from the historical record (even for relatively recent sites) with the archaeological record needs to be made, both for structures and archaeometallurgical residues. The understanding of different scales of operation and the organisation of industrial activity needs also to be improved. Archaeological recording of later 19th-century and 20th-century remains should be given priority, as they are often vulnerable to remediation of contaminated land and 'environmental restoration'. Rapidly changing technology makes it surprisingly difficult to move beyond the conventional historically-led interpretations.

The following lists indicate particular priority areas, first in the study of iron forges:

- The development of finery forges in the 15th-18th centuries.
- The development of puddling and associated technologies in the 18th century.
- Experiments with coke in the 17th century.
- Early cementation steel furnaces from the 17th century.
- The development of wire drawing and other secondary iron industries.
- 19th-century ironworks, especially the foundry and forge sectors.

and in the production of non-ferrous metals, away from the major centres:

- Identification and recording of copper production sites in Cornwall, to complement the better-known tin and silver ones.
- The 17th-century development of reverberatory furnace technologies for non-ferrous ore-roasting, calcining and smelting.
- Location of brass and copper production sites dating before the 18th century, and recording of 18th- and 19th-century brass production sites outside Bristol.
- Lead production sites of the modern period, particularly the urban lead-processing industries

4.3 Towards a strategy for archaeometallurgy in Britain

The widespread adoption of best practice with respect to archaeometallurgy is necessary to further the aims expressed in the research agenda above. This includes the appropriate integration of prior understanding of the archaeometallurgical potential of a site or landscape during the planning process, engagement with suitable archaeometallurgical specialist advice both during excavation and subsequently, and provision of scientific analysis of archaeometallurgical materials at a level appropriate to the project.

Current advice on best practice can be found in a number of places, especially in some of the documents listed under 'Further reading' below, on the website of the Historical Metallurgy Society (hist-met.org), and elsewhere. Some points have been highlighted in the text above, and it is worth re-iterating them here as they are basics that experience shows are often overlooked or ignored for too long:

- Metalworking landscapes are often too extensive and diffuse for scheduling; consideration needs to be given to integrated management and protection policies.
- Some SMRs/HERs would benefit from specific enhancement of data from metallurgical sites.
- Excavation of redundant industrial sites provides an opportunity to match documentary sources with archaeological reality.
- Record adequately and fully publish all metallurgically-important sites whose preservation cannot be guaranteed.
- Involve an archaeometallurgist from the very beginning of all projects.
- Use systematic fieldwalking to locate ironworking sites in fields under cultivation.
- Routinely use geophysical methods in prospecting for metallurgical sites.
- Excavation should only be carried out if the site is threatened or in response to unresolved issues raised in this research agenda.
- Make efforts to ensure adequate resources for both fieldwork and post-excavation study for all projects that are undertaken.
- Because of the likely size of features, brown-field sites require area excavation and appropriate sampling and collection policies (see Dungworth and Paynter 2006).
- Developer-funded projects should include the costs of relevant archaeometallurgical laboratory work.
- Analyses of metal artefacts should be undertaken to answer specific archaeological questions.
- The analysis of objects is a crucial part of understanding working practices, skills bases and technology, and needs to be conducted on a sufficiently large scale.
- Specialists undertaking laboratory work must be provided with appropriate archaeological information, such as contexts, phasing, dating, plans, etc.

- Publish promptly the results of all archaeometallurgical investigation (whether field- or lab-based).

4.4 National and regional research frameworks

Many national and regional research agendas have either been undertaken or work on them is in progress. Conventional publication is sometimes in summary form with supporting detail on the Web, while other are available only on the Web or in both formats. Most have at least some mention of metals and metalworking but it was the uneven nature of this coverage which prompted the production of this volume. The references below do however provide a complementary series of visions of the place of archaeometallurgy in the wider archaeological picture.

National agendas

The Prehistoric Society set up a working party to identify strategic areas central to future research on the British Iron Age. Their report includes sections on metal objects and metalworking (Haselgrove *et al* 2001, 21–2 and 26–7).

A session on 'Romano-British research agendas' at the 1999 Roman Archaeology Conference grew into a publication (James and Millett 2001) including papers on a range of thematic topics, but with barely a mention of metals or metalworking.

A conference organised by the Association for Industrial Archaeology was designed to formulate a research framework for industrial archaeology (Gwyn and Palmer 2005). The papers focus on the social and economic context of technical innovations and most can therefore be seen as defining and describing the archaeology of the industrial period rather than the technological details of metallurgical and other industrial processes.

The proceedings of a conference to develop a research framework for Welsh archaeology has been published (Briggs 2003). Considerable further details, subdivided by period and region, are available at www.archaeoleg.org.uk.

In Scotland work on a full research frameworks exercise is only now getting under way but a recent paper by Hunter *et al* (2006) has looked at the evidence for metalworking before AD 1100.

English regional agendas

For the South West the resource assessments, agendas and strategy are available at: www.somerset.gov.uk/somerset/cultureheritage/heritage/swarf/

The resource assessment notes the lack of pre-medieval evidence for metal production and contrasts this with the widespread use of these metals. Tin is likely to have been exploited since the Bronze Age but there is no direct pre-medieval evidence. The evidence for Roman exploitation of Mendip lead is largely restricted to ingots. The history of iron exploitation in the Forest of Dean is still poorly understood with no certain pre-Roman sites and the number of well-dated Roman sites is still too small to see how the industry developed. It is often suggested that later activity will have removed the earlier evidence for metal production but recent work suggests that this is overly pessimistic. The presence of hammerstones in museum collections could point to very early mining sites. The surviving earthworks and buildings of medieval and later industries form a major resource, especially where they can be linked to documentary evidence.

For the South East there are several sub-regional assessments: Greater Thames Estuary, Thames-Solent, Surrey and South-East (which covers Kent, Surrey and Sussex). The relevant websites are:

212.67.202.196/~teprep/dev/documents/uploaded/document/GreaterThamesResFrame.pdf

www.buckscc.gov.uk/bcc/content/index.jsp?contentid=-222423834

www.surreycc.gov.uk/sccwebsite/sccwspages.nsf/LookupWebPagesByTITLE_RTF/SURREY+ARCHAEOLOGICAL+RESEARCH+FRAMEWORK?opendocument

www.kent.gov.uk/serf

For London there is a published volume (Nixon *et al* 2002) that says little about metalworking, except in the prehistoric period when it mentions examining iron deposits and evidence for prehistoric bronze casting in Surrey.

Details of the regional research framework for the East of England are available at www.eaareports.demon.co.uk/research_framework. A research assessment (Glazebrook 1997) and a research agenda (Brown and Glazebrook 2000) have been published and both are available at www.eaareports.demon.co.uk/research_and_archaeology.htm. The proceedings of a review conference are due to be published in 2008; some chapters are available at www.eaareports.demon.co.uk/framework_review.htm.

For the East Midlands the resource assessments, agenda and strategy are available on-line at:

www.le.ac.uk/archaeology/research/projects/eastmidsfw/index.html, and the latter has been published (Cooper 2006). They note the likelihood that the region had an important iron industry which may extend into the pre-Roman era but that early evidence is limited. There is abundant evidence for Roman iron smelting but there is a need for better dating. The assessment also recommends work on the lead industry of Derbyshire.

For the West Midlands most of the papers presented at the preliminary seminars are available at:
www.arch-ant.bham.ac.uk/research/fieldwork_research_themes/projects/wmrrfa/seminars.htm

For Yorkshire there is a document that primarily consists of a very thorough resource assessment (Manby *et al* 2003). Among other things, it notes the lack of: systematic scientific study of Bronze Age copper alloy objects; direct evidence for Roman lead production (despite finds of ingots); evidence for metalworking in contrast to the extant high-quality metalwork of the post-Roman period; a modern synthesis of the Yorkshire lead industry; and publication of the evidence for iron mining.

For the North East the resource assessments are available at:
www.durham.gov.uk/durhamcc/usp.nsf/pws/Archaeology+-+Archaeology-Projects-Regional+Research+Framework
and a research strategy has been published (Petts and Gerrard 2006). The assessments regularly stress the lack of evidence for metal production and recommend: full metallurgical analysis of all early Bronze Age metal artefacts; geophysical survey and field survey (for example on bloomery sites) with excavation and C-14 dating; geochemical survey and fieldwork in the north Pennines to locate traces of lead and silver working; the need to integrate documentary, archaeological and scientific evidence for the lead-silver industry. The extant physical remains of the historic lead industry are identified as a major resource.

For the North West the resource assessments, agendas and strategy are all available at:
www.liverpoolmuseums.org.uk/mol/archaeology/arf/
The documents stress that pre-medieval metal production sites are virtually unknown and identify priorities: the need for the analysis of metalwork, including trace element and lead isotope analysis; examining river silts for evidence of past mining activity; the need for syntheses of existing work on industrial centres; extending geophysical survey for iron smelting sites (from the Lake District and Castleshaw valley); and further investigation of the copper mining at Coniston (where there is documentary evidence for German miners).

A research assessment is also being undertaken for Hadrian's Wall. Documentation is available at:
www.durham.ac.uk/archaeological.services/research_training/hadrianswall_research_framework/

4.5 Further reading

The many references in the text provide further information about specific topics. A more general introduction to archaeometallurgy in Britain is provided in the books below. The headings indicate the type of information included in each group.

General introductions to past metallurgical processes, structures and finds

Craddock P T 1995, *Early metal mining and production* (Edinburgh).
Crossley D W (ed) *Medieval industry* (London: CBA Res Rep 40).
Day J and Tylecote R F (eds) 1991, *The industrial revolution in metals* (London).
McDonnell J G 2001, 'Pyrotechnology', in D R Brothwell and A M Pollard (eds), *Archaeological Sciences* (Chichester), 493–505.
Singer C, Holmyard E J, Hall A R and Williams T I 1954–58, *A history of technology*, 5 vols (Oxford).
Tylecote R F 1986, *The prehistory of metallurgy in the British Isles* (London).
Tylecote R F 1992, *A history of metallurgy.* 2nd edn (London).

Advice on how to excavate archaeometallurgical sites, identify finds from them, and take samples

Bayley J, Dungworth D and Paynter S 2001, *Archaeometallurgy.* EH Guidelines 2001/01 (London).
Dungworth D and Paynter S 2006, *Science for historic industries: guidelines for the investigation of 17th- to 19th-century industries* (Swindon).
HMS archaeological datasheets (hist-met.org/datasheets.html).

Examples of technical and scientific investigations of artefacts

Bayley J and Butcher S 2004, *Roman brooches in Britain: a technological and typological study based on the Richborough collection* (London: Society of Antiquaries Res Rep 68).
Bowman S (ed) 1991, *Science and the past* (London).
Fell V, Mould Q and White R 2006, *Guidelines on the X-radiography of archaeological metalwork* (Swindon).

Hodges H 1964, *Artifacts* (London).
Lang J and Middleton A 2005, *Radiography of cultural material* (London).
Tylecote R F and Gilmour B J 1986, *The metallography of early ferrous edge tools and edged weapons* (Oxford: BAR BS 155).

Introduction to and explanations of scientific techniques

Andrews K and Doonan R 2003, *Test tubes and trowels: using science in archaeology* (Stroud).
Bachmann H-G 1982, *The identification of slags from archaeological sites* (London: Institute of Archaeology Occ Pub 6).
Henderson J (ed) 1989, *Scientific analysis in archaeology* (Oxford: OUCA Monograph 19).
Pollard M, Batt C, Stern B and Young S M M 2007, *Analytical chemistry in archaeology* (Cambridge).
Scott D 1991, *Metallography and microstructure of ancient and historic metals* (Los Angeles).
Tite M 1972, *Methods of physical examination in archaeology* (London).

Synthetic texts on particular topics

Barraclough K C 1984, *Steelmaking before Bessemer: i: Blister steel: the birth of an industry, ii: Crucible steel: the growth of an industry*, 2 vols (London).
Cleere H F and Crossley D W 1995, *The iron industry of the Weald*, 2nd edn (Cardiff).
Craddock, P T, 1998. *2000 Years of zinc and brass*, 2nd edn (London: BM Occ Pap 50).
Gerrard, S, 2000. *The early British tin industry* (Stroud).
Kiernan D T 1989, *The Derbyshire lead industry in the sixteenth century* (Chesterfield).
Newman P (ed) 1996, *Mining and metallurgy in south-west Britain* (Matlock)
Schubert H R 1957, *History of the British iron and steel industry* (London).

Examples of good practice

Astill G G 1993, *A medieval industrial complex and its landscape: the metalworking watermills and workshops of Bordesley Abbey* (York: CBA Res Rep 92).
Bayley J 1992, *Non-ferrous metalworking at 16–22 Coppergate* (London: The Archaeology of York 17/7).
Belford P and Ross R 2007, 'English steelmaking in the seventeenth century: the excavation of two cementation furnaces at Coalbrookdale', *Historical Metallurgy* 41(2), 105–123.
Burnham B and Burnham H 2004, *Dolaucothi-Pumsaint: survey and excavations at a Roman gold-mining complex 1987–1999* (Oxford).
Symonds J, O'Neill R and Jessop O 2007, 'What can we learn from the excavation and building recording of cutlery sites in Sheffield?', *Post-Medieval Archaeology* 40(1), 214–218.
Timberlake S and Prag A J N W 2005, *The archaeology of Alderley Edge: survey, excavation and experiment in an ancient mining landscape* (Oxford: BAR BS 396).

Archaeometallurgical journals

Journals that specialize in archaeometallurgy, or regularly contain relevant articles:
Archaeometry, Archeosciences, Bulletin of the Peak District Mines Historical Society, Bulletin of the Wealden Iron Research Group, Historical Metallurgy, Journal of Archaeological Science, Metalla (Bochum), Post-Medieval Archaeology.

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