Historic England

Science for Historic Industries

Guidelines for the Investigation of 17th- to 19th-century Industries

Summary

This guidance is intended to aid archaeologists working on sites of historic industries. For the purpose of this guidance 'industries' are non-domestic manufacturing activities (but not the production of foodstuffs) and 'historic' covers the period from the early 17th century to the late 19th century. The advice demonstrates the additional information that can be obtained by applying scientific techniques. Some of the issues explored are particularly relevant to urban sites, but the principles have wider application. Despite the crucial contribution that scientific techniques can make to archaeology, their application to the post-medieval and later periods has been rare (Crossley 1998). This guidance describes some of the techniques that are commonly used and include examples of the ways in which they have been, or could be, applied to the archaeological remains of historic industries.

This is one of four Historic England publications concerning materials science and industrial processes:

- *Archaeometallurgy*
- *Archaeological Evidence for Glassworking*
- *Archaeological and Historic Pottery Production Sites*

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Front cover:
Late 19th-century detached boiler house at Murray's Mills, Manchester, with circular foundation of a stair tower and the edge of a canal basin at the top.

Contents

Introduction

'The surface of the earth is covered and loaded with its own entrails, which afford employment and livelihood for thousands of the human race.'
The Autobiography of John Britton (Britton 1850)

Figure 1
Early stages of the excavation on the Riverside Exchange site in central Sheffield. The scale of many sites of historic industries can be daunting.

This advice is provided for curators (eg local authority archaeological officers and historic buildings officers) who advise on planning and listed buildings applications and write briefs for archaeological investigations, as well as for contractors who undertake such archaeological recording. The advice should be useful for anyone involved with the archaeology of post-medieval industrial sites.

This document is a response to the increasing pace of redevelopment of urban industrial sites in recent years (Fig 1). The large numbers of new houses being built in urban areas (DETR 2000) are frequently on the sites of historic industries (often referred to as 'brownfield' sites). Until relatively recently the post-medieval stratigraphy of urban sites was often removed before archaeologists began their work (eg Barker 1982, 128).

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The archaeological recording of such sites is now, however, increasingly accommodated through the planning process owing to a greater awareness of the importance of Britain's industrial heritage (eg Gould 2015; Symonds 2006).

When assessing whether a particular industry is likely to be present, account should be taken of the regional nature of many historic industries. Many early industries were located in rural locations where raw materials and sources of fuel and water power were abundant. Many secondary industries were located in urban centres where there was a sufficient market.

Starting in the 16th century, most industries succeeded in changing from wood (or charcoal) as a fuel to coal. The switch to coal forced many of the rural industries (eg iron and glass) to move from traditional wooded areas (eg the Weald) to the coalfields. Starting in the 18th century, industries increasingly made use of steam power to drive machinery, which allowed some industries to move away from traditional river valley locations. The development of transport networks (especially canal and rail) allowed industries to move even further afield. By the end of the 19th century some industries were beginning to move to coastal sites to enable easy access to international raw materials and markets.

Many industries also developed associations with specific locations. Parts of the West Midlands developed a reputation for producing high-quality puddled wrought iron and had a major share of the national industry. The flat glass industry flourished in Newcastle upon Tyne, in part because it had excellent trade links with London, the principal market for window glass. For transportation there, the uncut crown glass disks were often set into the cargo of small ships carrying coal.

Figure 2
A mechanical excavator clearing material from the site of the boiler house at Murrays' Mills, Ancoats, Manchester. The excavation of many urban sites offers an extreme contrast with most rural sites.

Archaeological approaches to historic industries

The sites of historic industries frequently differ from conventional archaeological sites (Fig 2; Symonds 2001) in terms of their scale (see section 1.2), formation processes (see section 1.3), standing buildings and contamination (see section 1.4). These sites often yield large quantities of material deriving from the historic industry, which can be divided into raw materials (eg ore, sand, limestone), tools (eg furnaces, crucibles, tongs, rakes) and waste materials (eg slag, sandever, 'soaper's waste'). Such materials are here referred to collectively as 'process residues'. Most sites yield a high proportion of waste materials and it can be difficult to identify raw materials or tools successfully. The scale of many historic industries can make it difficult to decide how much process residue should be retained for further study, in particular for scientific analysis (see section 1.7).

Archaeologists working on sites of historic industries have developed methods for overcoming some of the problems outlined above (Fig 2). In general, archaeologists are using methods from several different disciplines, including traditional archaeological fieldwork (Barker 1982; Cranstone 1992; Roskams 2001), standing buildings recording (Historic England 2016b), post-medieval archaeology (Crossley 1990), industrial archaeology (Cossons 2000; Palmer and Neaverson 1998) and archaeological science (Bayley and Crossley 2004; Bayley and Williams 2005). Elements of each of these disciplines have contributed to form the current range of methods employed (Cranstone 2004).

Doesn't history tell us everything we need to know?

Documentary sources for industries over this period frequently survive and are an invaluable source of information (see section 3). It is often difficult to make sense of the remains of an industry until it is placed in its historical context. Nevertheless, documentary sources sometimes omit or simplify details, sometimes to keep industrial secrets from competitors or because the writer did not fully understand the industry. Conversely, those writers that were very familiar with the industry often omitted details that they considered unimportant, or failed to include routine information. Unsuccessful experiments were almost never recorded, and many successful ones have received very limited coverage. Records for a site sometimes focus on a single process or technology and fail to mention the diversity of activities that took place. Further, 'even when industries were fully-fledged, surviving records are more concerned with money, building-plans or specifications of large pieces of equipment than with day-to-day details of people and processes' (Payne 2004).

The importance of science in understanding the industrial past

Scientific techniques (Brothwell and Pollard 2001; Pollard *et al* 2006) are routinely used to improve our knowledge of the prehistoric, Roman and medieval periods. They provide means of absolute dating, can help reconstruct past environments and reveal the nature of artefacts and how they were made (see section 2). Historic England (formerly English Heritage) has issued guidance on the use of various scientific techniques in archaeology, including archaeometallurgy, environmental archaeology, human bones, geoarchaeology, geophysical survey and dating (English Heritage 1998, 2004, 2006, 2008a, 2008b; Fell *et al* 2006; Historic England 2015a, 2015b, 2016a, 2018a).The application of scientific techniques to the study of post-medieval and later sites is showing that information not contained in historical accounts can also be gained from these sites.

1 Fieldwork and Sampling

The recording of sites of historic industries can be undertaken for a number of reasons but the most frequent is perhaps as part of the planning process following approval for development. This process is outlined in the National Planning Policy Framework (NPPF; MHCLG 2018) and Planning Practice Guidance (MHCLG 2014). Further considerations of the significance of heritage assets and decision making when assets face change (especially from changes in land use) can be found in Historic Environment Good Practice Advice Note 2 (GPA2) on managing significance in decision-taking in the historic environment (Historic England 2015d).

1.1 Project planning

These guidelines are of relevance in understanding the potential significance of below-ground archaeological remains of historic industries. They will help in designing evaluation strategies to assess the significance of remains potentially threatened by future redevelopment proposals as-well-as guiding mitigation strategies where it has been decided the evidence does not merit in-situ preservation. The guidelines will also help in the investigation of sites for research purposes. The process of recording archaeological sites depends on careful planning and implementation, whether they are small watching briefs or more extensive excavations. A local authority will usually produce a brief for the work, contractors (archaeological units) will then respond with a written scheme of investigation (WSI), and a contractor is selected by the developer to undertake the archaeological project.

The successful management of archaeological projects relies on identifying and managing distinct stages as well as the use of suitable project teams (Historic England 2015c). The exact number (and types) of stages in an archaeological project will vary depending on the nature of the project but should include review points at the end of each stage to assess results and potential so that further resources are effectively deployed. The WSI (or project design) should identify the project team (including specialists), the risks to the project (eg land contamination) and the products to be completed (eg publication, social media reporting and archives). A significant review point occurs once the fieldwork stage has been completed and an assessment made of the records, artefacts and samples recovered. This assessment often forms the basis and justification for an updated project design for post-excavation analysis.

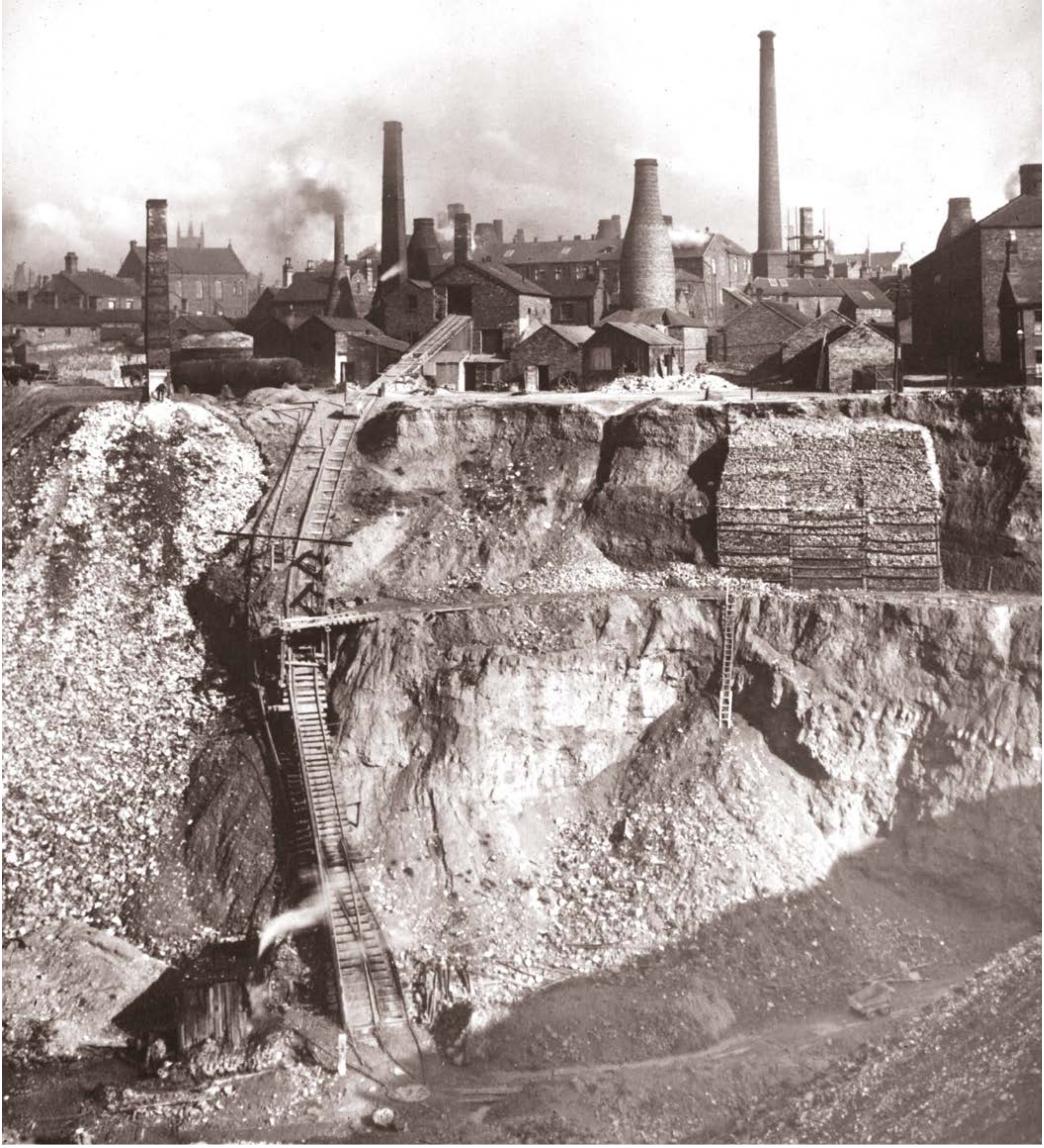

Figure 3
Daisy Bank. A marl pit in Staffordshire used to dump waste material from the pottery ovens during the 19th and 20th centuries. The scale of dumping on industrial sites can provide challenges for archaeologists.

1.2 The scale of industrial sites

The main difficulty posed by sites of historic industries is one of scale: both of the original activities and of subsequent earth moving.

Historic industries often used features and structures that were much larger than medieval and earlier counterparts (Fig 3). This can be illustrated by the changes in the furnaces used in the iron and steel industry. Late medieval furnaces were usually simple cylinders built of clay, up to 1m in diameter and probably 1–2m high. Early blast furnaces of the 16th and 17th centuries were square and were built of stone, 4–6m wide and about 6m high. By the mid-19th century, blast furnaces were again cylindrical but were up to 20m high (see Fig 16). The fact that many of these sites occupied several hectares must be considered when allocating resources and planning sampling strategies for industrial sites. It can be difficult, if not impossible, to recognise significant industrial features in a few, small evaluation trenches. The evaluation of 'greenfield' sites often uses long narrow trenches (2m by 30m) or 1m^2 test-pits (Hey and Lacey 2001). Such trenches on the site of an historic industry can easily fall wholly within a large feature and so fail to identify it.

Recent work on many industrial sites has shown that the trench size needs to reflect the scale of the archaeology (Belford 2014). Therefore, on the site of an historic industry, the trenches used for evaluation should be large. Given the size of many of these sites and the scale of the archaeological features, it is necessary to make use of machinery to excavate many deposits (Fig 4).

Figure 4
The site of the Percival, Vickers glassworks, Jersey Street, Manchester, before excavation started. The scale of many industrial sites makes the use of mechanical excavators essential.

1.3 Site formation processes

Archaeological stratigraphy is formed by the movement of soil and other sediments as features were dug and refilled. The development of canals, the steam engine and railways, however, opened up new possibilities for both the removal and dumping of enormous quantities of material. Dumping was often carried out to level a site and raise it above the water table — 'made ground' (although this term needs to be used carefully as some non-archaeological contractors use it to refer to all archaeological deposits). The 'made ground' that buries many low-lying sites in town centres often incorporates large quantities of domestic waste (as well as industrial process residues) that provides insights into everyday life (Egan 2005). Some sites were levelled by removing deposits (truncation), while on others a combination of truncation and dumping was employed.

Where later redevelopment has completely destroyed *in situ* evidence for an historic industry, information might still be obtained from process residues dumped on other sites. Process residues were often systematically removed from sites of historic industries. A typical blast furnace at the end of the 18th century produced around 2000 tonnes of cast iron a year and may have produced slag at a similar rate (depending on the quality of the ore). Many blast furnaces continued in use for decades or longer and so this slag had to be removed or reused as road metalling, 'ballast' for railway lines (eg Crossley 1995) or, if cast into blocks, as building materials (see Fig 5). In some cases waste products were dumped into the pits or quarries that had previously been used to extract raw materials (see Fig 3). There are also instances of reuse of waste materials many years after one industry ceased, such as crushing slag from old slag heaps in order to provide road-building materials (Belford 2014).

Where substantial 'made-ground' deposits are identified and assessed as of little archaeological value, however, they can be removed mechanically, thus saving scarce resources for stratified archaeological remains. This will work best when archaeologists maintain good links with others on site, eg demolition contractors.

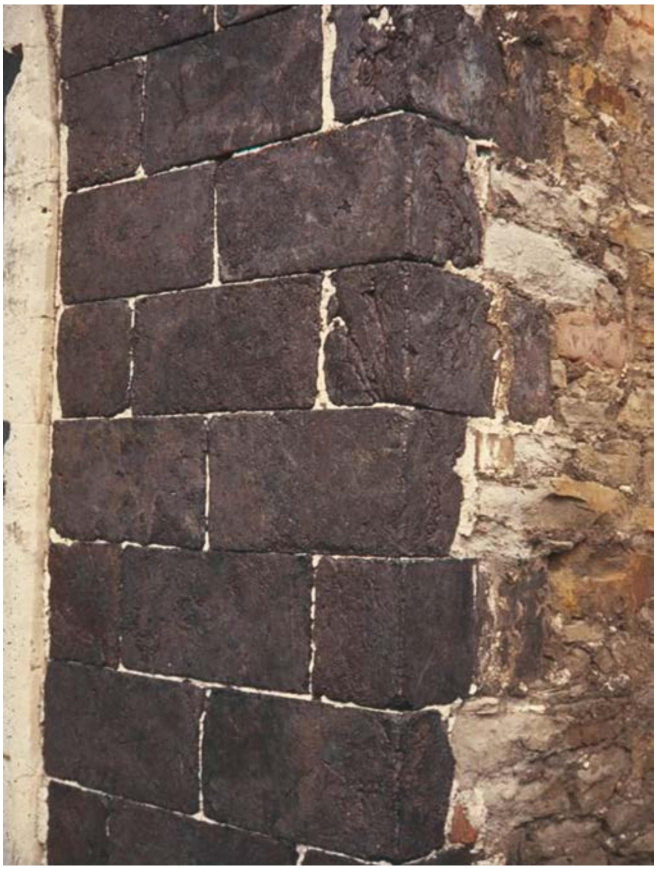

Figure 5
The large quantities of slag produced by some industries were occasionally disposed of by casting it into regular shapes for use as a building material. These slag bricks were produced by the copper smelting industry in the Bristol region.

Process residues are sometimes absent from a site because they could be reused by another industry. A good example of this is bottle glass manufacture, which initially used sand and a variety of plant ashes as raw materials (Dungworth 2012). However, cheaper ingredients were sought and, during the 18th century, glassmakers began to use waste materials from other industries, including iron-smelting slag and residues from soap and gas manufacture. In its turn, the glass industry regularly produced a waste material called sandever that was sold to brass casters for use as a flux. As a result the residues from some industrial processes are now rather rare. It is not always certain if the process residues recovered are waste by-products or raw materials. In industries using organic materials, such as textile production and tanning, some types of residue are rare because they do not survive, except in exceptional circumstances.

1.4 Contaminated land

The sites of historic industries may be contaminated (Environment Agency 2005; Historic England 2017) and excavation can pose significant health risks. Contamination was often generated on site as a waste material during periods when environmental controls were absent or less rigorous than today. Such contamination often requires remediation before the land can be used for development; however, this contamination is also direct evidence for an historic industry. Contamination can take many forms, but the two commonest types are heavy metals and organic compounds.

Before working on potentially contaminated sites, it is essential that archaeologists seek professional advice on the risks involved and appropriate mitigation strategies. Desk-based assessments should identify the industries that were present on site, and so indicate the forms of contamination that potentially might be present. Useful information can also be obtained through liaison with local authority contaminated land teams and relevant contractors, for example geotechnical contractors undertaking a borehole survey. Scientific analysis (see section 2) can characterise any on-site contamination, provide information about past industrial activities at the site and establish the existence of regional palaeoenvironmental data that can provide useful information on the local environmental impact of the industry.

The information on the nature and severity of contamination should be used to compile a site-specific risk assessment of the potential risk to the health and safety of site personnel before any site work is undertaken (Historic England 2017).

1.5 Historical sources

The study of sites of historical industries can frequently benefit from non-archaeological sources of information (see section 3). The archaeological excavation of relatively recent industrial sites can often yield rather limited information without reference to contemporary documents (Belford 2014; Reeves 2011). Archaeological and historical sources are also open to different interpretation, such as the function of the furnace excavated at the Swalwell ironworks (Cranstone 2011; Mackenzie in Proctor 2011).

Where detailed maps exist for a site (see section 3.1) these should be exploited to help interpret archaeological features and structures. Archaeological features can be recorded digitally using electromagnetic distance measurements (EDMs) and the plans superimposed on historic maps using computer-aided design (CAD) or a geographical information system (GIS). While this approach has been used to interpret features at a post-excavation stage (eg Krupa and Heawood 2002) it is increasingly being applied during fieldwork. The use of GIS allows the application of a wide range of spatial analysis techniques to the sampling strategy. GIS can also be used during post-excavation analysis to examine spatial patterns in data from the scientific analysis of samples.

The excavation of sites that have been abandoned, or that have undergone change of use only recently, can be facilitated by referring to oral history records (Badcock and Malaws 2004; Belford 2010; Howarth 1977). There are also photographic (Stoyel and Williams 2001) and even film records for some industries (Linsley 2000, 123–4).

1.6 Specialists

In order to maximise the information recovered as a result of the excavation of industrial sites, the project team should include people with appropriate specialist knowledge, for example of the relevant industrial processes and technologies, particular types of find, sampling techniques and analytical methods. Such specialists can advise on the potential importance of a particular site, what features to expect, the process residues that might be found, what to sample, how much material to retain and what type of analysis is appropriate. Some prior knowledge is particularly useful in instances where the residues may not be easily discernible by eye, for example chemical traces in a tanning pit or at the site of dye works, or parasites and seeds in deposits associated with textile sites. Specialists can provide some indication of the importance of the site since, although some processes and their associated structures are well known, for certain industries and periods there are gaps in our knowledge. For example, several charcoal-fuelled blast furnaces have been excavated (eg Magilton 2003), but there are very few excavations of coke-fuelled blast furnaces, and no typical 19th-century examples have survived as upstanding remains (Gale 1969).

Generally, it benefits all parties if specialists visit the site during the excavation. These visits provide an opportunity to discuss possible industrial uses for features, identify typical finds and review the sampling strategy, depending on what has been recovered. Some specialists will want to take their own samples, or will be able to carry out analyses on site, for example using portable geochemical testing or X-ray fluorescence (XRF) equipment (see sections 2.5.2 and 2.5.4). Many specialists can provide training in recognising and interpreting industrial residues and artefacts and have access to collections of reference material from different industries. When visits are not possible, specialists will need a detailed record of where samples have been taken from, including photographs and plans.

1.7 Sampling

Before excavation commences, a strategy should be devised that considers how the different types of evidence likely to be present will be recovered. Relevant information can be present as the remains of structures, artefacts and/or process residues (eg slag and crucibles) and deposits containing remains that are too small to be individually recognised on site (eg environmental evidence or hammerscale). A sampling strategy should aim to recover sufficient material relevant to the historic industries to answer the questions raised by the research aims identified in the project design. Sampling should be done in conjunction with appropriate specialists so that sampling for environmental remains, process residues and artefacts can be integrated (English Heritage 2011a; Historic England 2015a, 2016b, 2018a).

Material should be retained from each spatially and chronologically distinct deposit to ensure that any chronological or spatial changes in the use of the site can be investigated. The fills of flues, water courses, ditches, pits, destruction layers and made ground, are likely to contain the bulk of the material discarded on site (eg Proctor 2011; Reeves 2011). As some industries will have disposed of the bulk of their process residues off-site, made ground can often be a useful (and even the only) source of diagnostic waste materials. Some features may be more important than others, for example the fill of a tanning pit where anoxic conditions have resulted in the survival of remains that are normally susceptible to decay, a discrete dump of mould fragments in the corner of a foundry, or a well-preserved workshop floor (Smith and Trevarthen 2010; Trevarthen 2009). In addition, a specialist may require samples to be taken at regular intervals (eg a grid pattern to look at the spatial distribution of material, such as hammerscale; Historic England 2015a).

A rapid visual examination (of a proportion if there are tonnes of waste) should be sufficient to determine how many different types of material are present in a particular deposit, and then a sample of each can be retained. This will ensure that the overall sample is representative of that deposit. The amount retained should be sufficient for any analysis required (and leave material to be archived) and must include examples that show distinctive and diagnostic features, such as details and marks, dimensions, fabrics and forms.

It is not necessarily appropriate or possible to retain all of the industrial residues from a context, and the amount that needs to be retained is best decided by the relevant specialist(s). The quantities of material to be retained will vary greatly depending on factors such as the type and scale of deposit, its relationship with the industry, the current state of knowledge of that industry and the analysis planned. Where doubt exists, and only small quantities of a process residue are present, all of the material should be kept. However, where large quantities of material are present (more than 1 tonne), it is likely that it will only be possible to retain a proportion. It is essential that a record is made of the amount of material that is discarded, and also useful to roughly estimate and record the relative amounts of different types of residue. Once post-excavation assessment and/or analysis have taken place, an informed decision can be made about how much material to retain for the archive.

Consideration should be given to how artefacts and samples are processed, so that important information is not lost, for example the washing of industrial vessels containing residues will be inappropriate if they are soluble — if in doubt consult the relevant specialist(s). The need for risk assessments does not end with the completion of the fieldwork phase of a project; risk assessments should also be carried out for post-excavation examination of recovered process residues.

2 Scientific Analysis

The historic archive (see section 3) can provide useful information for the investigation of historic industrial sites (such as the date and layout of the site, the raw materials used and the industrial processes carried out), but important details may be lacking (see Introduction); scientific analysis can often fill these gaps. A variety of techniques has been applied to archaeological problems, including locating sites, dating, reconstructing environments, identifying raw materials and understanding how artefacts were made. Sediments, materials and residues adhering to features or artefacts can be sampled for scientific analysis. This section includes brief summaries of the scientific methods commonly used to address these problems.

The single most important issue when considering whether or not to use scientific techniques is the nature of the archaeological question (see section 1). Limited resources should be used to undertake the most appropriate scientific analysis with the best prospect of succeeding. The relevant specialist(s) will choose the appropriate scientific technique based on the archaeological question(s) and nature of the material to be analysed. Important factors include the type, size, number and heterogeneity of the objects or samples; whether it is acceptable for objects to be sampled or for samples to be destroyed; whether the technique can be used on site; and the speed and the cost. Analytical methods will vary in terms of their sensitivity for different elements and the accuracy, reproducibility and presentation of the results. Expert interpretation of the analyses is essential.

The finds and samples from historic industrial sites will include a range of materials, and advice on sampling (see section 1.7), assessing, analysing and reporting on these is also available in the Historic England guidelines series (English Heritage 1998, 2004, 2011a; Historic England 2015a, 2015b).

2.1 Locating historic industrial activities

Geophysical survey is a well-established technique for the exploration of archaeological remains on rural sites, but it has rarely been applied successfully to urban sites owing to the depth and complexity of the stratigraphy, and interference from metallic objects, services and adjacent structures. Nevertheless, under favourable conditions geophysical survey can provide useful indications about the nature and location of subsurface features relating to historic industries (English Heritage 2008a; Gaffney and Gater 2003).

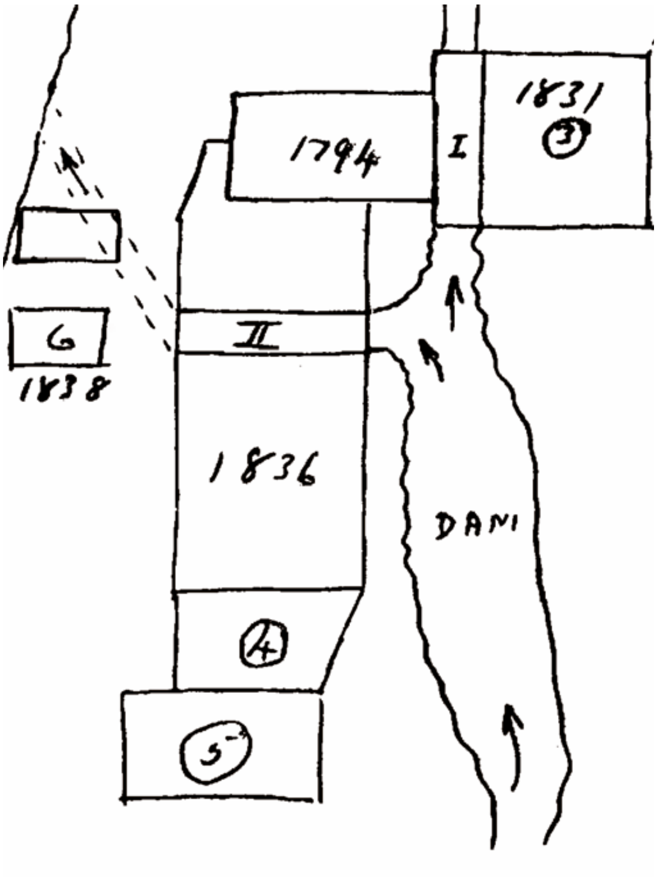

Figure 6
1838 map of Grove Mills, Keighley, West Yorkshire. All of these buildings have been demolished but could be detected using ground penetrating radar (see Fig 7).

The use of earth resistance survey is difficult on most urban sites, as the ground cover (such as tarmac or rubble) usually prevents the insertion of the electrodes. Electromagnetic surveys can work well in detecting large features or those with significant contrasts between their conductivity or magnetic susceptibility and the surrounding deposit; however, these instruments are affected by the presence of extraneous metal structures.

The performance of magnetometers is variable: in some cases the response can be related to historically known industrial structures but in other cases the significant anomalies are obscured. Fluxgate gradiometers measure variations in the Earth's local magnetic field and are strongly influenced by the presence of iron objects. Historic industry sites frequently contain large numbers of iron objects that can mask the presence of archaeologically significant features. Some urban sites also contain very large iron objects, which can produce extreme anomalies that extend across the entire site. Nevertheless, where anomalies are produced by large iron objects that are *in situ* remains (such as machine bases and frames for buildings), a low sensitivity fluxgate gradiometer survey can show the extent and location of such features.

Ground-penetrating radar (GPR) survey has been applied to urban archaeology using individual transects and can image targets through a variety of surface layers, such as asphalt or concrete (Reynolds 1996). A better approach is the collection of data in closely spaced, parallel transects (certainly no coarser than 0.5m, for a sampling interval of 0.1m), from which a three-dimensional block of data can be compiled. This can then be used to create amplitude 'time slices' (Figs 6 and 7) which provide a series of horizontal plans mapping the strength of GPR reflectors at a particular depth (eg Conyers 2004). The signal from GPR will be heavily attenuated in high conductivity soils or by the presence of ferrous reinforcement bars within concrete, which may limit its application on some sites.

Filters are used to process the geophysical survey data from archaeological sites and may suppress unwanted signals, such as large-scale trends due to geology or small-scale anomalies, especially those produced by near-surface iron objects. Data from sites of historical industries, however, often require extensive processing and this may also remove archaeologically significant anomalies as well as the unwanted signals.

In contrast to geophysical survey, geochemical survey, which identifies and maps the distribution of elements or compounds, is at present not much used in archaeology. There is, however, potential for its application to sites of historic industries, for example to locate activities by detecting increased levels of chemicals associated with that activity. In most cases, samples of soil are taken for later analysis in a laboratory (Wild and Eastwood 1992), but recent improvements in the accuracy and robustness of portable instruments now enables on-site analysis of soils for some elements with portable XRF (see section 2.5.4).

The most useful elements in such situations are ones that can be associated with particular historic industries (these will vary from industry to industry, and chronologically). Geochemical survey and testing has been most widely applied to metals industries. However, there has been some successful application of geochemical testing to the textile (Russell 2001) and tanning industries (Shaw 1996), primarily to understand the function of excavated features.

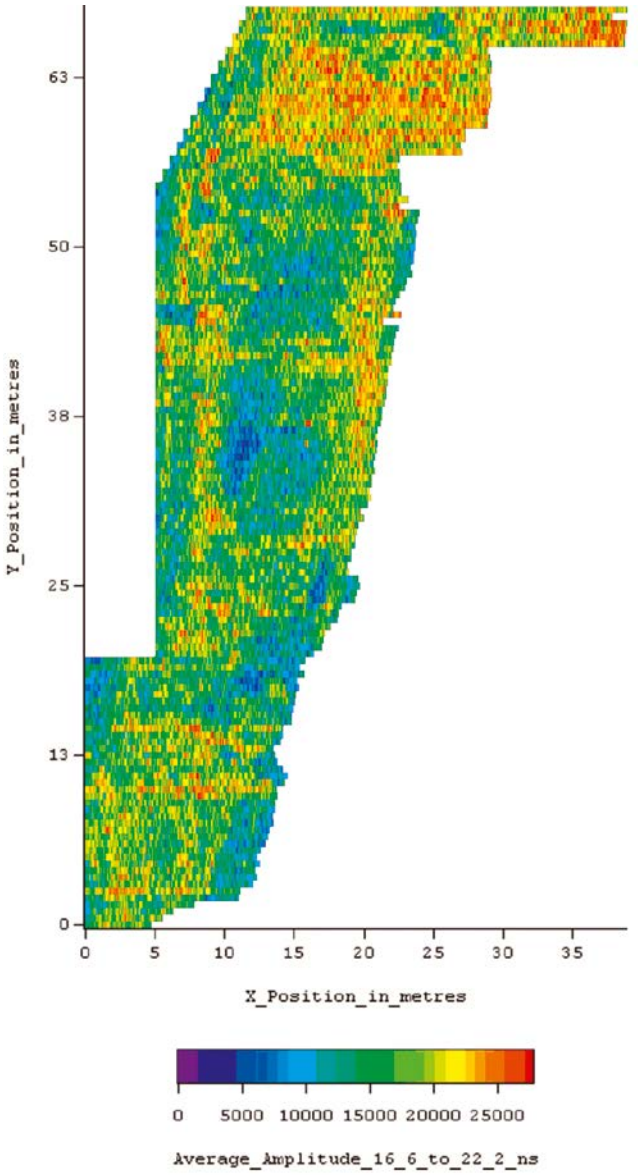

Figure 7
Grove Mills, Keighley, West Yorkshire, ground-penetrating radar (GPR) time slice (Hamilton 2002), showing the 1794 and 1836 buildings recorded on the historic plan (see Fig 6).

2.2 Dating historic industries

It is often possible to obtain very precise dating for sites of historic industries from documentary sources (see section 3) or from excavated artefactual evidence (domestic pottery, clay pipes, etc). In some cases, however, scientific techniques may offer the only way of dating a site, feature or artefact. The most widely used scientific dating technique in archaeology as a whole is radiocarbon dating, but this is of limited use for the period 1650–1950, as there is a plateau in the calibration curve (Stuiver and Pearson 1986), and so errors are generally larger than can be obtained from archaeomagnetic or thermoluminescence dating (Aitken 1990).

Directional archaeomagnetic dating can date *in-situ* fired features (typically composed of baked clay or stone) that have acquired a thermoremnant magnetisation (Aitken 1990; English Heritage 2006). The technique is at its most precise for the post-medieval period, as direct observations of variations in the direction of the Earth’s magnetic field have been made in Britain since 1650. Furthermore, the change in field direction has been rapid throughout this period. Hence, it is often possible to date the last firing of features at 95% confidence to within 35–50 years, and possibly to about 20 years for dates after 1700 (eg Linford 2016). Unfortunately, it is often not possible to date iron-working features because iron metal or iron-rich slag become strongly magnetised as they cool. Any parts of the structure cooling in the vicinity will become magnetised in the direction of this strong local field rather than in the direction of the Earth’s field.

Ceramic structures and artefacts can also be dated using thermoluminescence (TL), which is not limited to *in-situ* fired features (Aitken 1990). TL has great potential for dating artefacts or features of historic industries, as the errors are a percentage (typically ±8–10%) of the central date. Thus, a TL date indicating that a sample is 200 years old gives an error of ±20 years. However, moisture content and burial history, which vary from site to site, can have a strong influence on both the central value and the error.

Dendrochronology is an accurate and precise dating method for wood (English Heritage 1998), which can be used to date some industrial structures. The type and origins of the wood are important factors: in England oak is most commonly used for dating purposes, but in the post-medieval period there was a noticeable rise in the use of native hardwood species other than oak and a dramatic escalation in the use of conifer timbers, the vast majority of which are presumed to have been imported (Groves 2000). It is rarely possible to produce a long chronology for each species under consideration, but some species, such as elm, have been dated by producing a site master curve and comparing this with native oak reference chronologies (English Heritage 1998). The ability to date conifer timbers relies on the availability of reference data from the relevant source areas.

The rapid pace of technological development and changes in many materials in the 17th to 19th centuries means that knowing the chemical composition of a sample can occasionally help to date it, providing similar materials of known date have already been analysed for comparison (Bowman 1991). Sometimes the date when a particular element or compound was first isolated is known, and this provides a terminus post quem for the manufacture of this material.

2.3 Environmental impact of historic industries

'For several miles before they reached Milton, they saw a deep lead-coloured cloud hanging over the horizon in the direction in which it lay.'

North and South, Elizabeth Gaskell, 1854–5 (Gaskell 1994)

This quote provides a reminder that one of the major effects of industry on the environment is the pollution of air, earth and water, and that this pollution can spread well beyond industrial sites and affect the wider environment. When investigating industrial sites it is important to consider these effects at both a landscape and a local scale. Contaminated ground reflects local pollution of the soil, but increased concentrations of heavy metals are also found in sediments bordering industrial sites as a result of airborne pollution (Mighall *et al* 2004). This evidence, along with the presence of microscopic charcoal, spherical carbonaceous particles (SCPs) and different types of fly ash (eg inorganic ash spheres – IAS), in such sediments will reflect the location, type and intensity of industrial activity (Smol 2002). SCPs, in particular, are associated with the use of coal, and their appearance in a palaeoenvironmental sequence is often taken as marking the onset of the industrial age (Renberg and Wik 1985).

Studying pollen assemblages from the levels where SCPs first appear gives an immediate insight into how vegetation cover was affected, especially as regards the extent of woodland. While in some cases decline in woodland cover is seen (Mighall *et al* 2004), it is argued that industrial use of woodland led to careful management and conservation (see Fig 15) rather than destruction (Rackham 2003). Here, one of the problems may be that the effects of pollution causing vegetation to die out are difficult to distinguish from exploitation for fuel.

Heavy metal pollution is also seen in river sediments. Lead levels in dated flood sediments in York have been shown to relate to lead working in the Yorkshire dales (Hudson-Edwards *et al* 1999), while increased levels of lead, arsenic, zinc and copper in a palaeochannel at Sexton, Dartmoor, against a background of tin contamination, are thought to reflect the exploitation of silver-lead lodes at Loddiswell mine in the mid-19th century (Thorndycraft *et al* 2003).

Processing of textiles, tanning and horn working are also highly polluting of the water supply and tend to be situated downstream and on the edges of settlements. Waste from these processes leads to oxygen depletion and, if anoxic conditions are maintained, fragile biological remains will be preserved. These remains can be used not only to elucidate the types of activity that are taking place at a site but also to investigate water quality. Cladocerans (water fleas) and chironomid (non-biting midge) larvae may prove particularly useful for this purpose (Hall and Kenward 2003; Ruiz *et al*

Figure 8
The Spetchells, a dump of process residue (calcium carbonate), which has provided an isolated example of chalk downland in the North East.

2006). However, diatoms (single-celled algae) and ostracods (small crustaceans), which are found in all types of water, are particularly sensitive to changes in water quality and will survive in less favourable conditions; both deserve more attention. Sampling water features, such as drains and culverts, for these remains should help in discovering whether these features contained clean water or effluent and thus establish function and help in understanding site layout (English Heritage 2011a).

Another aspect of industry in the past was the vast consumption of raw materials. In addition to studying the types of fuel used, from sources of coal (Smith 2005) to types of charcoal (Gale 2003), studies of plant and insect remains from sites can also provide information on the sources of different components, such as raw textile materials. It has long been known that certain alien species arrived in this country with imported wool. Nearly 350 species were recorded in the early 20th century growing by the side of the river Tweed (Salisbury 1964) but as yet few archaeological deposits have been investigated for evidence of this kind.

Waste deposits represent unique environments for plants. Plants that can tolerate contamination by heavy metals are known as metallophytes and form a distinctive flora, more common in the north Pennines than anywhere else in Britain (Buchannan 1992). Typical species are alpine pennycress (*Thlaspi caerulescens*), spring sandwort (*Minuartia verna*) and thrift (*Armeria aritime*) (Lunn 2004). Coal tips can also support distinctive floras. American cudweed (*Anaphalis margaritacea*), an early New World introduction, is a common sight on Welsh coal tips, along with native colt's-foot (*Tussilago farfara*) and birch trees. One spectacular example of a waste deposit that has developed a unique flora is a 1km-long ridge known as the Spetchells, on the south side of the Tyne at Low Prudhoe, Northumberland (Fig 8). The site is a dump of calcium carbonate produced as a by-product of the synthesis of ammonium sulphate fertiliser during the Second World War. The dump was turfed over to make it less obvious to German bombers and now supports plants typical of the ungrazed chalk grassland of southern England (Lunn 2004). Again, these artificial environments, and their development, could be investigated by sampling during archaeological investigations of industrial sites.

2.4 Investigative conservation

Investigative conservation uses a range of techniques (see section 2.5) to understand how materials are preserved or altered in the burial environment. Conservators can provide advice and expertise that will ensure that the maximum information is obtained from excavated artefacts and materials. In some cases, special techniques (eg X-radiography, X-ray; Fell *et al* 2006) can be used to understand artefacts and materials that have undergone significant post-depositional alteration. In other cases, organic materials that have been preserved in anoxic burial environments require particular treatment to prevent deterioration (Historic England 2018b, 2018c). The requirement to preserve archaeological remains *in situ*, wherever possible, has led to increasing research by conservators and other scientists into the burial environment (Historic England 2016c).

2.5 Understanding historic technologies

A wide variety of scientific techniques can be used to investigate the technologies employed in historic industries. It important that the scientific techniques selected are the most appropriate to answer the archaeological questions. Common questions include the following:

- What were the industrial processes, conditions and environment?
- What materials were consumed in the process?
- Where did these materials come from?
- What products and wastes resulted?

The range of materials recovered from historic industrial sites can include raw materials, fuel, fragments of structures (eg furnaces, pit linings, cementation chests), industrial ceramics (eg crucibles, moulds, saggars), waste (eg slag, chemical residues) and products. Scientific techniques can help identify these materials and link them with a particular industrial process and/or environment. Occasionally they can be traced to a specific source. Even when some of the materials do not survive, they can often be inferred by analysing those products and/or by-products that do survive.

The amount of material required for scientific examination or analysis varies depending on the nature of the technique, but often this can be very small (eg <0.1g). In many cases, however, the heterogeneous nature of the materials being studied (eg slag, crucibles with adhering glass) makes larger samples advisable (eg 1–10g) in order to obtain results that are representative. The techniques described below are grouped by the method of investigation: visual inspection, low-power microscopy, high-power microscopy, elemental analysis, analysis of compounds and physical testing.

2.5.1 Visual inspection

The first stage of any scientific examination of archaeological material is its systematic visual examination and comparison with reference collections. The size, shape, colour, density, texture and other properties of materials can be assessed without the need for complex instruments (Historic England 2016a).

2.5.2 Low-power microscopy

Low-power microscopes (magnification in the range x4–x50) are frequently used to extend the range of visual examination. Low-power microscopes require no sample preparation and are used to detect finer details on the surface of objects.

2.5.3 High-power microscopy

At magnifications greater than x50, optical microscopes have a small depth of focus and so are usually used with polished specimens. These provide information about the small-scale internal structure (microstructure) of materials (Fig 9). To obtain a polished specimen it is necessary to cut a sample from the object. High-power microscopy is routinely applied to stone, ceramic and soil samples (petrography) as well as specimens of slag and metal (metallography).

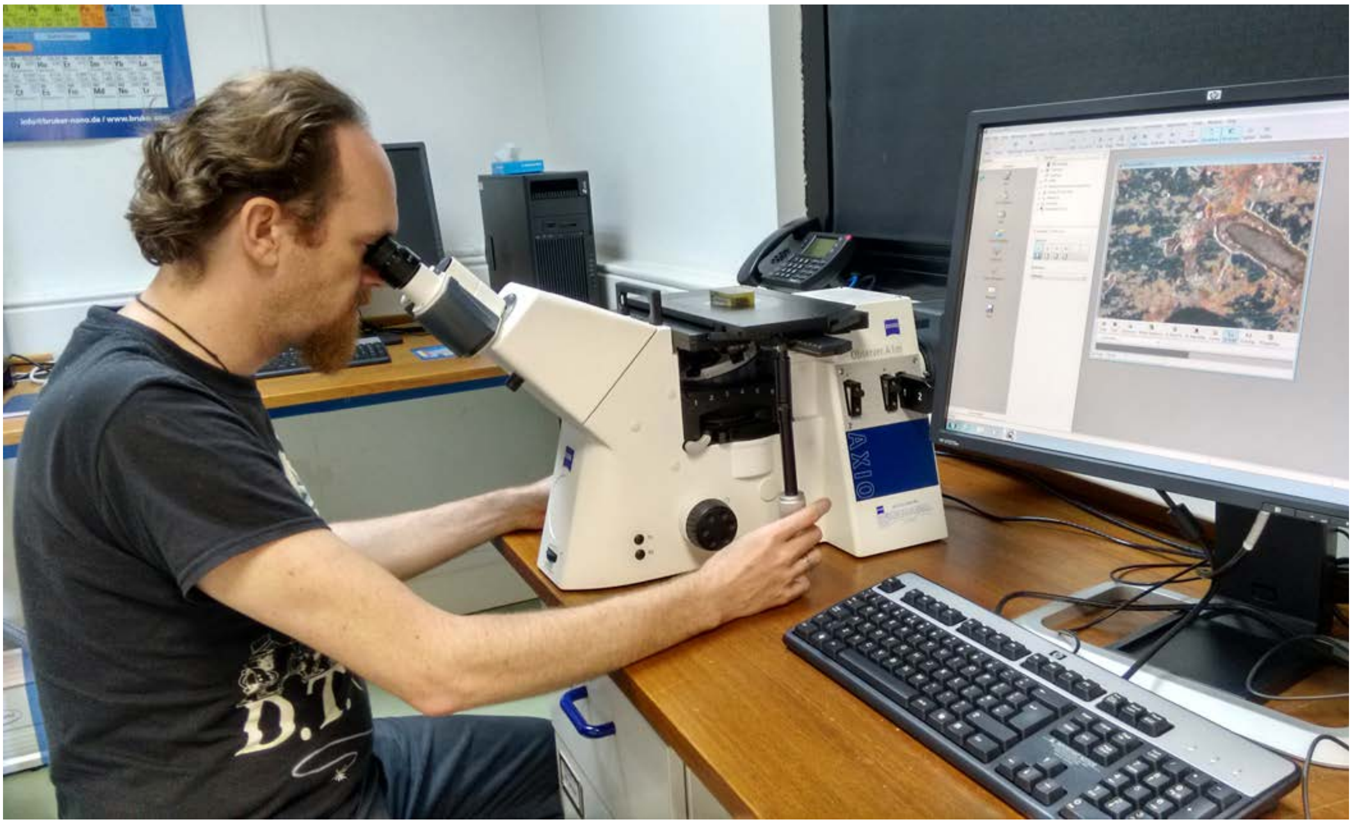

Figure 9
The high-power microscope can reveal the microstructure of many materials.

Petrography is the study of the minerals present in geological materials and ceramics. Sometimes the origins of the material can be determined by identifying the combination of minerals present. A slice from the sample is ground until it is thin enough to allow light to pass through (usually 30 microns). When these thin sections are examined using a suitable microscope, the minerals in them display optical properties that enable them to be identified. As well as being widely applied to geological materials (eg stone and coal), this technique is routinely used to study archaeological ceramics (Whitbread 2001; White 2012).

Metallography is the study of the structure of metals and slags on a microscopic scale (microstructure). The technique provides information on how the materials formed and also on the composition of alloys (Scott 1991). Samples are polished flat so that they can be examined using a high-power microscope (Fig 9). The shape of crystals in the object will show whether it has been cast or hammered into shape, and if it has been heat treated. The common alloys of iron, such as steel and cast iron, contain different levels of carbon, which are hard to differentiate with many analytical techniques but which can be easily estimated by metallographic examination (Mackenzie and Whiteman 2006). In addition, weld lines and other features associated with fabrication can be detected. The microstructure of slags can be examined in a similar way, to obtain information about the ores smelted, the metal produced and the smelting conditions used (such as furnace temperature) (Historic England 2016a; Photos-Jones 2008).

When a specimen has been prepared for metallographic examination, the same sample can then be hardness tested. A small, pyramid-shaped diamond is pressed into the sample surface and the hardness is calculated from the width of the impression. Hardness testing can reveal how an object has been fabricated and can help distinguish different iron alloys.

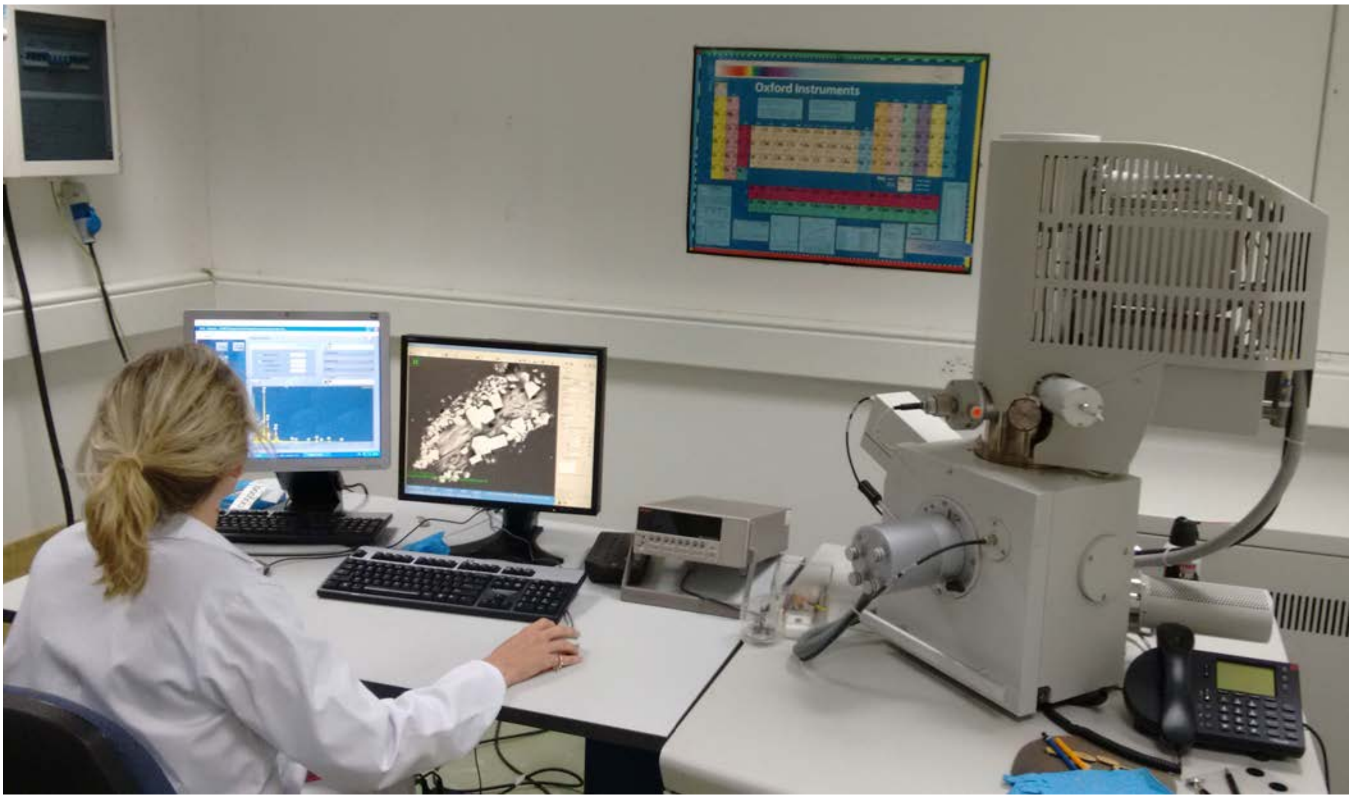

Figure 10
The scanning electron microscope (SEM) is a versatile tool for examining both the surface topography and microstructure of archaeological materials.

The scanning electron microscope (SEM; Fig 10) can be used to form images at much higher magnifications (up to x50,000) than can be achieved with an optical microscope, and has a superior depth of focus (José-Yacamán and Ascencio 2000). SEMs can provide many different sorts of images: the two commonest are secondary electron and back-scattered electron images. Secondary electron images provide a detailed picture of the surface topography of a sample and are widely applied to the recognition of a range of materials, but especially to organic ones (eg plant macrofossils, pollen, bone, shell, wood and mineral-preserved organics). Back-scattered electron images are used to look at the microstructure of a material and to obtain some chemical information. Inorganic materials (eg slags, ores, metals, glasses and ceramics) are often examined in this way. When an X-ray spectrometer (see section 2.5.4) is attached to an SEM, selected areas of a polished sample can also be analysed. Overall, SEM, combined with X-ray spectrometry, is one of the most useful analytical tools for archaeological materials. It allows the determination of chemical composition, but this can always be related back to aspects of the microstructure, which is particularly useful for heterogeneous or composite materials (Dungworth 2008).

2.5.4 Elemental analysis

The goal of elemental analysis is to determine the proportion of different elements present in a material, and it is generally used for characterising inorganic materials (eg metals, glasses and ceramics). As organic materials are mostly made of carbon, hydrogen, oxygen and nitrogen in proportions that vary only a little, elemental analysis is of little value, and it is the nature of the compounds present that is important (see section 2.5.6). Many different analytical techniques have been applied to archaeological material (Pollard *et al* 2006) and only the most commonly applied techniques are described here: inductively coupled plasma mass spectroscopy (ICPMS) and different types of X-ray spectrometry.

The ICPMS heats samples in solution to extremely high temperatures to ionise the atoms in the sample. The ionised sample is then fed into a mass spectrometer, which separates the atoms based on their mass (using a magnetic field). Samples are destroyed by the analysis and the results are for the entire sample, rather than for specific parts of it. The main advantage of ICPMS is its sensitivity: most elements can be detected in parts per million, or even lower (Pollard *et al* 2006).

Another commonly used technique is X-ray spectrometry (Moens *et al* 2000; Pollard *et al* 2006). There are various types of X-ray spectrometer but in each case the sample is made to emit X-rays, and their energy and intensity are used to work out the composition of the sample (Fig 11). Some of these techniques, known as energy dispersive X-ray spectrometry (EDS), wavelength dispersive spectrometry (WDS) or electron microprobe analysis (EPMA) are used in conjunction with an electron microscope (see section 2.5.3), which allows the user to analyse small features selectively, a few microns across, or to look at changes over a larger area or along a line. Weathered areas can also be seen and avoided where necessary. Another advantage is that even unexpected elements will often be noticed. Analysis by EDS or WDS uses a sample removed from the object and polished flat. EDS is faster than WDS, whereas WDS is more sensitive (Pollard *et al* 2006).

XRF analysis is another commonly used X-ray spectrometry method. It is a very fast technique and many XRF machines are large enough to accommodate intact archaeological objects, so there is no need to damage the object by taking a sample. However, the technique only analyses the surface of the object and, if this is badly corroded or encrusted, it may be necessary to take a sample. XRF is the ideal technique for a ‘quick look’ and portable instruments (pXRF) are available that can be used on site.

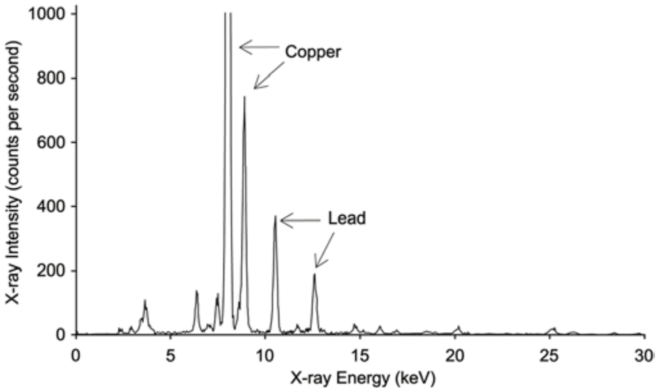

Figure 11
X-ray fluorescence (XRF) spectrum: the position of the peaks indicates which elements are present, and the height of a peak indicates the abundance of that element.

2.5.5 Isotope analysis

The analysis of samples to determine the proportions of different isotopes of the same element can be used to understand the origins of specific raw materials. ICPMS (see section 2.5.4) can be used to determine isotopic ratios (although thermal ionisation mass spectrometry is also used). The determination of lead isotopes is frequently undertaken to investigate the origin of metallic ores but has also been applied to post-medieval glazed ceramics (Marzo *et al* 2009). The proportions of strontium isotopes can also shed light on the nature of plant ashes used in the post-medieval glass industry (Dungworth *et al* 2009).

2.5.6 Identifying compounds

Many analytical methods will measure the amounts of different elements present in a sample (see section 2.5.4), but this is not always enough to identify a material conclusively. For example, shell and limestone are chemically the same (calcium carbonate), but the atoms are arranged differently in each. It would be difficult to tell the materials apart using elemental analysis. Some techniques, however, such as chromatography, Fourier transform infra-red (FTIR) spectroscopy, Raman spectroscopy and X-ray diffraction (XRD), provide information on the way atoms are arranged in a sample. These techniques are able to distinguish different materials, even when they are chemically similar.

Chromatography is a technique for identifying organic compounds (Pollard and Heron 1996). The sample is passed through a column as a gas (gas chromatography) or a liquid (liquid chromatography). The various components of the sample are separated because they flow through the column at different rates depending on their size; small ones more quickly than large ones. Chromatography can be used to analyse very small samples and is extremely sensitive. Gas chromatography can only be used on samples that are both thermally stable and volatile. However, liquid chromatography, and high-performance or high-pressure liquid chromatography (HPLC), can be used to analyse a wider range of materials. The chromatogram generated is compared with those of known reference materials. In addition, chromatography can be used in combination with a mass spectrometer (MS), which provides extra information to help identification (Evershed 2000; Historic England 2017). Chromatography is widely used to examine the remains of foodstuffs in pottery but has also been applied to a variety of resins, waxes, dyes and other organic compounds.

FTIR spectroscopy provides information about the chemical bonds in a sample, and their molecular environment (Bacci 2000; Cariati and Bruni 2000). Bonds between different types of atom can be distinguished because they absorb in different regions of the infra-red spectrum. Raman spectroscopy uses a laser beam, which is shone onto the sample and scattered by it. The resulting spectrum is matched against ones from reference materials. FTIR and Raman spectrometers can be combined with microscopes to analyse small samples or to target a specific area. These techniques have been applied to a range of materials, including paint binders, plastics, corrosion products and minerals.

In XRD, X-rays are passed through a sample at different angles. The intensity of the emerging X-rays varies over the angle range, and is dependent on the spacing between the atoms of the sample. The results are compared against reference XRD patterns for known materials to identify the compounds present. XRD analysis is usually carried out on a powdered material, and many machines can use very small samples. Any type of material (organic or inorganic) can be identified except non-crystalline ones, such as glass. The technique is commonly used for corrosion products, minerals, pigments, efflorescent salts and chemical residues.

2.5.7 Investigating process temperatures

Many industries use heat to transform raw materials into finished products, and there are a number of different methods for determining the temperatures achieved (Odlyha 2000). Many compounds undergo a change of phase at high temperature: XRD identification of these phases can be used to reconstruct furnace temperatures (Eramo 2005). Sometimes samples of the product itself can be tested, for example reheating a glass to see when it becomes fluid. The temperatures achieved during the production of a material can also be estimated from the composition of the material itself. Various different methods have been used, including phase diagrams and models (Ettler *et al* 2009; Young and Taylor 2015). Alternatively, replica materials can be made up and their properties measured (Cable and Smedley 1987).

There are also a number of methods for testing ceramics to see what temperatures they have been exposed to. These methods have been used for domestic pottery but can also be used for industrial ceramics, for example crucibles and furnace linings. Dilatometry measures the dimensional changes of a sample during heating and cooling: ceramics generally expand as they are reheated but start to shrink as the previous firing temperature is approached (Tite 1969). Changes to archaeological ceramics over time, however, including the absorption of water, can affect the results. The firing temperature of a ceramic material can also be estimated by looking for microscopic changes in the structure of the ceramic after it has been reheated (Tite and Maniatis 1975; Dungworth and Cromwell 2006). Samples are reheated to incrementally higher temperatures and then examined using scanning electron microscopy. The structure alters little (compared to that of the sample prior to reheating) until the original firing temperature is exceeded, at which point changes are observed.

3 Historic Archives

Historic archives can provide detailed information about the range of activities and structures that were present on a specific historic industry site. In addition, archives can provide generic information about the processes and by-products of historic industries. This section provides a guide to the most commonly found classes of archive material, and those likely to give the best yield to researchers, particularly those with little background in work on historical records.

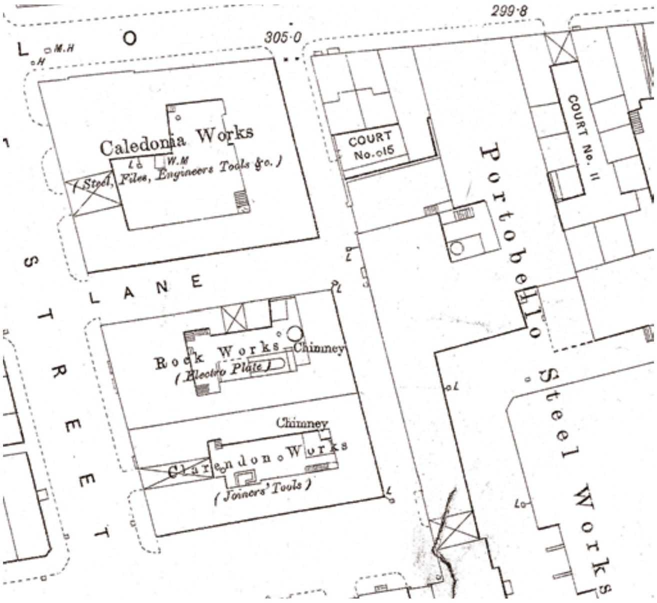

Figure 12
Late 19th-century Ordnance Survey map of part of Sheffield, with the products of some factories and workshops noted.

3.1 Maps

Cartographic evidence provides the most effective starting-point, and it is usually best to work back from modern surveys, to seek indications of phases of development that may correspond with stratigraphic and structural evidence (often referred to as 'map regression'). The Ordnance Survey (OS) 6-inch and 25-inch to the mile maps (now 1:10 000 and 1:2 500) are the essential starting point (Oliver 1993); the former appeared from the middle of the 19th century, the latter from about 1890, and both have gone through numerous editions. For the major conurbations there are also large-scale plans (1:1 056 and 1:500); the former start in the 1840s, the latter in the last quarter of the 19th century. They are valuable for the precise establishment of property boundaries and frequently indicate the uses to which land and buildings were put (Fig 12). The 1-inch:mile OS maps are useful for the first half of the 19th century, but the recording of detail is apt to be selective, and not always predictably so.

Before the 19th century, there were national or regional maps (Wallis and McConnell 1994). These start late in the 16th century with county maps of England by Saxton, followed by Speed's series early in the 17th century, and continue in the 18th century with, for example, those of Burdett for Derbyshire, Dury and Andrews for Hertfordshire, and Jefferys for Yorkshire. Detailed maps were largely made by local surveyors. Their skills developed over the 16th and 17th centuries when active land-markets made accurate recording of boundaries essential. The convention of representing buildings in bird's-eye view (Fig 13) was replaced by the measured plan, and this became standard on maps by the second quarter of the 18th century (Fig 14). The earlier convention, however, was much used for panoramas, such as those of the Bucks in their series of views of towns (eg Bristol or York). With few exceptions,

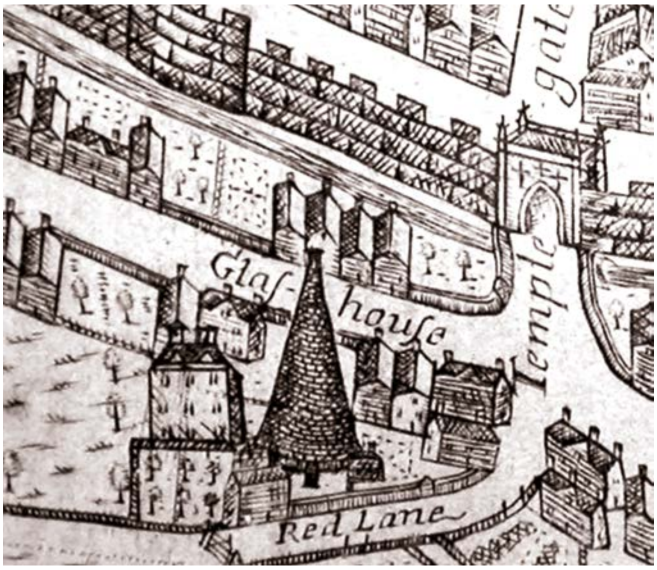

Figure 13
Bird's-eye view of Red Lane, Bristol, *circa* 1711, showing a glasshouse.

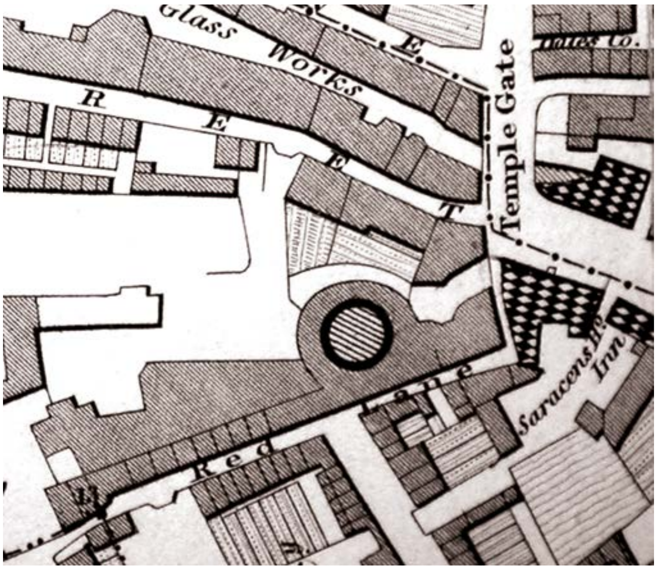

Figure 14
Plan view of Red Lane, Bristol, *circa* 1743, with the glasshouse shown as a circle.

surveyors' output is to be found in the archives of their landowner clients (Fig 15), rather than in those of the surveyor firms themselves, of which very few collections survive, examples being Fairbank for Sheffield, Bell for Tyneside or Kyle, Denniston and Frew for Glasgow (Crossley 1997). Some surveys were widely circulated, particularly if they accompanied projects such as land-enclosure, turnpike-road building or canal or railway construction, which required Parliamentary authority in the form of a private Act. Many surveyors operated a commercial side-line in combining information from their property surveys to compile town maps for sale.

There are non-OS maps and plans, made in the 19th century for specific uses, which are also worth seeking out, but whose universal compilation, or survival, cannot be assumed. Some Poor Law Unions commissioned maps of their territories, frequently emphasising properties such as mills, factories and mines, which were properties with rating potential. Fire-insurance companies required plans, and many towns were mapped for this purpose by the firm of Goad, who recorded valuable details of building-use. Goad plans continued to be produced well into the 20th century. Equally valuable are sale plans, which were commonly made by local surveyors for auctioneers.

Mining for coal and iron ore is well covered by maps produced by the pre-nationalisation companies, often going back to the 19th century. These were preserved by the former National Coal Board as a safety measure, showing where potentially hazardous workings lay, and much of this collection has been safeguarded by deposit in record offices. Particularly important are Abandonment Plans, which from 1872 were required to be made and deposited under Home Office legislation when workings were closed down.

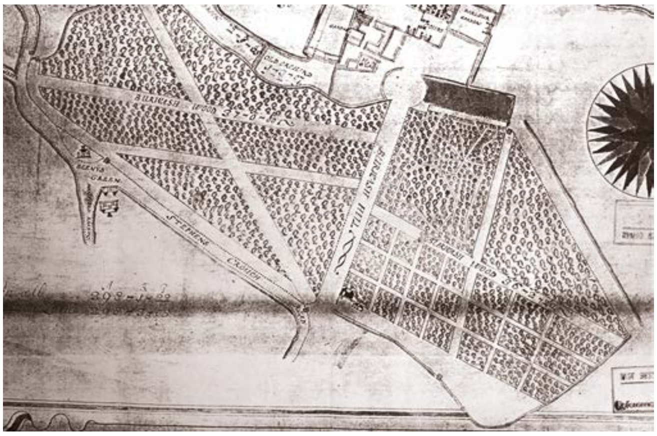

Figure 15
Survey of woods, 1717, on the Ashburnham Estate, East Sussex, showing coppices divided into plots (lower right-hand corner) for rotational cutting of wood, for charcoal supplied to the local iron industry.

3.2 Public records

Public bodies, especially local and national government, have made numerous records that contain information relevant to understanding historic industries, including rate books, bye-laws, and parliamentary records. Local rates were paid for maintenance of the parish facilities; originally just the church but from the 17th century onwards the rates were used to support the local poor and maintain roads. Rate books, which survive to a varying extent for many urban areas, comprise assessments of property values on which rates were charged to cover growing municipal commitments. Their detail is variable, some assessors being meticulous in recording the purposes to which buildings were put, for example showing power generated by steam engines or by the fall of water over mill-wheels. Bye-laws concerning building standards go back as far as London's Great Fire of 1666, but were commonly introduced over the middle quarters of the 19th century. Survival of related material is variable but, at best, plans and structural descriptions can be found.

The records of central government can provide information about historic industries, especially from the early 19th century onwards. Private Acts of Parliament often dealt with land enclosures, road, canal and railway building and reservoirs for municipal water supply. The proceedings themselves include material such as maps and surveys, and also descriptions of works and, in particular, petitions for and against such schemes and their proposed routes, which include contextual information, such as the industries that would be served. In some cases, opposition was considerable over long periods, for example by mill owners against reservoir schemes. Royal Commissions reported on numerous relevant topics, such as the health of towns or children's employment. For example, the enquiry into the 'Sheffield Outrages' of 1867 contains witnesses' statements that shed light on local industries and their processes, particularly where these were injurious to health. The Royal Commission on the Board of Excise reported on the state of a number of industries, including the glass industry in 1833 (Brown 1980).

3.3 Private records

The survival and availability of archive material from private records is unpredictable, although, at its best, rewarding. When assessing an archive collection in a record office, the quality of cataloguing is all-important. The Access to Archives project (www.a2a.org.uk) provides on-line searching of more than 300 archive repositories in the United Kingdom, as well as those of the National Archives.

Directly managed industry was rare on great landed estates after the middle of the 18th century. Where this was the case, however, estate accounts include material for coal mines or ironworks along with the corn mills and farms. Woodland management was apt to remain in estate hands, and long-term contracts for charcoal with neighbouring ironworks were often recorded. More usual were tenanted works, identified from lease- books and rentals. The former are important for construction, where the landowner and tenant shared costs, sometimes by a rent reduction over an initial period. The rentals confirm identity and continuity of occupation.

During the 18th and 19th centuries, certain industries generated and preserved significant archives. The survival rate does not match papers of landed estates, where there was often a pride in the keeping of long-term records. In many industries, changes of ownership have been the occasion for wholesale destruction of papers. Many business archives have been catalogued by the National Register of Archives of the Historical Manuscripts Commission (now part of the National Archives).

3.4 Legal papers

Legal documents are particularly significant for the immediate post-medieval period. In the 16th and 17th centuries, in the absence of several key sources referred to above, court cases involving or peripheral to industrial activities can be important. Access to justice was a key policy of Tudor government, and the records of the national Equity Courts (Chancery, Requests, Star Chamber) are well preserved in the National Archives (formerly Public Record Office), although not yet fully calendared or indexed. The facts of legal cases can be valuable contributors to the history of industrial concerns, but it is among the depositions of witnesses that information can often be found, particularly where the witness digresses into the context of a dispute. At the local level, records of proceedings in Quarter sessions or magistrates' courts can be relevant, where disputes or disorder involved industries or those identified as working within them.

The study of vernacular architecture has proved the value of inventories of goods compiled to secure probate of wills. It was common in the period 1550–1750 for appraisers to list goods on a room-by-room basis, their record thus comprising an impression of houses and workshops, sometimes listing materials. Written evidence of ownership of property comes from deeds, whose survival is variable. Private deeds can contain descriptions of property, often concealed within a conventional wording. In some cases Abstracts of Title have been compiled by lawyers, listing and consolidating past changes. These are a mixed blessing for, although convenient, they have often accompanied the destruction or dispersal of original deeds, with the loss of the valuable incidental information that these can contain. Sales of lands generated significant records, whether new deeds, sale plans, or, in cases of estates where there were long-term legal restraints on disposal, private Acts of Parliament permitting this to happen.

3.5 Contemporary publications

Contemporary publications can be divided into two categories: those that provide information about a specific site and those that provide generic information about particular industries.

The investigation of a specific site can benefit from the examination of a number of local resources, such as street directories and newspapers. Street directories exist year-by-year for large towns from late in the 18th century, and in many cases the publishers included surrounding rural townships. Early directories may not be comprehensive, as there was no obligation for the occupier of property to be included. However, by the 1820s most give a complete listing of occupants and uses of urban property.

Newspapers, such as the *Penny Magazine*, occasionally contain useful information, for example descriptions of factory tours, but can be a frustrating source, as local paper collections are rarely indexed. External evidence of the date of a key event, such as the passing of a private Act of Parliament, local agitations against such schemes or bankruptcies of prominent firms, can lead to reports that include descriptions of industrial premises and activities. Advertisements and catalogues are useful for their engravings of works-views taken from firms' bill-heads, although such illustrations are not always accurate.

In the 18th century, descriptions of industry in Britain were compiled by observers from overseas. An example is Angerstein's Diary (Berg and Berg 2001), which describes numerous English industrial sites. During the 18th and 19th centuries lists of ironworks were compiled and, although not published at the time, have been reviewed (Riden 1994; Riden and Owen 1995). Forerunners were the lists of Wealden ironworks of 1574 and 1588, drawn up by Crown officers in the face of a perceived threat of illegal export of ordnance to Spain. Another national record of an industry is Houghton's list of glassworks of 1696 (Vose 1980).

Accounts of specific industries can be found in various contemporary encyclopaedias and textbooks. Particularly useful early accounts are Agricola's 16th-century *De Re Metallica* (Hoover and Hoover 1950) and Diderot's *Encyclopedia* (Gillispie 1959). Technical textbooks became increasingly popular in the 19th century, from early examples such as Rees' *Cyclopedia* of 1819–20 (Cossons 1972), and developed to rigorous descriptive works such as Percy's *Metallurgy* (1861, 1864, 1870). The dictionaries compiled by Andrew Ure (1839) and James Muspratt (1860) contain much useful information (Fig 16) and were published in such large numbers that they are both commonly available. In the 19th century technical journals became important, examples being the *Journal of the Iron and Steel Institute*, the *Proceedings of the Institute of Mechanical Engineers* and the *Journal of the Society of Chemical Industry*.

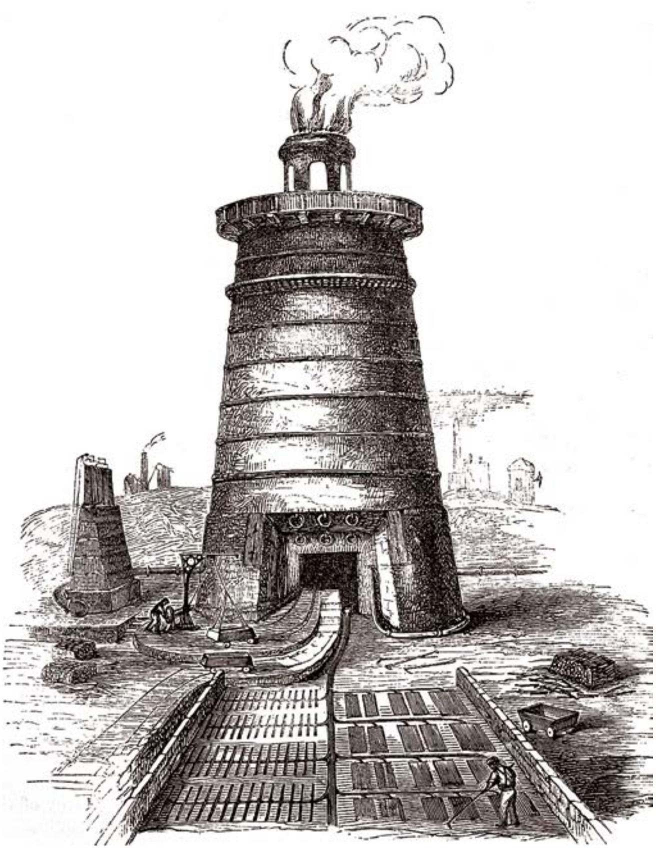

Figure 16
A mid-19th century blast furnace, from Muspratt (1860).

Figure 17
Buildings housing a cutlery grinding wheel, Endcliffe, Sheffield, by C T Dixon, 1868.

3.6 Paintings and photographs

An often-ignored source is the work of landscape artists, from the 18th century onwards (Fig 17). Paintings need to be treated carefully, as composition or convention could take precedence over strict accuracy of detail, and they should be interpreted in their historical and artistic contexts (Klingender 1972). At the very least, the inclusion of a feature, however portrayed, seen to exist at a particular time, has its value. The attraction of railways to artists is well known, from the mid-19th century paintings and engravings of newly built railways, to the portrayals by French Impressionist painters visiting England in the 1870s. Architects' drawings of such schemes are important, although use of them should include verification that buildings were finished as projected.

The more modern counterpart is the photographic collection, and the value of the widely disseminated work of commercial photographers such as Frith of Reigate, Mottershaw of Sheffield or Frank Sutcliffe of Whitby cannot be overstated. Many towns had firms whose work survives, and the recent interest in publishing selections has emphasised the value of such sources.

Case Studies

Figure CS1.1
Excavation at the Riverside Exchange, Sheffield, revealed wheel-pits and water channels. To the right is a wheel-pit; the area to the centre-left shows the remains of a grinding shop with troughs.

Case Study 1: Riverside Exchange, Sheffield

James Symonds, Anna Badcock and Roderick Mackenzie

The extensive industrial remains at the Riverside Exchange provided an important opportunity to investigate the evolution of the steel-making technology that made Sheffield one of the capitals of the steel industry. The size of the site and the scale of earth moving and deposition provided particular challenges, and the lessons learnt in solving these problems can be applied to other archaeological sites (see Fig CS1.1). The information provided by the excavation enabled some of the archaeological remains to be preserved *in situ*. Numerous artefacts were recovered that could be sampled for metallography (see section 2.5.3), whereas this is often not possible with objects in museum collections.

This four-hectare site, in the centre of Sheffield, next to the River Don, was identified for redevelopment in the early 1990s, by which time there were no visible signs of former industrial activities (Symonds 2006). There are numerous historical sources relating to the site: of particular value are the surveys undertaken by four generations of Fairbanks during the late 18th and early 19th centuries (Badcock and Crossley 2008) (see section 3.1). The water-powered town mill had been established in the 12th century, with a number of cutlery workshops set up in the post-medieval period. In the 1760s John Marshall established one of the earliest integrated steelworks, which included cementation and crucible steel furnaces. His innovative use of technology helped to establish Sheffield as a steel and cutlery making centre, and his works attracted industrial 'spies' who tried to discover the secrets of his success. The site continued to develop in the 19th century with the establishment of water-powered rolling mills. Surrounding the steelworks were numerous workshops where the knives and other items that made Sheffield steel famous were manufactured.

The archaeological evaluation of the site faced a number of difficulties related to the scale of past activities and the extensive reworking of archaeological deposits (Symonds 2001). The area identified for redevelopment was large and, like many brownfield sites, had had large quantities of mixed hardcore and domestic refuse dumped on it at various times. While, in some cases, industrial features and structures survived immediately below the modern ground surface, in others they were buried under several metres of overburden, or truncated by 20th-century foundations. A flexible approach was necessary: as demolition contractors revealed deposits they were characterised by the archaeologists, and areas of archaeological significance were targeted for detailed excavation. Owing to the scale of the industrial features, evaluation trenches could not provide sufficient information; instead, careful mechanical excavation of the upper layers identified the extent and depth of archaeological features and deposits over large areas. Greater emphasis was placed on the interpretation of deposits, features and structures as they were encountered, often with specialist input on site. The developer's building plans were not finalised until after the archaeological evaluation, so important archaeological remains could be preserved *in situ*.

The archaeological investigation uncovered the truncated remains of three cementation furnaces, one of which had only a single chest and appears to be a prototype. It is possible that this furnace is the one described and sketched by French industrialist Gabriel Jars after his 1765 visit to Sheffield. The uncovering of the prototype furnace provides an opportunity to see how steel-making technology evolved. The water channels and wheel pits across the site provided many artefacts relating to industrial activity, which were particularly useful in characterising the activities in the smaller workshops (Andrews 2015).

Many metal artefacts were recovered, including finished and unfinished fragments of cutlery. X-radiography (see section 2.4) revealed 18th-century cutlers' marks on two of the knives. The earlier of the two is a simple cross (+) and belonged to an unrecorded cutler, while the second (+L) was registered in 1750 to Joseph Antt. The similarities between the cutlers' marks suggest that Joseph Antt had been apprenticed to the earlier cutler. Metallography and hardness testing (see section 2.5.3) revealed that the blade marked '+' was made using cementation, rather than crucible, steel. The number of layers within the blade suggests that the steel used was a type known as single shear steel. The knife made by Joseph Antt was more heterogeneous, with abundant slag inclusions and variable carbon content, and was perhaps made from recycled blades. While the differences in metal quality could reflect the skill levels of the two cutlers, it is more likely that the lower quality knife was from a cheaper range, deliberately made to a price.

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Case Study 2: Upper Forge, Coalbrookdale, Shropshire

Case Study 2a: Steel production

Paul Belford, David Dungworth and
Ronald A. Ross

Excavations at Upper Forge, Coalbrookdale, aimed to investigate early cementation steel production (Belford 2003; Belford and Ross 2004, 2007). The site investigated is believed to have been Sir Basil Brooke's cementation steel furnace which operated from *c*1620 to *c*1680 (Belford and Ross 2004). The excavation recovered numerous artefacts and industrial process residues. Samples of stone from the (collapsed) furnace superstructure were examined using scanning electron microscopy-energy dispersive X-ray spectrometry (SEM-EDS), X-ray diffraction (XRD), and optical microscopy.

The surface of the sandstone has undergone partial melting; the surface shows signs of slumping (Fig CS2.1). Modelling the viscosity–temperature relationship for this vitrified layer (chemical composition determined by SEM-EDS) suggests that it would have started to soften at *c*1300°C and would have been completely molten by approximately 1450°C. This indicates a working temperature of 1300–1400°C, which is substantially higher than the 1050–1100°C reported by Barraclough (1984, 35). While a eutectoid steel (0.8wt% carbon) would not begin to melt below 1400°C, cementation could produce a steel with 1.7wt% carbon that would begin to melt at 1200°C. The discrepancy between the historically attested working temperature and the archaeological evidence may result from the fact that not all parts of the cementation steel would be at the same temperature. The contents of the cementation chests would need to be in the region of 1050–1100°C but the combustion zone in the furnace would need to be somewhat higher (due to the loss of some heat as exhaust gases). The temperature difference seen in this case might indicate a poor heat efficiency for the Upper Forge cementation steel furnace; however, there are no comparable data for later cementation steel furnaces with which this site can be compared.

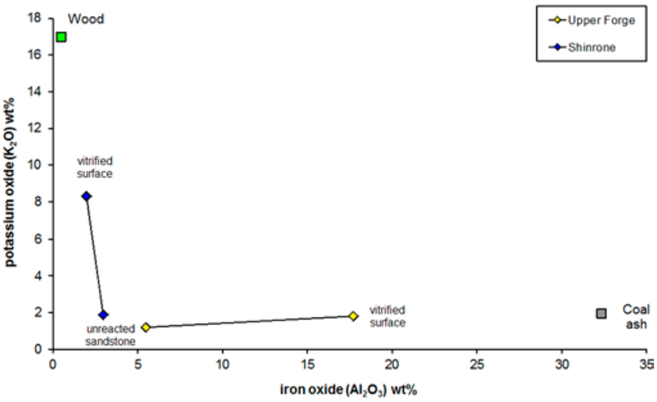

Figure CS2.1
Cementation furnace fragment showing slumping of vitrified surface.

Figure CS2.2
Iron oxide and potassium oxide composition of refractory sandstones and their vitrified surfaces from Upper Forge and Shinrone (Farrelly *et al* 2014). While the Shinrone vitrified surface formed by reactions with wood ash, the Upper Forge surface formed by reactions with coal ash.

The vitrified surface of the stone is chemically different from the core, which suggests that another material has reacted with the stone. Within solid fuel furnaces, the ash from the fuel often attacks exposed surfaces of the furnace. The chemical composition of the vitrified surfaces of furnace components can help identify the sort of fuel: wood ash is rich in calcium and potassium but coal ash is rich in aluminium and iron. The composition of the vitrified surface of the Upper Forge furnace stone shows that it was heated by coal, not wood (Fig CS2.2).

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Case Study 2b: Copper production

Paul Belford, David Dungworth, Rob Ixer and Ronald A Ross

The archaeological excavation at the Upper Forge, Coalbrookdale, Shropshire, provided the earliest evidence for the production of cementation steel in England (*see* Case Study 2a). The excavation also yielded raw materials and process residues relating to other industrial activities in the area. The evidence for copper smelting is of particular importance because there is little physical evidence nationally for this industry.

In addition to the evidence for steel cementation, the excavation at Upper Forge provided a wide range of process residues that appear to relate to other historic industries, including copper ore, copper slag, blast furnace slag and lead slag. These were mostly found in many later (18th- and 19th-century) contexts; that is, from periods when the use of the site was largely domestic. The copper ore and slag are particularly interesting as they can be linked to activities by Abraham Darby in the early 18th century. In about 1706 Abraham Darby set up a copper smelting furnace in Coalbrookdale (Trinder 2000). In 1710 Darby and partners obtained a lease from the Countess of Bridgewater to mine copper ore at Pymhill, near Clive, 10km north of Shrewsbury (Cox 1990). The copper smelting may have continued until the death of Abraham Darby in 1717. Documentary evidence (Belford 2007) suggests that the copper smelting took place in the vicinity of the Lower Furnace, approximately 400m to the north of the excavations at Upper Forge (and it is unlikely that any significant features or deposits survive *in situ*). Very few historic copper smelting sites in England have been excavated and there are almost no scientific studies of historic copper smelting residues. What little is known about copper smelting technologies is based largely on late 19th-century accounts (eg Percy 1861) and there is not much information on how these techniques might have changed over the preceding three centuries.

Figure CS2.3 (top)
Copper ore from Upper Forge, Shropshire.

Figure CS2.4 (bottom)
Copper smelting slag from Upper Forge, Shropshire.

Samples of both copper ore (Fig CS2.3) and smelting slag (Fig CS2.4) were examined using SEM-EDS (Fig CS2.5), XRD and optical microscopy. The copper ore is a sandstone (with some baryte) and cemented by chrysocolla (a hydrated copper silicate). The mineralisation is typical of that found in the Permo-Triassic rocks of central Britain (such as those just north of Shrewsbury).

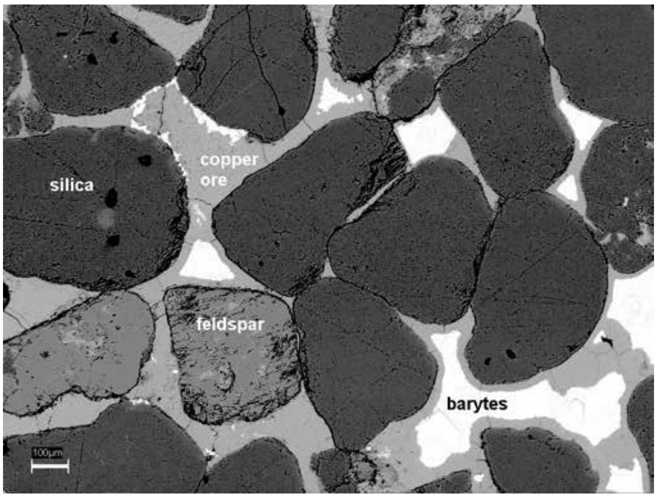

Figure CS2.5
Scanning electron microscope (SEM) image of a sample of copper ore from Upper Forge, Shropshire, showing sandstone (silica) grains (with some feldspar) cemented by chrysocolla ore and baryte (scale bar = 0.1mm).

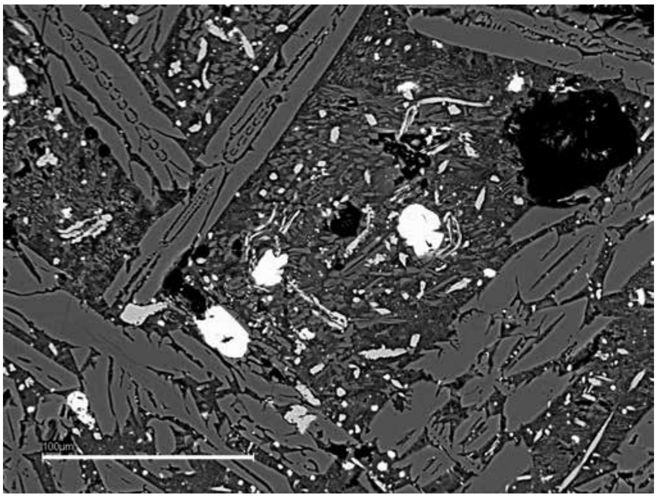

Figure CS2.6
Image of a sample of copper slag from Upper Forge, Shropshire. The bright droplets are copper sulphide and indicate that the ore was smelted using a matte process (scale bar = 0.1mm.

The examination and analysis of the slag (Fig CS2.6) confirms that it was produced by smelting copper ores. The barium content of the slag suggests that it relates to smelting the ore described above. The presence of copper sulphides, however, suggests that other ores were also used. The 'Welsh process' of copper smelting (Percy 1861) relied on mixed charges that contained copper sulphide and oxide ores. The evidence from Coalbrookdale suggests that this process was in use there in the early 18th century. Although the copper smelting evidence from the Upper Forge is not *in situ*, it provides important evidence for the industrial activities of Abraham Darby.

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Case Study 3: The Beswick pottery, Barford Street, Stoke-on-Trent

David Barker and Jonathan Goodwin

Stoke-on-Trent is famous for its pottery industry (Barker 2004) and, while some aspects have been recorded (eg Baker 1991), much more has been lost to redevelopment. Before 2002 only five 19th-century or later ovens had been excavated. Since then the increasing pace of development has led to the recording of 14 more sites (Goodwin 2005). The excavation of pottery ovens, and the 'hovels' (see below) that housed them, is providing information that is often absent from historical accounts and cannot always be obtained from intact standing structures (Fig CS3.1).

The redevelopment of an area on Barford Street covering almost 8000m^2 led to an archaeological evaluation followed by a watching brief. Throughout the 20th century the site was occupied by the Beswick pottery, which produced a range of domestic wares and ornamental ceramics, including flying ducks! Previously, the site had been used by various 19th-century pottery firms including Batkin and Deakin, Deakin and Son, and Hannah and Mary Shubotham. All of the buildings on the site had been demolished in the past but three evaluation trenches, approximately 20m^2, 200m^2 and 400m^2, respectively, located the remains of two circular pottery ovens, as well as a 20th-century tunnel kiln. In certain areas the ovens had been partially or completely truncated by 20th-century activity but sometimes floor surfaces and a few courses of brick walls survived.

The traditional, coal-fired oven consisted of a central oven proper, surrounded by a cover building known as the 'hovel', which usually had a distinctive bottle shape. The hovel helped induce a strong and even draught through the oven, necessary to achieve the temperatures required for firing the pottery. Each oven would hold thousands of pieces of pottery in saggars. At the Barford Street site, the brick floor surfaces inside the hovels survived, at least in part, and in one case four successive hovel floor surfaces had been laid one on top of the other (Fig CS3.2).

Figure CS3.1 (top)
The distinctive traditional bottle-shaped 'hovel' that housed the pottery kiln. There were perhaps 2000 pottery ovens in the 19th century but the switch from coal to smokeless fuels in the 1960s led to many being demolished, and there are now fewer than 30 left.

Figure CS3.2 (bottom)
The excavated remains of a 19th-century pottery oven at Barford Street, Stoke-on- Trent showing multiple flues round the oven and the foundations of the hovel outside.

The foundations of one of the ovens consisted of a mixture of sandy loam, pottery and saggars, seemingly a wholly unsuitable material, but this sort of foundation has been found beneath most of the pottery ovens excavated. Factory records are frustratingly vague about oven construction and operation, but a careful examination of early 20th-century written accounts suggests that the use of this material, called the 'cork', for oven foundations was a deliberate policy. The high temperatures achieved in a pottery oven could dry out the subsoil underneath the furnace, leading it to contract, and so weaken the foundations of the hovel wall and possibly causing collapse. The materials selected for the cork were intended to ensure that this did not happen. The existence of the cork would not be apparent from an examination of a standing hovel and oven; it can only be seen in excavated examples.

The hovel floor surfaces were not associated with any closely dated artefacts. The approximate date at which some of the later ovens went out of use could be estimated by reference to Ordnance Survey maps but this left many structures with rather broad date ranges for their construction and use. More precise dates could have been obtained using scientific methods, such as archaeomagnetic dating for the *in situ* fired floor surfaces and thermoluminescence dating for individual bricks (see section 2.5.2). The dating of individual floor surfaces could be refined to within a decade or so by applying Bayesian statistical methods to a series of date probability ranges from successive floors (Buck and Millard 2001). Such an approach would have provided a detailed chronology for the construction and use of the ovens and hovels that would not have been obtainable in any other way.

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Case Study 4:
Steam-powered cotton-spinning mills in Ancoats, Manchester

Ian Miller

Manchester experienced an explosion of factory building at the end of the 18th century, fuelled by a breakthrough in the application of steam power to textile-manufacturing and the cheap and reliable transport for goods offered by the construction of canals. This led to the creation of a new generation of textile mills, which were built on an unprecedented scale and employed developing techniques of structural and mechanical engineering.

Ancoats evolved as an early focus for these new mills, although the sole survivor of the initial boom in factory building is Murrays' Mills, which has been the subject of comprehensive archaeological recording. The fabric of this mill complex retains considerable evidence for all stages of its development, and analysis has provided a valuable tool for interpreting the buried remains of other mills in Ancoats. Several of these have been excavated recently, with the remains of the steam-power plants providing a focus for investigation (Fig CS4.1).

An important stage in the transition from water power to steam power involved the use of a pumping engine to furnish a waterwheel with a regular and continuous supply of water. Excavation of New Islington Mill (Fig CS4.2) revealed the key elements of this system, including a narrow waterwheel pit, stone-block foundations for a pumping engine, and a network of large culverts. Excavation also exposed the footings of an engine room that contained stone-block foundations for a beam engine, with square-section iron mounting rods typical of the early 19th century. The walls of the engine room contained sockets for the engine frame and abrasion scars, which helped to determine the size of machinery housed there.

Figure CS4.1
The late 19th-century detached boiler house at Murrays' Mills, Manchster, with the circular foundations of a stair tower to the right and the edge of the canal basin at the top of the image.

Buried remains demonstrate the evolution of power-plant structures. The first working steam engines had chimneys whose design was based on domestic houses (Douet 1991). The introduction of more powerful engines placed greater demands on the boiler's steam-raising capacity, as well as on the foundations of internal boiler houses and the very narrow flues taking irregular routes to small, square-section chimneys, which were all typical of the late 18th century. Examples of these structures exposed at Waller's Mill and Salvin's Factory were built largely from hand-moulded bricks, with only occasional use of refractory materials. The early 19th-century boiler house and flue at Moore's Mill showed the increased use of refractory bricks within its build, while the late 19th-century detached boiler house at Murrays' Mills displayed extensive use of refractory bricks, many bearing makers' stamps.

All of the excavated mills yielded large quantities of ash and clinker, which offered little potential for analysis, reflecting the lack of process residues generated from cotton-spinning. The 20th-century use of some sites created contaminated ground conditions requiring mitigation prior to excavation. Historic mapping, when integrated with digital records of the excavated features, has consistently proved crucial to the interpretation of sites. The excavations have clarified numerous aspects of the mills' development that were not clear from documentary sources, including structural details and information on power generation (eg waterwheels, boilers, engines and fuel economisers) during different phases, with implications for the machinery operating within the mill. Social contexts could be established through assemblages of stamped mineral water and botanic beer bottles, which were traced through trades' directories.

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Figure CS4.2
A general view of the engine house for the steam returning-engine at New Islington Mill, Manchester, showing (on the left, horizontal) one of the iron pipes used to carry water from the underground sump to the waterwheel (the wheel pit in the centre has been backfilled), and the vertical iron restraining rods that tied down the engine.

Case Study 5: Leadmill, Sheffield

Anna Badcock and Andrew Lines

The Leadmill site in Sheffield illustrates one of the most significant problems inherent in investigating historic industrial sites: contaminated land. As is often the case, the historic industry was the source of the contamination and the modern investigation of the site was only possible once the health and safety risks were addressed. The excavation provided tangible evidence for processes described in historical documents (Fig CS5.1) but also yielded artefacts and process residues that are not described in these sources.

From 1759 until 1903 the Leadmill site was occupied by a works producing pigments (white and red lead). Prior to this, the site was occupied by a cutler's workshop, and in the 20th century it housed a bus and tram depot. During the 19th century, white lead (a hydrated lead carbonate) and red lead (a lead oxide) were used in paints, pigments, glasses and pottery glazes. Both compounds were made from metallic lead but by very different processes. White lead was produced by arranging strips of lead over pots of vinegar, surrounded with dung or spent bark from tanning works (Campbell 1971). Over a period of weeks, the vinegar reacted with the lead to form lead acetate and this was converted to white lead by the fermentation of the organic matter (Cossons 1972). Red lead was produced by roasting metallic lead to form litharge (a lead oxide), which was then ground and roasted to red lead (Muspratt 1860; Percy 1870).

The excavation of an archaeological site that is contaminated with toxic chemicals, such as lead, poses health and safety problems. A risk assessment was carried out before fieldwork started to determine safe working procedures. In order to minimise exposure to lead, everyone working on the Leadmill site wore protective body suits, and food and drink could not be consumed

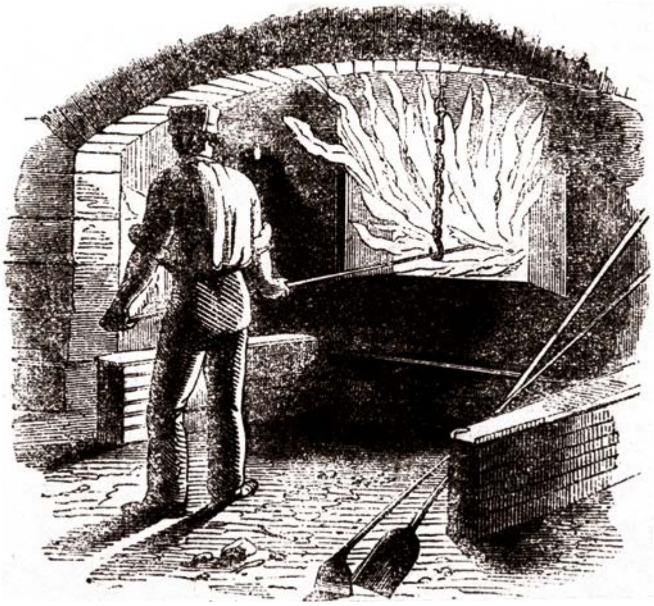

Figure CS5.1
Red lead manufacture in the 19th century. The molten lead was 'rabbled' to accelerate its oxidation.

Figure CS5.2
Excavation in progress at the Leadmill, Sheffield. The curved brick wall to the left was part of the flue that directed fumes towards the chimney. The white deposits inside the flue had a high lead content.

on site. Staff received regular medical checks, with two blood tests (one before work started and one at the end of the fieldwork) and urine tests at the end of each week.

Deep features associated with the bus and tram depot had truncated much of the earlier stratigraphy. The features associated with the lead works were overlain by 0.5–1.5m of demolition material and sealed by a layer of clay. The only substantial features associated with the lead works that survived were some foundation walls, a series of flues and floor surfaces (Fig CS5.2). The internal faces of the flues were covered in a sooty deposit. Subsequent analysis of soot samples showed that they contained high levels of lead. The flues probably fed into a chimney shown on the 1896 Goad insurance plan (see section 3.1).

The excavation also yielded artefacts and materials associated with the production of the white and red lead: scrap lead, partially oxidised lead spillages, industrial pottery and fragments of furnace. The industrial pottery (unglazed bowls and internally glazed jars) had powdery, lead-rich, white deposits on their surfaces. The glazed jars resemble those mentioned in contemporary accounts (eg Muspratt 1860), but none of these accounts describe the unglazed bowls. The fragments of furnace consisted of pieces of millstone grit that had reacted with lead oxide to variable extents. Some of the partially oxidised lead corresponded almost exactly with Percy's description: 'a dam across the floor of the oven . . . consists of the coarse particles of intermixed lead and protoxide of lead' (Percy 1870).

The manufacture of lead pigments was confirmed by the scientific study of artefacts and residues recovered during the excavation. X-ray fluorescence (XRF) analysis (see section 2.5.4) enabled inferences to be drawn about the pigments being manufactured and about the operating temperatures. A variety of other scientific techniques could have been used to extract additional information. XRD analysis (see section 2.5.6) would have differentiated the lead compounds present, for example oxides, acetates and carbonates, whereas the XRF analysis could not. Such an approach might also have uncovered the function of the unglazed bowls. Further sampling of the features associated with the lead works could have provided information concerning the types of fuel used and environmental evidence for other raw materials or process indicators, such as spent tanning bark and dung (see section 2.3). Integration of the scientific analyses into the fieldwork stage (eg portable XRF) might also have aided the interpretation of archaeological features.

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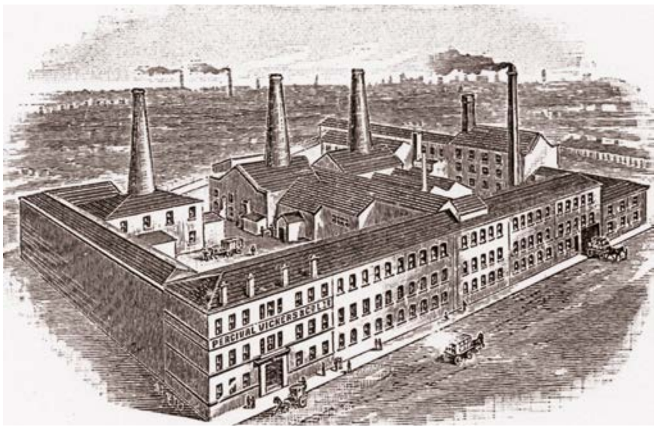
Case Study 6:
Percival, Vickers glassworks, Manchester

Ian Miller

The excavations at the Percival, Vickers glassworks provided information on innovations in furnace design, and analysis of the glass recovered is providing information on the wares produced and the types of glass from which they were made, as well as the likely raw materials and process conditions used. Methodologies were developed using pen computers to facilitate the recording and interpretation of the archaeological remains.

The Percival, Vickers and Co Ltd British and Foreign Flint glassworks on Jersey Street, Ancoats, Manchester, was established in 1844 with two glass furnaces, an annealing house, and associated buildings (Fig CS6.1). The factory produced a wide range of high-quality tableware and homeware. During the 1860s, the firm began to register designs for press-moulded wares. By 1863, it had become the largest of the city's glass factories. The development of the site can be traced from a series of cartographic sources, particularly Ordnance Survey maps (see section 3.1). The earliest map showing the works, published in1851, includes two furnaces; subsequent maps show that a third furnace was added (Fig CS6.2).

In the absence of company records, an eyewitness account of a guided tour of the works provides one of the best descriptions of the glassworks. This mentions the furnaces and various workshops for the storage and mixing of raw materials, the manufacture of crucibles and steel moulds, and the cutting and engraving of glass vessels. Six catalogues survive (see section 3.5), and the final catalogue includes an engraving of the glassworks showing the three large chimneys of the glass furnaces (Fig CS6.1).



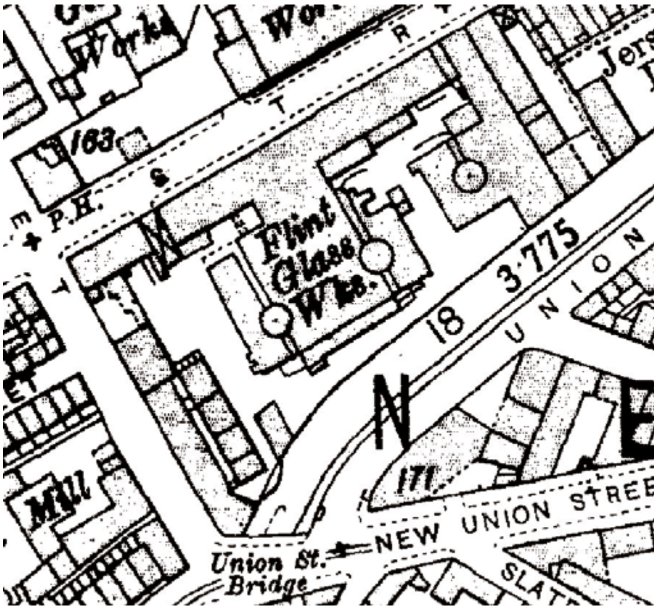


Figure CS6.1 (top)
The Percival, Vickers glassworks, Manchester, from the north-east, as shown in a 1902 trade catalogue. The three large chimneys can be seen on the contemporary map (see Fig CS6.2).

Figure CS6.2 (bottom)
The 1891 Ordnance Sur vey map showing the Percival, Vickers glassworks, Manchester. The three circular features shown inside the buildings are the chimneys for the glass melting furnaces (see Fig CS6.1).

Excavation started with five machine-dug trenches covering 500m^2, targeted on the furnaces and their associated flues. This work led to more detailed excavation, exposing and recording an area of approximately 2030m^2. A total station (a surveying instrument that combines an electronic theodolite and an electronic distance measuring device) was used during the excavations to record all structures three-dimensionally on to a pen computer (Fig CS6.3). This computer was loaded with Ordnance Survey data that allowed archaeological detail to be overlaid on to historic maps, which proved valuable in interpreting features. The survey data was used as the basis for a manually drafted plan of the entire site. This ensured accuracy and dispensed with the need for a site grid, as getting grid pegs into thick deposits of rubble is difficult if accuracy is to be maintained. The total station was also used in reflectorless mode to record elements of the site that were difficult to access, such as the underground flues, and to generate accurate cross-sectional profiles.

The remains of all three furnaces, an annealing house and associated workshops were revealed. The furnaces generally survived to the height of the siege foundations, and were approximately 6m in diameter. The flues were almost 3m deep. The furnace erected *c*1881 was evidently of an improved design, and incorporated the latest technology, including a Frisbee feeder for replenishing the fuel and an innovative system of air supply. The fire chambers of two of the furnaces were filled with abundant fragments of glass and glassworking waste.

More than 100kg of variously coloured glass were recovered; some of it was cut glass, but the majority was press-moulded. The assemblage was examined by eye and categorised typologically, with a view to identifying the working practices undertaken at the site. The method of forming glass objects by press-moulding was developed in the early 19th century. The forms produced were often intended to imitate the style of cut glass, but the pressing left a surface that was less brilliant. Press-moulding was used to mass-produce cheaper versions of cut-glass vessels.

Figure CS6.3
The foundations of an annealing furnace with ancillary structures behind.

Samples of glass, including some of the working waste, were analysed using inductively coupled plasma spectrometry (ICPS) (see section 2.5.4). The preliminary results suggest that there are six broad compositional groups, dominated by lead- (and potash-) rich types of glass and others that are soda-rich. The soda-rich glass appears to have been used for the press-moulded vessels and contained relatively low concentrations of lead, although there was probably sufficient lead to influence the melting properties of the batch.

Case Study 7: Iron-working sites at Rievaulx and Bilsdale, North Yorkshire

Jane Wheeler

Iron-working sites have been located within the environs of the ruins of Rievaulx Abbey in North Yorkshire and at a number of locations throughout Bilsdale, immediately to the north. The aim of this project was to investigate the environmental effects of human industrial activities and evidence for woodland management in relation to the fuel requirements of the iron industry between the 12th and 17th centuries. This has been achieved by using a variety of scientific techniques to extract data from off-site core samples (English Heritage 2011a). The sites of interest are in a rural location and contemporary land use is pastoral. As the study area is large (28 hectares), a systematic approach was used to locate the archaeological remains of furnaces for excavation, and to identify suitable sites for the retrieval of cores. This approach made use of a variety of evidence, including surface scatters of slag, field name evidence and the results of geophysical survey (Vernon *et al* 1998).

Using a Russian corer, pollen cores were taken at sites slightly distant from the ironworking furnaces. The cores were assessed for their pollutant content by ascertaining whether the sediment sequences contained a magnetic record of airborne pollution (specifically iron and burnt charcoal) generated by the iron- smelting processes. This was done in a laboratory using a Bartington dual-frequency magnetic susceptibility sensor (model MS2B) to scan the cores. In each case, the preliminary magnetic susceptibility results appear to reflect the accumulation of atmospheric pollutants in quantities that can be associated with phases of ironworking activity, and act as an environmental marker for iron smelting (Fig CS7.1).

The ironworking sites included in the project date to different periods (according to the results of archaeomagnetic dating and historical records), and there is evidence that the technology developed over time from bloomery furnace to blast furnace, with implications for the utilisation of natural resources, fuel consumption and metal output. When this study is complete, the data from the cores will be linked in more detail to the results from the excavation, for example correlating the local pollen data with the wood types found in the

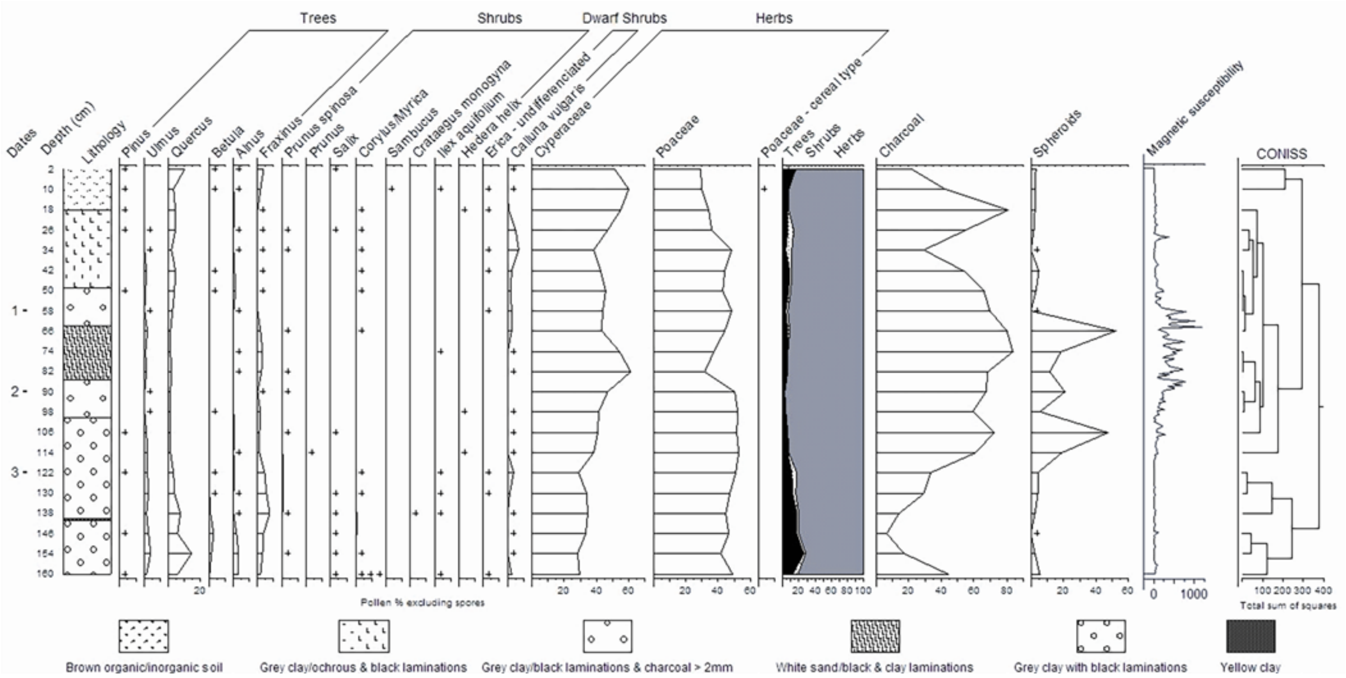


Figure CS7.1
Selected taxa pollen diagram from Rievaulx Abbey, North Yorkshire, including spheroidal and microscopic charcoal data, and magnetic susceptibility values.

archaeological charcoal assemblages. It will also be possible to compare the environmental impact of the ironworking at different types of furnace site.

However, this case study focuses only on preliminary results for a core from the vicinity of the charcoal-fuelled blast furnace at Rievaulx village, which operated from *c*1570 to *c*1647 (McDonnell 1963, 1972, 1999). The site is contained within an area designated a Scheduled Monument, and a licence was obtained to conduct field-walking and environmental sampling, and to conduct an investigatory excavation in the refectory building of the abbey ruins.

The preliminary results from the pollen core (Fig CS7.1) taken from the meadow immediately west of the blast furnace site, show high charcoal, spheroid carbonaceous particles (see section 4.3) and magnetic susceptibility values between points 1 (0.58m) and 3 (1.22m). The pollen data show the local arboreal pollen to be very low and a dominance of grass and sedge reflects the pastoral nature of the surroundings. The low counts for arboreal pollen suggest either there were few trees present, or that the trees that had survived into the late medieval and early modern period were being tightly managed using traditional strategies such as coppicing and pollarding. The correlated peaks for charcoal and spheroids have been interpreted as representing the period of blast furnace operations, beginning *c*1570 until closure of the ironworks *c*1647. Point 2 (0.9m) reveals a reduction in the output of spheroids and a slight decline in charcoal, yet relatively stable (elevated) magnetic susceptibility values. This decline in spheroidal output recorded between 0.98m and 0.74m may be indicative of reduced iron production, although the furnace continued to be operational, a fact that is supported by the consistently high charcoal values.

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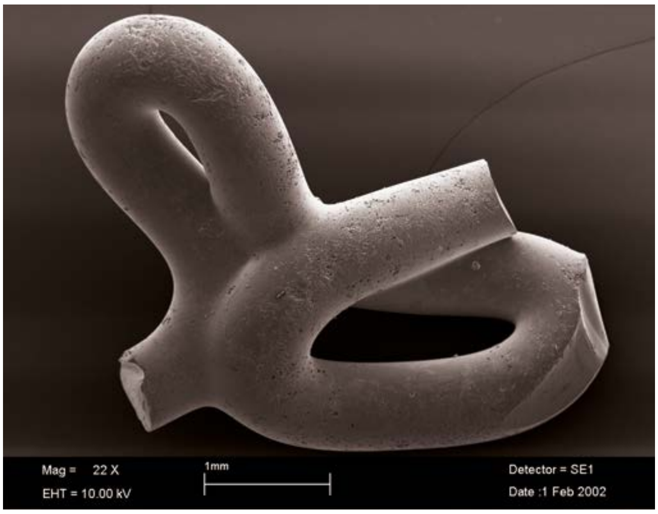
Case Study 8:
Silkstone glassworks, Yorkshire

David Dungworth and Tom Cromwell

The investigation of the site of a glassworks at Silkstone was driven by the need to identify the site and inform decisions about designation and preservation. However, the evaluation also provided the opportunity to develop both field- and laboratory- based methodologies for industrial sites. The scientific examination was intensive and aimed to test which methods would be most effective.

Documentary evidence suggested that a glasshouse had operated in the Yorkshire village of Silkstone from the middle of the 17th century into the early 18th century. A small evaluation trench revealed floor surfaces and dumped layers extending to a depth of about a metre. As the stratified sequence was finely dated by clay pipes, the assemblage provided a good opportunity to test various sampling strategies and scientific techniques for investigating post-medieval glasshouses. Soil samples (10 litres) from selected contexts were sieved to recover small fragments of debris normally missed during excavation, such as fine glass threads (Fig CS8.1). More than 400 of these small fragments of glass and glassworking waste were analysed to determine the chemical composition of the glass produced and how this changed over time (Dungworth and Cromwell 2006).

The detailed examination and analysis of a large number of samples from a single site has provided important information about the sorts of samples and scientific techniques that can provide the most useful information. The scientific work has shown that many categories of glassworking waste had been subjected to transformations and reactions with other process residues (eg clinker from the coal ash) and so provide only limited information about the types of glass that were manufactured. However, some types of waste, in particular the fine threads (Fig CS8.1), provided reliable information on the composition of the glass made at the site.



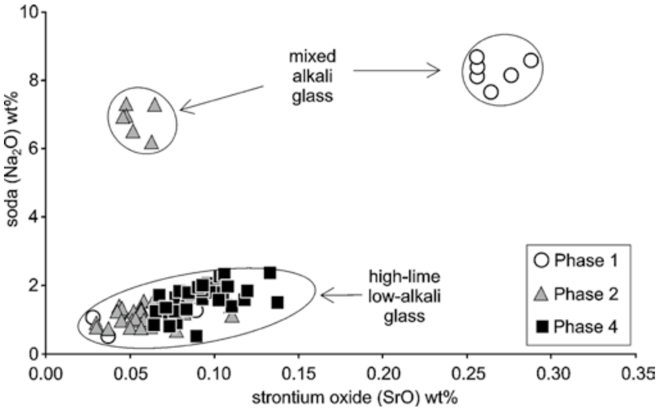


Figure CS8.1 (top)
Glassworking waste: scanning electron microscope (SEM) image of a fine glass thread (see section 2.5.3) (scale bar = 1 mm). Threads were produced as the glass was refined: by watching how a lump of molten glass dripped off an iron bar, the glassworker could gauge if the glass was ready to blow.

Figure CS8.2 (bottom)
Graph of the different soda and strontium oxide contents of some of the glassworking waste from Silkstone. The high strontium content of the phase 1 mixed alkali glass suggests that it was made with kelp (seaweed).

Prior to phase 4 (*c*1680–*c*1700) the glasshouse produced a dark green bottle glass (high-lime low-alkali type) and pale green glass (mixed alkali type) probably used for tablewares (Fig CS8.2). This corresponds with the documentary evidence (see section 3) for two glasshouses at the site: a ‘greenhouse’ and a ‘whitehouse’. The glass composition also indicates the raw materials used. The bottle glass composition is consistent with the use of plant ashes, such as the rape ash recorded in a will as being part of the stock of the glasshouse. The composition of the pale green (mixed alkali) glass changed over time (Fig CS8.2). During phase 1 (*c*1660–*c*1670) it was probably made from kelp (seaweed) ash (indicated by the high strontium content of the glass and confirmed by strontium isotope analysis; Dungworth *et al* 2009), while during phase 2 (*c*1670–*c*1680) it was perhaps made from the ashes of a relatively soda-rich coastal plant such as glasswort; the low strontium content rules out seaweed.

About 1680 the glasshouse underwent major alterations, indicated by a thick layer of demolition rubble. The bottle glass production continued, but a clear lead glass replaced the mixed alkali glass. Lead crystal glass was developed in the 1670s in London and it displaced most other tableware glass recipes by the end of the 17th century (Dungworth and Brain 2009). The evidence from Silkstone shows that the new technology was rapidly adopted outside London.

The intensive scientific study of glassworking process residues from Silkstone has provided insights that are not available using other approaches. The historic record for Silkstone gives no impression of the ways in which glassmaking recipes changed over time. The scientific results show that at least some of the raw materials had been transported long distances; Silkstone is more than 80km from the nearest source of seaweed. The quick adoption of lead crystal shows that this provincial glasshouse was dynamic and open to new ideas.

The nature of the glass produced at such sites can only be understood by analysing a large number of samples, and these samples need to be selected with reference to the stratigraphy. The small-scale excavation did not locate any structures associated with glassworking, such as a furnace. Nevertheless, the excavation showed that *c*0.5m of stratified deposits associated with glassworking survived, and the site has since been scheduled.

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4 Where to Get Advice

4.1 Historic England

Historic England can provide a range of advice on the application of scientific techniques to the investigation of historic industries. Historic England (and its predecessors) has undertaken the thematic study of individual industries as part of the Monuments Protection Programme (MPP; English Heritage 2000). These surveys resulted in two 'step' reports: the step 1 reports contain overviews of each industry while the step 3 reports include a list of all sites that are potentially of national importance. The completed step 1 and step 3 reports (Table 1) are available for consultation at the Historic England Archive (Swindon), the Council for British Archaeology (York), Leicester University and the Institute for Industrial Archaeology (Ironbridge). Introductions are also available for mills (English Heritage 2011b), pre-industrial ironworks (English Heritage 2011c), lime kilns (English Heritage 2011d), pre-industrial mines and quarries (English Heritage 2011e), pre-industrial slatterns (English Heritage 2011f) and medieval and early post-medieval glassworks (English Heritage 2012).

	Step 1	Step 3
Alum	✓	✓
Arsenic	✓	✓
Brass	✓	✓
Chemicals	✓	
Clay	✓	
Coal	✓	✓
Copper	✓	✓
Dovecotes	✓	✓
Electricity	✓	✓
Gas	✓	
Glass	✓	✓
Gunpowder	✓	✓
Icehouses	✓	✓
Iron/steel	✓	✓
Lead	✓	✓
Lime	✓	✓
Minor metals	✓	✓
Oil	✓	
Salt	✓	
Stone	✓	✓
Tin	✓	✓
Water supply	✓	✓
Zinc	✓	✓

Table 1
Details of completed MPP reports. Historic England scientists can provide guidance on a range of materials, industries and sites, and can be contacted via Fort Cumberland: HistoricEngland.org.uk/about/contact-us/national-offices/fort-cumberland/ Science advisors can also be contacted through the regional offices: HistoricEngland.org.uk/advice/technical-advice/archaeological-science/science-advisors/

4.2 Other sources of information and advice

Further information about particular industries can be found in the Department of the Environment Industry Profiles (www.environment-agency.gov.uk). The primary aim of these reports is to identify the range of possible contaminants on sites of historic industries, but in so doing they provide information on the processes, materials and wastes associated with individuals industries.

Several specialist societies are also active in the investigation of historic industries:

Historical Metallurgy Society
www.hist-met.org

The Association for Industrial Archaeology
http://industrial-archaeology.org/

Society for Post-Medieval Archaeology
http://www.spma.org.uk/

4.3 Health and safety issues relating to contaminated land

The investigation of sites of historic industries poses many potential risks to the health and safety of the personnel involved. Before any fieldwork begins it is essential that a site-specific risk assessment is drawn up. This should set out the risks in terms of the likelihood that personnel will be exposed to a hazard as well as the outcome of that exposure. Desk-based assessments, site evaluations and data from non-archaeological contractors will all provide information about potential hazards. Risk assessments should be carried out with reference to appropriate legislation, for example the Health and Safety at Work Act (1974), the Management of Health and Safety at Work Regulations (1999), the Control of Substances Hazardous to Health (COSHH) Regulations 2002, and the Personal Protective Equipment at Work Regulations (2002).

More detailed information on the hazards posed, and how to carry out risk assessments, can be obtained from a number of sources, in particular the Health and Safety Executive (www.hse.gov.uk), as well as local authority health and safety teams. Further guidance is available from the Department of the Environment, Food and Rural Affairs (www.defra.gov.uk) and from the Environment Agency (www.environment-agency.gov.uk). Specific guidance for land contamination and archaeology can be obtained from the Institute of Field Archaeologists (www.archaeologists.net), the Construction Industry Research and Information Association (www.ciria.org) and the Association of Geotechnical and Geoenvironmental Specialists (www.ags.org.uk).

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