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.

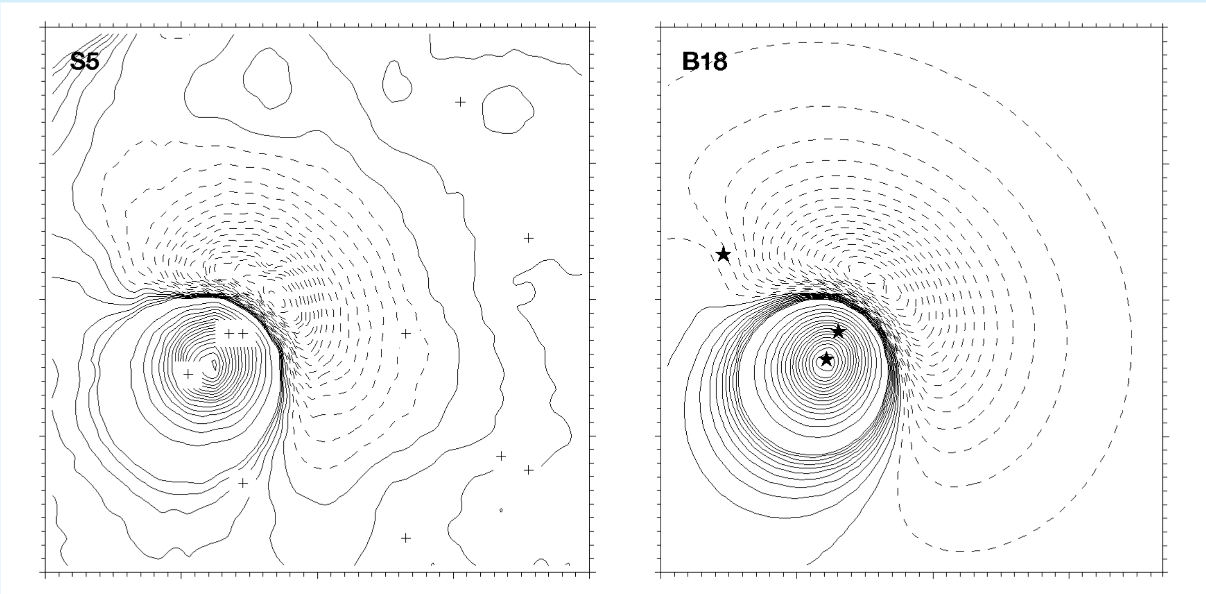

Figure 32: Left: High-resolution magnetometer survey results for a 4m square containing a furnace at Crawcwellt. Right: Calculated map of multiple dipoles (stars mark the centre of each dipole) which closely models the survey, allowing the direction of the calculated dipoles to be used to estimate the 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

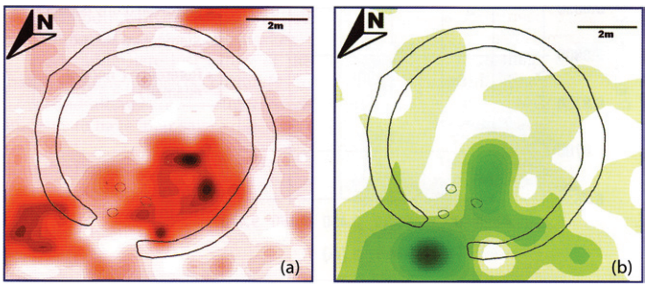

Figure 33: Schematic plan of an Iron Age round house at Billown, Isle of Man, overlaid with areas of enhanced magnetic susceptibility (a), and geochemical survey results for copper (b), showing that metalworking activities were restricted to the NW part of the structure.

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

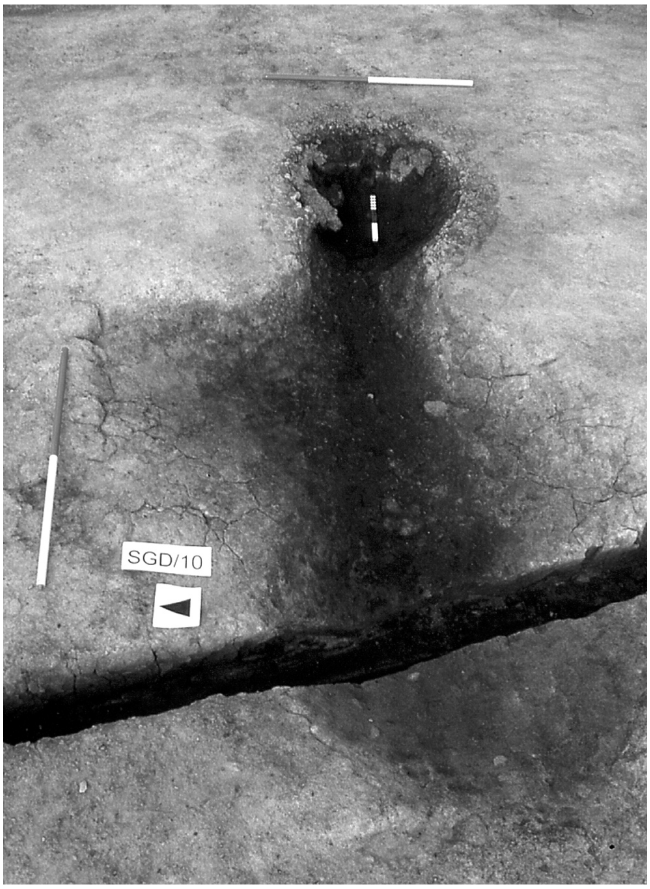

Figure 34: Iron-smelting furnace 137 at Stanley Grange, Derbyshire, after the removal of superficial material and the fill of the slag-tapping pits. Scale bars 1m and 0.3m. After Challis 2002.

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.

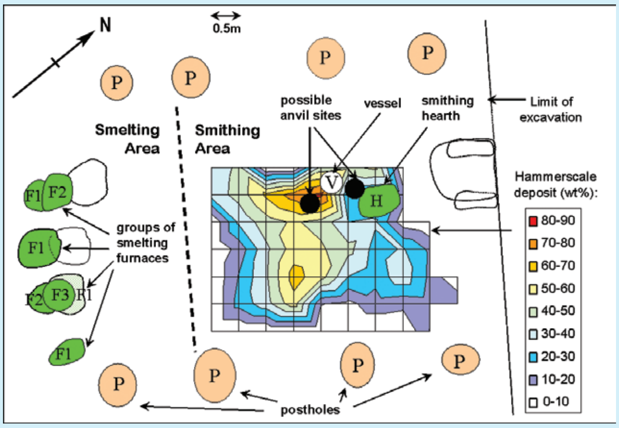

Figure 36: Plot of hammerscale distribution in workshop R at Westhawk Farm, Kent, in relation to other features. Soil samples were collected on a grid and the hammerscale extracted; warmer tones show increased hammerscale concentrations. After Paynter 2007a.

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.

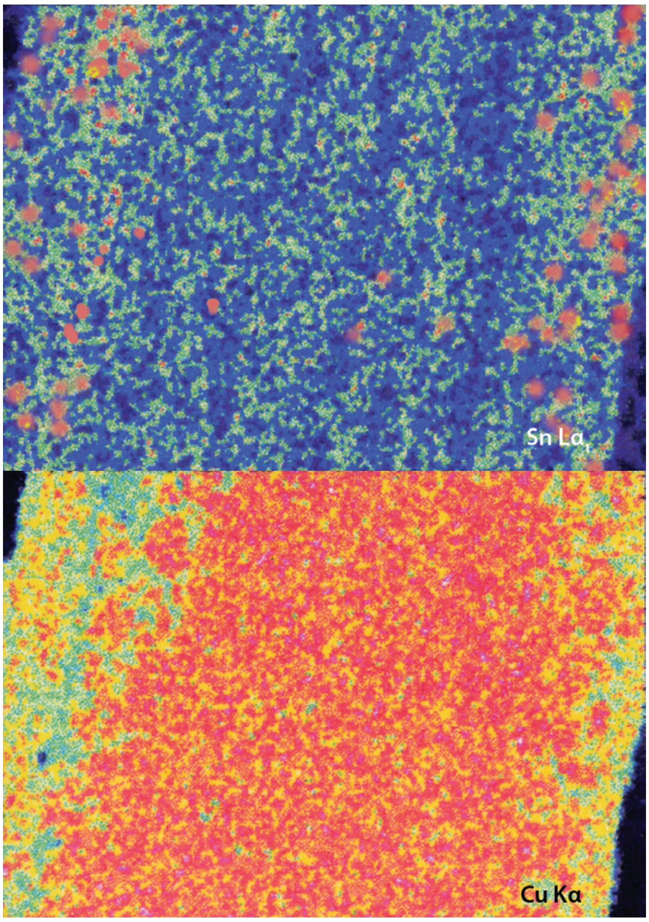

Figure 38: Elemental maps of tin (upper) and copper (lower) in a cross-section of a prehistoric bronze sheet. The warmer colours (yellow and red) indicate high levels of each element. It is easy to see that there are areas of tin enrichment towards the surfaces of the section that also correspond to 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%.

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.

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 (*eg* Dungworth 1995; Blades 1995) have consciously adopted an 'all-in' policy of artefact selection to enable as representative a body of data as possible to be produced. There will of course be circumstances where an analytical campaign will concentrate on particular artefact types or chronological/cultural horizons, but these too should be based on independently-justifiable sampling strategies.

Strategies for sampling individual artefacts will depend on the homogeneity of the material, the analytical technique being used, and whether quantitative, semi-quantitative or qualitative results are required (see section 2.4). Samples must be representative, ie larger than the material's heterogeneity. If all that is needed is a qualitative identification of the alloy type, for example brass or bronze, or identification of a surface coating such as gilding, then analysis of a freshly-cleaned surface is sufficient. However, the effects of burial and corrosion are to change the proportions of many elements in the surface layers of a metal object (Fig 38) so if some idea of the relative amounts of alloying components is required, an area of the surface will need to be cleaned down to bright metal. This will sometimes require negotiation with the archaeologist or conservator responsible for the object, but usually only an area a few millimetres across in an inconspicuous location is sufficient. Such techniques are often referred to as 'non-destructive', a term that can be misleading because the level of sample preparation is directly related to data quality. If there is a need for fully-quantitative analysis, and especially where accurate minor and trace element quantification is required, then there is no alternative to some form of 'destructive' analysis. However, the degree of destruction varies and samples sizes are now often very small. Many analytical techniques do not consume the sample (see section 2.4), so in these cases it can be retained and re-used when further information is required.

2.4 Laboratory investigations

Laboratory based studies of materials can be divided into two main categories; the analysis of finished artefacts and of production waste. Scientific dating techniques also have metallurgical applications (see below).

What should be analysed?

In the past the study and analysis of artefacts (see section 2.3) revolved around museum collections but appreciation of the potential of newly-excavated material is changing this. What is important is not where the material is kept, but rather the questions that are driving the investigation. In the past the emphasis has been on the analysis of finished artefacts, but much current work focuses also on production wastes, which are often absent from museum displays. Part 3 raises some of the questions to which archaeologists and archaeometallurgists would like answers, and many of these could be provided by laboratory analyses. In some cases a large body of data is necessary, with cost implications.

Certain topics are quite well understood but other areas remain unclear. The production technology and composition of Bronze Age artefacts are relatively well known, but less is known of the transition to the Iron Age or of methods of manufacture of some medieval and post-medieval artefacts. Even in the study of Roman metalwork there remain unresolved questions that could contribute substantially to our broader knowledge of the period and especially its aftermath. Surprisingly, in the post-medieval and early modern periods scientific approaches have rarely been used (Bayley and Crossley 2004) though there is potential, as in earlier periods, as recent work has shown (Dungworth and Paynter 2006). Funding large-scale analytical programmes is often difficult but in cases where development-led archaeology has funded the analysis of metallurgical material, the results have been well worthwhile (*eg* Niblett 1999) and this is a pattern that should become more common. Where resources are not available, a possible alternative route is to encourage students studying archaeological materials to undertake analyses as part of their studies, provided sufficient supervisory expertise is available within their department; the downside of this type of arrangement is the long lead time. For all specialist investigations it is necessary for the 'client' to frame specific questions, as well as providing adequate background information.

Relating elemental composition and structural details to both technological and cultural features of metal artefacts offers a much more meaningful approach than one looking only at provenance, and is increasingly considered standard in archaeometallurgical research. Areas that require further development are: the identification of ore types exploited for both the major constituent and the alloying components (Northover 1989; Ponting 2002), the type of smelting process used (Craddock and Meeks 1987), and the identification of compositionally-discrete groups of metalwork that correspond to other archaeological categories such as artefact type or style, association with other diagnostic cultural material, or a particular geographical distribution. The potential information that can be gained from ironwork is often 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

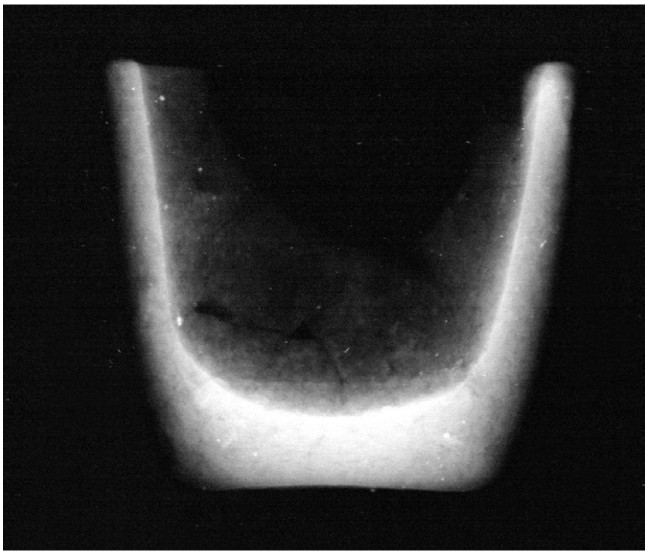

Figure 39: X-radiograph of a post-medieval crucible in section, with the metal-rich slag on the inside surface showing as bright zones, and metal droplets as white spots, especially in the thickness of the base.

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

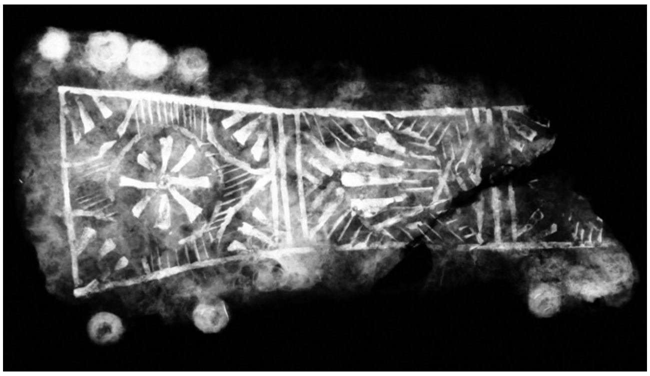

Figure 40: X-radiograph of a Roman dagger sheath plate made of iron and decorated with tin (which shows as brighter lines). The round rivet heads are also tinned. Both metals are totally mineralized but X-radiography provides a simple and non-destructive method of investigation. Length 105mm.

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).

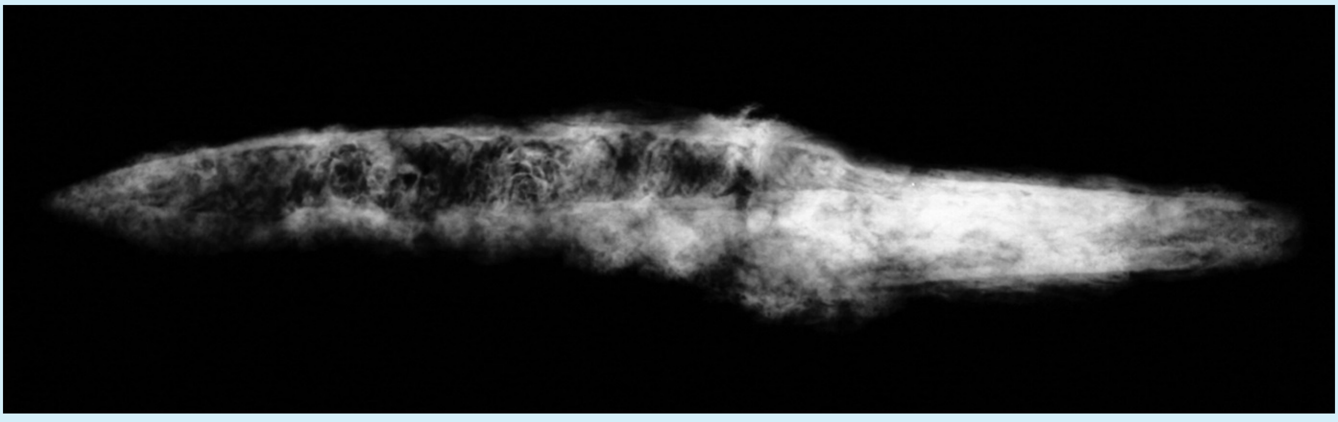

Figure 41: X-radiograph of early-medieval knife with pattern-welding visible in the back of the blade. Length 178mm.

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.

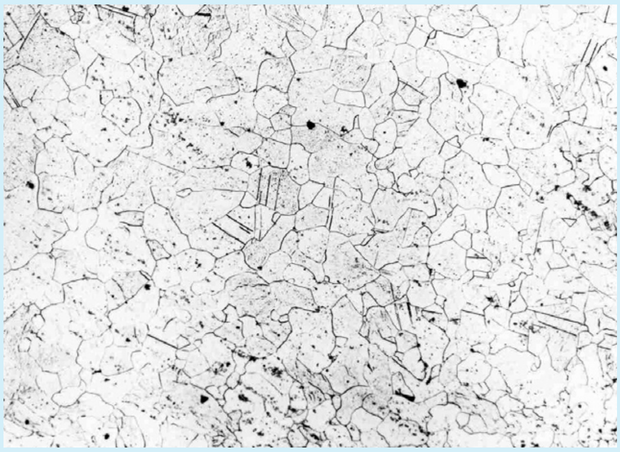

Figure 43: Micrograph of pure ferritic iron. Image width 1mm.

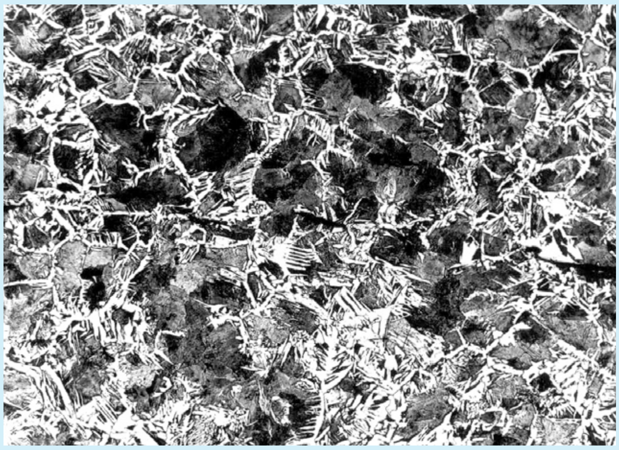

Figure 44: Micrograph of unhardened steel containing 0.7% carbon. Image width 1mm.

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-

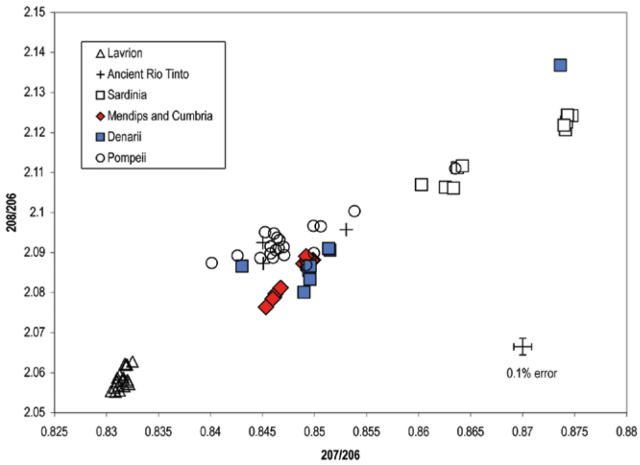

Figure 47: Lead-isotope plot of data from Mendip lead (red lozenges) and Roman silver denarii (blue squares) superimposed on data from other ore fields.

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.