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THE CLASSIFICATION OF EARLY IRONWORKING SLAGS

VOL I

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SUMMARY

Ironworking slags are usually recovered from archaeological excavations of Iron Age and later sites. There has been no method of distinguishing between the slags derived from the two processes, i.e. smelting and smithing. This has led to a general trend to interpret all slags as deriving from the smelting process.

Detailed investigations have been made of slags from a number of British sites, dating from the Iron Age to the Medieval Period. Several types of smelting and smithing slag have been examined.

The attributes used to differentiate between slag types were morphology, and chemical and mineral composition. The mineral volumetric analysis was obtained via the metallurgical microscope. Chemical bulk and phase analyses were determined by Scanning Electron Microscopy with an attached Link Energy Dispersive System. The chemical analyses were converted to a theoretical mineral composition using Normative Calculations.

It is shown that there is no single attribute that can distinguish smelting from smithing slags, although the presence of significant levels of manganese oxide is indicative of smelting slags. However the absence of manganese oxide does not indicate necessarily a smithing slag. The application of sophisticated statistical techniques could not distinguish between the slags types.

The heterogeneity of each slag type was determined, but this did not enable the smithing slags to be differentiated from smelting slags despite their relative greater heterogeneity.

Key Words: slags, smelting, smithing, heterogeneity, normative composition.

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My sledge and hammer

Lies declined, my bellows

Too have lost their wind. ·

My fire's extinct, my forge

Decayed and in the dust

My vise is layd, my cole

Is spent, my iron is gone.

The nail is driven,

My work is done.

Epitaph on the tombstone of a blacksmith in Ince Parish Church, (Lancashire) dated 1796, (Courtesy of Mr A.Rigg).

CHAPTER 1

INTRODUCTION

The study of Archaeometallurgical processes has lagged
behind that of other archaeological studies, including other
technological processes, notably that of pottery production.
This is despite the great attention paid to the study of typol-
ogies of metal artefacts, in particular of weapons. It was in
1836 that Christian Thomsen (1788-1865), the first Curator of the
National Museum of Denmark, published the 'Three Age System'. In
this he proposed an historical development of material culture,
from the first use of stone, through copper and into the Age of
Iron. This was further expounded by his student J.J.A. Worsae
(1821-85) and laid the foundation for the European Chronology
until the Carbon-14 revolution.

The technological processes of metal manufacture were
largely ignored, despite the collection of information on
primitive technologies by explorers and travellers of the time.
This situation prevailed until the early 1950's and 1960's,
although processes were discussed in relation to individual
archaeological sites and excavations. There were exceptions, for
example the work of Straker[1] in the Weald.

Research during the last twenty to thirty years has
established a base for archaeometallurgical studies. The main
areas of research have been the exploitation and use of the
precious metals (gold and silver), copper and its alloys, and to
a lesser extent iron. Copper has retained the most interest
because of the possibilities of sourcing the largely uncorroded
artefacts by trace elemental analyses, and as the first metal to
be smelted it represented a major technological breakthrough in

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man's evolution.

The study of ironworking technology has proved to be of
less interest to archaeologists for a number of reasons. Firstly,
the invariably heavily corroded nature of the iron artefacts,
leaves little opportunity for metallurgical studies. Secondly,
the widespread availability of iron ores makes sourcing studies
potentially very difficult. Thirdly, the wide geographical dis-
tribution of smelting sites makes the study of technological
developments difficult. This can be contrasted with the study of
copper smelting where the evidence for smelting and its develop-
ment is restricted to the locality of the ore sources.

It is apparent that there has been considerable
misunderstanding of the ironworking process, resulting in
erroneous and misleading reports appearing in archaeological
publications, which has only served further to confuse the
evidence for the development of ironworking technology. In the
course of this study it has become clear that many of the
assumptions, some of which developed for a-priori reasons over
the last twenty years, have to be radically reconsidered in the
light of recent research. It is a fact that at present the
archaeometallurgical and archaeological study of the historical
development of early ironworking is in a state of change.

The methods of approach to ironworking process studies
are numerous: structural and chemical analyses of artefacts, the
recording and study of the archeological evidence of structures-
furnaces and hearths, and the analysis of the process residues.
All three approaches have been used with varying degrees of
success, but they all suffer from drawbacks. In summary, the
evidence available within an artefact cannot relate to the whole

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process, but must be considered as the primary source of evidence for smithing techniques. The evidence of structures depends greatly on the process ascribed to them, e.g. whether smelting furnaces or smithing hearths, and are commonly negative features i.e. pits etc.. The residues vary not only within individual processes but are also heterogeneous within specimens. It has been common practice on archaeological excavations to note the presence of ironworking slags and residues but not to ascribe them to any process, assuming they derive from the smelting process.

It has become apparent during the last ten years that slags have been found on all types of archaeological sites. e.g. urban and rural, domestic and military etc., in varying quantities to which no process could be certainly ascribed, and thus were only adding further confusion to the understanding of ironworking processes. It was therefore necessary to clarify the situation and develop techniques that could enable an interpretation of the evidence to be made.

In general archaeology goes much further than recording the structures and features in the ground. Attempts are made to understand the economic basis, the social and religious structure, and hence the function of a site. This is achieved by the application of many methods, and increasingly by the use of scientific techniques of analysis both in the physical, chemical and biological disciplines.

Therefore the ability to ascribe slags to particular processes would greatly help to establish one aspect of the economic basis of a site. For example the site of Mucking (Essex), an important excavation of a (primarily) Anglo-Saxon

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settlement site, produced 300 kg of ironworking residue. It is therefore of interest to know what proportion of the residues derived from the smelting and smithing processes, and whether different smelting techniques were used on the site at different periods, and if so, do they represent an intrusive technology from the continent or a local variation? Investigation of the distribution of smithing residues may ascertain whether the settlement had a central 'full-time smithy', or if the smithing was carried out at each settlement unit.

It is the purpose of the present work to describe the residues derived from the ironworking process encountered in the archaeological record. In particular, it is hoped to establish criteria by which smelting slags may be distinguished from smithing slags. This will enable an archaeologist to better understand the economy of the sttlement being studied. The slags occurred in many different forms and, therefore, not all types of slag have been examined, but the criteria established should enable the investigator to analyse and, probably, identify any other slag type. The slags examined were analysed by different methods, e.g. morphologically, chemically; and the results from the various slag types were compared, using statistical techniques, to investigate any differences between the slag types.

It has been necessary to restrict this work to archaeological sites mainly from England, although evidence from other British sites will be introduced. In historical terms the evidence spans the period fron the introduction of iron into Britain to the emergence of the blast furnace as the principal production process of iron (circa 700 B.C. to 1500 A.D.).

CHAPTER 2

THE IRONWORKING PROCESS

2.1 Introduction

The ironworking process under study was termed by Percy[2] 'The Direct Process', i.e. the manufacture of 'wrought iron' or 'malleable iron' directly from the ore, as opposed to the Indirect Process of later periods in which the cast iron produced by the blast furnace was subsequently reworked (in the finery and chafery forges and later by puddling) into 'wrought iron'.

The ironworking process is a general term to describe the practices involved in producing iron artefacts from the ore. It, therefore, includes a number of different processes which can be considered under three headings. Firstly, the smelting process in which metallic iron was extracted from the ore and which included any ore preparation. Secondly, the smithing process where the iron was refined and subsequently worked into artefacts; it also includes any secondary working such as repair or reworking of the artefacts. Thirdly, there were other processes that might be practised but did not occur as distinct processes in the ore-to- artefact manufacture, and might be carried out during the smelting or smithing process. Techniques such as carburisation and general heat treatments can be considered here. For example, it is not clear whether high carbon 'wrought iron' (i.e. steel) was produced during smelting in the furnace or as a separate carburising process at a later stage. Thus, the manufacture of high carbon irons may have occurred during either the smelting or smithing process.

In the literature there have been many terms used in the discussion of the smelting and smithing processes. This renders

much of the literature of little use unless the terms have been defined. In this work terms will be defined as they are used but the broad description 'ironworking' refers to the complete process from ore to artefact, 'smelting' to the extraction of the metal from the ore, and 'smithing' as the fabrication and repair of artefacts (Figures 1 and 2, Vol II pp206/7).

2.2 The Smelting Process

The smelting process includes the preparation of the ore and its subsequent reduction to metallic iron. The term 'bloomery process' has also been used, derived from the Old English 'bloma' meaning iron[3].

The three requirements for smelting are ore, fuel, and material for the furnace structure. Until recently it had been assumed that the dominant factor was ore supplies. In 1962 Tylecote[4] in Metallurgy in Archaeology pointed out that there were nine counties in England that contained no recognised ore sources, (London, Suffolk, Cambridge, Essex, Hertfordshire, Berkshire, Bedfordshire, Middlesex, and Buckinghamshire). These can no longer be excluded as possible iron producers; for example, Mucking in Essex, the Bulbourne Valley in Hertfordshire, and Amersham in Buckinghamshire have all produced evidence of iron smelting.

The location of the ore was thought to be of major significance in that this would determine the positioning of the smelting site.   In the West Yorkshire Survey Moorhouse[5] provides documentary evidence from the Medieval Period for the transportation of ore over distances of twenty miles. During this period there was pressure on timber resources; wood was needed

not only as the fuel for all industrial processes but for building, especially ships. Woodland management was a highly developed industry, and charcoal was made from coppiced or pollarded timber rather than fully grown trees. Thus there would appear to have been little conflict between the charcoal burners and other timber users. The source of charcoal would be more likely to determine the location of the smelting site, since either the raw timber could be transported, a difficult and expensive process, or the prepared charcoal could be moved. The movement of charcoal over any distance along rutted roads would result in its rapid disintegration. Charcoal is believed to be the major fuel used in smelting in Lowland Britain, but peat could equally have been used in the Upland Zone; peat charcoal was extensively used in a variety of industrial processes in Orkney[6] during the 17th and 18th Centuries.

The evidence for furnace structures indicates the widespread use of clay as the main refractory material; stone has also been used in furnaces. although with a clay lining. Recent investigations in Iceland have produced evidence for iron smelting[7]; it is of interest to note that there appears to be no clay or suitable building stone in Iceland, and it has therefore been tentatively proposed that turf/stone structures may have been used.

Clay as the primary furnace building material was an important factor in the smelting industry, but it has recently been proposed that there may have been closer correlation[8]. The principal industrial use of clay was in pottery manufacture and in the Roman Period (for example) large quantities of clay were excavated. Many of them contain ironstone nodules which could, if

in sufficient quantity, have been used as an ore source. A further probable connection is that it is believed that in the production of (Roman) reduced ware pottery types the wood fuel used would be charcoalled and could have been used as fuel in the smelting furnace. A firm correlation between iron smelting sites and pottery production sites, particularly those making reduced wares, has yet to be confirmed archaeologically.

The organisation of the supplies of fuel, ore, and building materials varies with the nature of the smelting activity, whether a 'one-off' smelt to satisfy immediate local needs or a full-time industrial smelting site. When the materials had been collected on the site further preparation could begin, e.g. the building of the furnace, the dressing of the ore.

The reduction processes have been the most intensely studied aspect of early ironworking technologies, through analyses, theoretical and experimental work, and ethnographic parallels. These aspects were discussed recently by S. Fells[9] in her study of smelting slags. She relied heavily on the observations of Richard[10] and Francois[11] as quoted by Percy[2] of the Catalan furnace, which were re-assessed in the light of Tylecote's[12] experimental work, and Morton and Wingrove's[13] observations on a lump of partially reduced ore.

The reduction of the ore is primarily through the action of carbon monoxide gas rather than by direct contact with the charcoal, although the latter reaction occurred and may have been important in some furnaces.

The gas reduction process would have operated in all types of furnace (see Section 3.2) to produce the bloom of metal. The processes diversify in the method of slag removal. It is quite

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apparent, from both archaeological evidence (Section 3.2) and the slag types (Section 5), that this was removed by a number of different methods, and in some cases may have been left to cool within the furnace, only the bloom being removed. The different types of furnace are discussed in Section 4.

In most recent work it has been assumed that the primary product of the furnace was ferritic 'wrought iron', i.e. iron containing slag inclusions and no carbon. Metallurgical investigations of early iron tools e.g. from Novgorod[14], Helgo[15] and most recently Coppergate, York[16], illustrate that steel played an important part in tool manufacture. Further the Coppergate study showed that the common form of iron was phosphoric iron, containing up to 0.5% phosphorus, and that pure ferritic iron was uncommon. The usual type of knife manufacture was a steel cutting edge welded to a phosphoric iron knife back. It has not yet been established clearly whether the steel was a direct product of the furnace or whether selected irons were pack carburised. The occurrence of phosphorus in most ores, and its inhibiting effect on carbon diffusion would indicate that the steel was manufactured from especially selected low phosphorus ores in the furnace by increasing the fuel to ore ratio. However, recent work[17] has indicated that steel may have been manufactured from phosphoric ores; the method used may have removed the phosphorus by accident.

2.3 The Smithing Process

The smithing process was the working of the smelted bloom into a refined bloom, the manufacture of artefacts, and their subsequent repair or alteration. In archaeometallurgical

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discussions other terms are used, primarily 'forging' and the 'forge' in place of 'smithing' and the 'smithy'. There is no technical distinction between the two sets of terms; the latter will be used in this work. In order to establish a terminology: the fire in which the smithing was carried out is termed the 'hearth', and not a furnace.

When the bloom of iron was extracted from the smelting furnace it required refining by hammering to remove excess slag. This was strictly a smithing operation although carried out at the smelting site, and has been termed primary smithing. It was probable that the residues from this process were recycled through the furnace since they would contain considerable amounts of metallic iron, and easily reducible ferrous oxide.

The major activity to which the smithing term applies was the making and repair of artefacts. (Wrought iron or 'malleable iron' could be cold worked, but this work hardens the metal, reducing its malleability. Therefore, most of the work was carried out at elevated temperatures.).

The essence of the smithing hearth was a fuel bed with an induced draught. Charcoal is believed to have been the predominant fuel used although coal and peat or peat charcoal could have been used. The temperature of the fire was increased by increasing the air flow, but this resulted in oxidising conditions prevailing in the hearth. Reducing conditions may have been present on the side furthest from the tuyere. Only a small volume of fuel was fired since only short lengths of metal could be worked at any one time. Special hearths were used to weld blooms together to form massive constructional iron, e.g. at the Roman site of Corbridge to manufacture supporting beams for

the hot tank in the bath house[18]. The temperature required depended upon which operation was being performed – from shaping of the metal (circa 500 – 700° C), to fire welding (1000° C plus). The major problem facing the smith was oxidation of the metal (there being increasing oxidation with increasing temperature). resulting in 'burnt' metal. This was controlled by the scattering of sand on the metal which formed a silicate slag that impeded oxygen diffusion.

The craftsmanship of the smiths varied between the archaeological periods under consideration and also within the periods themselves. Initial studies of artefacts suggest a high degree of skill in the Anglo–Saxon/Early Medieval Periods. while in the Roman Period the everyday artefacts appear to be less sophisticated, and in modern terms it was a 'throw-away' society dependent on mass production. It is therefore impossible to make general statements concerning the development of smithing techniques, especially when the small number of 'well-preserved' artefacts analysed is considered. It is therefore reasonable to consider techniques that may have been used at one time or another.

The basic fabrication techniques (of welding. shaping. bending, and cutting the metal) would have been the same throughout the periods under consideration. This is reflected by the virtual identical appearance of ancient smiths' tools found in hoards and as grave goods with those seen in a modern smithy. e.g. the Iron Age hoard from Waltham Abbey[19]. The use of steel or carburised artefacts was widespread. a possible exception being the Roman Period when they appear to have relied on 'natural' steels, notably Norricum iron. Techniques that were not so common were pattern-welding or piling. and heat

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treatments.   Pattern   welding   was   the   climax   of   smithing techniques in that it required careful selection of the irons to be worked. sophisticated welding, and often the ability to think in three dimensions as exemplified by the 'Ulfberht' inscriptions on Norwegian Viking Swords[20].

Whatever   the   level   of   techniques used   the   smithing   was carried out between the hearth. the anvil. and the water tank. The evidence for the techniques can only be extracted from the artefacts and not the hearths or the slags.   The residues   are fully discussed in Section 5, but in general the smithing slag was derived from the accumulation of oxides and silicates in the hearth. and hammer scale from the oxide/silicate scale on the surface of the iron.

CHAPTER 3

THE ARCHAEOLOGY OF SMELTING AND SMITHING SITES.

3.1 Introduction

The archaeology of smelting and smithing sites considers the
structural evidence remaining within the archaeological record.
In common with other aspects of archaeology the evidence relies
heavily on 'negative features', i.e. those cut into ground
surfaces, e.g. pits and ditches. The nature of the processes
under consideration, especially the smelting process, utilises
superstructures and positive features. It is only on a few sites
that preservation has been sufficiently good to allow the
superstructure to survive, e.g. Levisham Moor, North Yorkshire[21].
Therefore, the interpretation of the majority of ironworking
features relies heavily on the associated evidence, principally
the slags. Thus the earlier tendency for archaeologists to
interpret 'slag' as evidence for smelting has meant that features
associated with such material have been identified as 'furnaces',
e.g. Tiddington, Warwickshire[22]. It is therefore necessary to
re-examine the evidence from earlier reports in the light of more
recent excavations.

A general interpretation of all the available evidence
suggests that throughout the period of study there was a heavy
reliance on local production to meet local needs. There is clear
evidence for 'centres of production', notably in the Roman
Period. But in many cases the local smelter was closely
associated with a smithy, e.g. at Stamford[23]. Thus smelting and
smithing evidence may occur on the same archaeological site
within a few metres of each other. There can, therefore, be no
strict distinction between smelting and smithing sites.

3.2 Smelting Sites

The archaeological evidence for ore and fuel preparation is insubstantial. Both processes require little in the way of permanent structure. Typically charcoal was prepared in 'wigwam'-like clumps standing on the ground surface. Charcoal 'spreads' are common archaeological features on many industrial and domestic sites, and may only represent the place where the fuel was stored.

In general all ore needed some preparation, washing, crushing, and sieving. Some ores, notably sideritic ones required roasting, and roasting hearths have been found. e.g. at Bardown, Sussex[24]. Such purpose-built hearths tend to be found on major centres of production. On the local scale, roasting could be carried out in a bonfire. Experimental work carried out by Moorhouse[25] showed that the ore was liable to fracture violently and that a protective screen of wattle contained most of the flying fragments. The reducibility of an ore is dependent on four factors: porosity, crystallinity, dehydration, and decomposition. For example ferrous carbonates decompose less readily than ferric hydroxides (dissociation temperatures are $580^{o}C$ and $350^{o}C$ respectively). Porosity of any ore would be enhanced by roasting (due to micro-cracking); therefore, it is probable that most ores were roasted.

Ore fragments and ore fines have been recorded on many sites. It should be noted that ferruginous stones or pebbles may occur naturally on the site, and may not represent the ore used in the furnace, nor should it be used solely as evidence of smelting rather than smithing when found in association with ironworking 'slag'. The ore recovered from a known smelting site

should not be too readily accepted as the ore used for two reasons. Firstly, it is possible that the ore remaining was that discarded by the smelter as not of the right quality. Secondly, the evidence from a number of sites suggests the use of a number of different ores. These aspects are of particular importance when the ore-slag relationship is being studied. These problems are illustrated by the Roman site of Amersham Mantles Green, Bucks., (Section 9.4) on which two possible 'ores' were recovered. The first was a ferruginous sandstone that contained no manganese (as the slag did), and a low percentage of iron, and the second which was high in iron and contained some manganese. The latter was a suitable ore, and recent fieldwork has identified a possible ore source.

The study of smelting furnaces has formed the major archaeological approach to the study of the ironworking technology, and several typologies have been proposed, notably those of Coghlan[26], Cleere[27], and Gibson-Hill[28] in Britain and Martens[29] in Europe.

Cleere divided furnaces into two broad groups, the non-slag-tapping type of furnace which was subdivided into simple bowl furnaces, (no superstructure), and those with superstructure. The second type was the tapped furnace, again sub-divided into either those with a shaft superstructure and those with a conical (or dome) one. The furnaces were further sub-divided into those blown by natural or forced draught. This classification has formed the basis for most descriptions of furnaces since its publication, with, it would appear, a tendency to fit the archaeological evidence to the classification rather than adapting the classification. Therefore, this typology has come under scrutiny, not least for its heavy reliance on the nature of

the superstructure, which rarely survives in the archaeological record.

Gibson-Hill desribed a typology based on a large number of Roman furnaces from the Weald, since they derive from a limited geographical area and a limited time span it is interesting to note the variation that can occur. Thus too much reliance should not be placed on furnace typologies.

The majority of furnaces were built of clay although stone was also used. Unless the clay was well fired, i.e. to a sufficient temperature to bake or vitrify the clay, it would break down during burial and be lost from the archaeological record. An extant clay structure, unless well supported, and one that will have suffered thermal shock, will be unstable and unlikely to remain standing for long after abandonment. It will also be susceptible to degradation and post-burial damage, e.g. ploughing. Therefore only the base of a furnace is likely to survive. The furnaces which have been found that survive to a reasonable height, e.g. Ashwicken, Norfolk[30], Levisham Moor, North Yorkshire[21] (Plate 1, Vol II p230), Scole, Norfolk[31], were supported and protected by being built into a clay bank. There is evidence (most recently from Bulwick, Northamptonshire[32] Plate 2, Vol II p230) that many furnaces were built in a clay supporting pad, presumably not only for structural support but also for thermal insulation.

In order that a valid comparison can be made between an extant definite smelting furnace and an archaeological feature that may be a furnace, the fill and nature of the Levisham furnace was examined in detail, on site.

The Levisham furnace was first excavated in 1964 and had survived to a height of just over 0.5 metres. The site was recorded and then backfilled, but in 1982 an opportunity arose to re-examine it. There was evidence for three furnaces (I, II, and III), but only the later one (III) survived intact; the two earlier ones had been partially destroyed by the third. All three were cut into a low natural bank probably heightened by the the ironworkers, which supported the back and sides of the furnaces; the front was open to allow tapping of the slag. Furnace III had been rebuilt at one stage. The clay walls were 0.10 - 0.15 m thick, well fired on the inner face, degrading to poorly fired on the outside, and formed a shaft 0.30 m in diameter. The tapping hole was 0.25 m wide at the base, and extended the full surviving height, although there was evidence from the sides that it would have arched over just above the surviving height. The fill from the base of the furnace had not been completely removed during the 1964 excavation. It consisted of degraded furnace structure and loose earthy fill. No doubt this was part of the superstructure that had collapsed inwards. The base and lower walls of the furnace were well-fired red clay, the furnace floor sloped from the back wall gently down towards the tap-hole. The furnace had been efficiently cleaned out after its last use since there was no adhering slag, or slag-attacked lining or charcoal present. The slag attack on the lining and the cleaning had resulted in the removal of part of the furnace wall, with the result that it had a slight concave curvature from the surviving top towards the base (Figure 10, Vol II p217). There were two tuyeres on either side of the tapping arch, at a height of about 0.40 m; they were both 10 - 20 mm in diameter and pointed down into the furnace at an angle of about 30° from the horizontal. There could have been a third or more tuyeres above

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the surviving height either at the back or front. There was slight vitrification on the inner face of the furnace wall in the region of the tuyeres.

The base and lower wall of the Levisham furnace gave little indication that it was an iron smelting furnace, i.e. the clean fill and lack of slag or evidence of slag attack. The slag-tapping channel only contained a very small amount of slag, which could not be ascribed to having been derived from the furnace. It was only the other evidence, e.g. the superstructure, the tuyeres, that identified the structure as a furnace.

This quality of evidence was present in the other sites listed above, enabling the structure to be ascribed to a slag-tapping shaft furnace utilising forced draught.

It is the identification and classification of other arch-aeological features described as 'furnaces' that present the major problem. This problem is faced when 'slag' is found and attempts are made to identify the 'furnaces' from many archaeological features. The situation is further confused when attempts are made to ascribe them to a particular typology.

The Iron Age/Roman site of Wakerley, Northamptonshire[33] produced several furnaces (discussed by Fells[9]). Three furnace types were identified. All were clay-lined pits; the first group were shallow pits 0.60m in diameter, and cut 0.10 - 0.20m into the bedrock, with an extension to the pit to enable the slag to be removed. The second type were only 0.30 - 0.40m in diameter. but cut some 0.40 - 0.75m into the rock, again with a facility to extract the slag. The third type were similar in diameter to Type 2, but had a channel for slag extraction.

The Wakerley furnaces were not ascribed a classification under the Cleere typology, since it was apparent that they could be classified only loosely under the typology. Recent work in Northamptonshire[32] has shown that the furnaces recorded at Wakerley were not 'unique' and probably represent a furnace technology not previously recognised in Britain.

Virtually the majority of furnaces that have been recorded have been described as Cleere Type A, i.e. the bowl furnace. They were typically pits of various diameters (varying from circa 0.3m up to 1.5m), and depths (from 0.05 - 1.00m), with a fill that also varied. Classic examples were those from Brooklands, Surrey[34]. There five furnaces were excavated, all were bowl-shaped pits varying in diameter from 0.35 - 0.80m and in depth from 0.10 - 0.30m; the bulk of the fills were made up of fired clay, (furnace structure), and charcoal; no slag was found in these features. There was about 20 kg of slag recovered from across the site, but no slag-heap or concentration of slag was found. This leaves the interpretation slightly open to doubt, since it would be expected that five furnaces, even if only used once, would produce a reasonably large quantity of slag, although it could be argued that it was removed for other purposes, e.g. hard core. The lack of slag in the furnaces corresponds with the evidence from Levisham, but in the case of Brooklands there was no alternative evidence, except the slag, of which the descriptions in the report lack sufficient detail for them to be ascribed to a particular process. The recent evidence from Northamptonshire might alleviate the problem, since the descriptions are similar, and large D-shaped furnaces may have been utilised.

There are sites on which the archaeological evidence, no

matter how slight, in association with other evidence (mostly the slag), can confirm the presence of iron smelting. Three typical sites for which there are detailed records are Cherry Willingham (Lincs)[35], Millbrook (Sussex)[36], and Howe of Howe (Orkney)[37]. Fired-clay structures were excavated on the three sites, but need not have been ascribed to the ironworking process. In particular, the Howe of Howe smelting furnaces showed no evidence of vitrification and/or slag attack.

3.3 Smithing Sites

Two types of smithing activity can be discerned; the first is the smithing found on many settlement sites, on which there appears to be no focus of activity, i.e. a smithy, but it is thought that smithing was carried out where convenient. Only a basic level of smithing would have been practised, and may have been a widespread skill, especially in agricultural communities. The second type is that of the 'full time' smithy, i.e. a building or area whose sole function was that of a smithy, although this may include other metalworking activities, notably copper alloy working. There is no clear distinction between the two types of smithing site; for example on many Viking farm settlements in Greenland, one out-building is described as a smithy[38]. It is probable that other activities such as woodworking etc. were carried out in it, so a more general term such as a workshop may be more applicable. The low-level smithing activity is more generally associated with rural sites, and full-time smithies occur in an urban context. The above interpretation should be treated as only a broad generalisation; the status of the smith was dependent on the type of society in

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which he functioned. Thus, the activities of smiths in the different periods cannot be too closely compared.

The reliance of archaeology on negative features is clearly illustrated in the evidence for smithing. A survey of the literature suggests that most of the smithing hearths identified were ground-level bowl hearths.

There is no doubt that such hearths were used, but the near total absence of waist-high smithing hearths cannot be believed. The evidence for such a hearth at floor level would be virtually non-existent in the archaeological record. A reconstructed smithy of the 17/18 th Century from Hutton-le-Hole Folk Museum, (North Yorkshire), is illustrated in Plate 3 (Vol II p231), and one from Sanday, Orkney, Plate 4 (Vol II p231). The layout of both smithies is typical, although the Hutton one had two hearths. The hearths were elevated to waist height on stone/brick supports. The bellows could be operated by the smith, and directed the blast into the hearth through one side. The nozzle of the bellows emerged through a circular clay pad, (Plate 5, Vol II p232), that acted as a protector of the leather of the bellows from the fire (see Section 6.3). The two smithies can be analysed archaeologically, by studying what would remain in the archaeological record after destruction/abandonment. They were both stone buildings with large double-door entrances. The floors were either flagged or beaten earth, the masonry hearths had at most only one course of stones below floor level. The anvil rested on a wooden block that would have been set into the ground, but there would have been few other post/stake holes. Thus, archaeologically they would consist of a stone building outline with a 'stone platform' along one wall, and some post holes. Unless the residues were recovered and analysed there

would be nothing to identify the building as a smithy.

The commonest feature described as a 'smithing hearth' is a bowl-shaped pit filled with charcoal and 'slag'. It is similar in size and shape to the 'bowl smelting furnace'. Cleland undertook a detailed study of sixteen 'smithing' hearths from Deansgate, Manchester and included several from Northwich[39]. Four hearth types were identified. PI was an irregular clay area containing random 'perforations' (holes like stake-holes). PII was a fired clay hearth with a recognisable elongated trough or channel with perforations on either side of the trough. PIII was a circular fired clay hearth in the form of a bowl surrounded by perforations. PIV was as PIII but with perforations within the bowl. The 'perforations' were interpreted as either stake holes for bellow supports or holes from the insertion of portable anvils, which are known from Roman sites, and from military sites in particular. The working temperature of the hearths was determined from the clay and found to lie within the range 450° - 800°. Since these measurements were taken from the clay hearth lining it is likely that in the local area blown by the bellows, temperatures of 1000° plus could easily be attained, without affecting the clay, if there was a sufficient bed of charcoal between the fire and the hearth lining. One hearth was identified as a carburising 'furnace' because of its tile construction.

A small clay smithing hearth was excavated in a 'workshop' area on the Brough of Birsay, Orkney[40] (Figure 15, Vol II p220). The hearth was sub-rectangular measuring 0.6m by 0.5m; it was not cut into the ground but had built-up clay walls about 0.1m high. The fill of the hearth contained charcoal, hammer scale, fuel ash slag, and some smithing slag. The area was surrounded by a

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charcoal spread containing hearth bottoms. smithing slag and hammer scale. This was clearly a purpose-built smithing hearth.

Many sites provide evidence of smithing from the presence of slag but no hearth features can be identified. The excavations of Hamwih (Saxon Southampton) at Six Dials are a classic illustration[41]. Figure 3 (Vol II p208) shows the distribution of smithing slag (there was no evidence for smelting on the site). Two concentrations can be recognised. The largest concentration came from a small area next to the road and seemed to respect property boundaries. Recent excavations (1983/4) on the other side of the road produced very little slag. It is clear therefore that the area was either a slag dump or a smithy. There was no reason to think that the slag was acting as a building material or hard core. The quantities present (500 kg) would suggest the smithy was close by, if not on the same site. There has been some loss of the upper levels of the archaeology through later activity, but any bowl hearths would survive in part. Since there was no such evidence, except for a very disturbed feature, it was reasonable to suggest a waist-high hearth.

Manning[42] argued for the raised hearth during the Roman Period, probably on brick or iron supports, on the basis of contemporary documentary evidence (carvings etc.). He concludes by adding "These have not as yet been recognised in the archaeological record".

The excavation at Gatcombe Roman Villa[43] uncovered a building (Building 5), divided into two rooms. the second of which had evidence for industrial activity in the form of two 'pit hearths', but no slag was recorded as coming from the room.

In the north-east corner of the room there was a stone platform (approximately 3m by 2m) for which no explanation was proposed. If the room was used as a smithy, then it would be equally reasonable to propose the platform as the hearth, and the pit hearth as supplying another function (carburising?).

Other sites that may possibly have had waist-high smithing hearths were Tiddington and Alcester. The Tiddington site was first excavated by May in 1927[22] and was initially identified as a Roman smelting furnace producing cast iron. Recent excavations[44] have produced more slag but were unable to locate May's hearth. Examination of the slag clearly showed it to be smithing slag, and therefore the 1927 hearth might be regarded as a smithing hearth. May was convinced that it was a smelting furnace producing cast iron, and so the report was not easy to understand. There is now some doubt about the identification of the hearth itself, but if true it would be reasonable to propose it as a waist high hearth.

A similar structure, again of Roman date, was excavated at Alcester[45]. In this case the stones clearly form the base of a higher structure. Only a little slag was retained from the excavation, but this was definitely smithing slag.

Waist-high hearths of medieval date and of similar construction have been excavated from Waltham Abbey, Essex[46], and Alstead, Surrey[47], the latter surviving to its full height.

There are a large number of rural sites, on which scatterings of smithing slag have been found, which probably derive from low level occasional smithing. They also occur in small concentrations, although commonly in features that were not

directly associated with the smithing process, e.g. pits and ditches. The Iron Age site of Beckford (Worcestershire)[48] was an example. The site was occupied from the Bronze Age through to the Roman Period, but with some later activity, presumably agricultural. There was one area of concentration of smithing slag, dated to the Middle Iron Age, and the remainder was scattered across the site. The excavations at Wetwang Slack, North Humberside, sampled a farm settlement enclosure that comprised building structures and small field enclosures[49]. This also produced a small scatter of slag, with one large concentration in a boundary ditch close to a small four-post structure which enclosed a burnt area, that could be interpreted as a smithy. This settlement/enclosure plan could be paralleled with the type of pattern observed on Greenland Viking farmsteads (p 34).

A functioning smithing hearth could be built on the ground surface, used for a short period and then abandoned. The archaeological evidence for such an activity would probably be non-existent. The probability that waist-high hearths were in use from at least the Roman Period, would indicate that any study of the archaeological evidence for smithing hearths, i.e. primarily the 'bowl hearth', means that only one particular aspect or level of technology is being studied. Therefore, any conclusions derived from the archaeological evidence, at present, should be treated with caution.

CHAPTER 4

THE HISTORICAL APPROACH TO EARLY IRONWORKING

4.1 Introduction

The technologies used in ironworking during the last two thousand years have varied both in a temporal and spatial context. To be able to discuss the evidence of the residues and slags that occur in the archaeological record, the historical development of ironworking must be considered. It will be apparent that some changes in technology appear to coincide with cultural changes, as evidenced by other archaeological data, e.g. the Romano-British/Migration Periods hiatus.

4.2 The Iron Age (Smelting Evidence)

The beginning of the Iron Age in Britain is generally regarded as having taken place in the seventh century B.C.. Hallstatt bronzes were being imported into Britain, and similar artefacts of iron, showing local adaptations, also appeared, e.g. the Llyn Fawr Hoard from Glamorgan[50]. From archaeological records the quantity of ironwork surviving from this early period is very small, and the definition of the Iron Age is very dependent on cultural changes, e.g. innovations in pottery styles. The sixth century B.C. site of Staple Howe, North Humberside[51], produced only two small objects of iron.

The actual date of the introduction into Britain of ironworking technology cannot be determined. The local variations in style of some ironwork of the continental Hallstatt Type, e.g. Llyn Fawr, indicate the presence of a local smithing technology, but it does not necessarily follow that smelting was

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being carried out.

At present there is a great lack of direct evidence for either process during the Early Iron Age (Figure 4, Vol II p209). The smelting slag from Farthingstone (Northamptonshire) (p 79) was dated to the sixth century B.C., but derived from the primary ditch fill of the hillfort enclosure ditch. After circa 400 B.C. the quantity of evidence, although much of it was doubtfully interpreted, increases, e.g. Kestor, Devon[52]. Several sites produced evidence of ironworking, mostly in the form of slags, and the structural remains were insubstantial. Many of the sites were excavated before scientific dating and archaeometallurgical techniques were available.

Tylecote[4] listed twelve English sites on which slag had been found, to these a further thirty can now be added, but with little increase in our knowledge concerning their technology.

Generally, it has been argued that iron-smelting was at a technological low level during the Iron Age and that the 'bowl furnace with a domed super-structure' was the principal type used. This interpretation of the evidence is currently under review[53], the reassessment being based on two factors. Firstly, the surviving structural evidence. (mostly negative features, e.g. 'bowl hearths/furnaces') was not exclusive to bowl furnaces and could be interpreted as the base of a shaft furnace. Secondly, the quality of the iron artefacts and the smithing techniques. e.g. the Welwyn Fire-Dog[54], suggests a sophisticated technology, not compatible with simple bowl furnaces producing small quantities of iron.

Features that have been interpreted as bowl furnaces were bowl-shaped depressions of the order of 0.30 - 0.45m in diameter

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and surviving to a depth of circa 0.25m, for example Chelms Combe[55]. Kestor[52], and Rowberrow[56], (bowl depth 0.40m). There were no details of the furnace linings, but the fills consisted of soil, slag and charcoal. The fill of the furnace from West Brandon (Durham)[57] was given in more detail, and three layers can be discerned; an upper layer of broken lining and fired clay. which was interpreted as collapsed dome, but could equally be collapsed shaft (cf. Levisham p 31), a middle layer of slag. and a basal layer of charcoal containing some slag droplets.

Larger 'bowl furnaces' were discovered at Brooklands (Surrey)[34], being up to 0.8m in diameter and 0.3m deep. Cleere suggested that these may have had a superstructure of a low shaft rather than a dome. These could be paralleled with the recent discoveries from Bulwick[32].

The excavations at Wakerly. (Northamptonshire)[33] uncovered eight furnaces which were classified into three types. of which two were dated to the Iron Age and one to the Roman Period. Type I were described as bowl furnaces 0.6 - 1.3m in diameter and up to 0.3m in depth; although they were not tapped there was a pit in front of the furnace to enable the slag to be raked out and the bloom removed. They were dated approximately to the first century B.C.. The second type was described as a sunken shaft furnace and resembled, to some extent, the slag-pit (schlackenklotz) type furnace found on the continent[20]. The essential feature was a pit 0.40 - 0.75m deep. one side sloping steeply down to the front of the furnace which was 0.30 - 0.70m in diameter with an arch facing the pit. about 0.35m high. The shaft itself probably stood above ground level. The steeply sloping pit could not be used for tapping the furnace. although

it probably served for raking out, and may also have helped to regulate the furnace atmosphere. This type was dated to the Belgic Period (50 B.C. - 43 A.D.).

The shaft furnace, previously thought to have been a Roman innovation, can be considered to have been introduced in the Iron Age. The sites of the Cow Roast and Dellafield in the Bullbourne Valley (Hertfordshire)[58,59] produced shaft furnaces that were dated on typological grounds to the Roman Period, but study of the pottery dating evidence in the published report indicates an Iron Age date. The Late Iron Age settlement on Levisham Moor (North Yorkshire)[21] had a complex of three shaft furnaces; although described as bowl furnaces, they have recently been re-examined and are now designated as shaft furnaces.

The previous interpretation of the earliest smelting technology in Britain was of small bowl furnaces, often prepacked with ore, in which the slag would liquefy and collect at the base of the furnace leaving the metallic bloom at a higher level. These furnaces produced only very small quantities of iron. Such furnaces or larger versions were the producers of iron throughout the Iron Age until the introduction of the shaft furnace by the Romans. The evidence cited above now indicates the introduction of the shaft furnace prior to the Roman Conquest. This could be paralleled with the introduction of wheel-turned pottery in the Belgic Period of the latter part of the first century B.C., although the evidence from Farthingstone (p65) may indicate a much earlier introduction.

In recent discussions[53] a more suitable interpretation of bowl furnaces has been proposed. Their small size would suggest that there was insufficient volume to enable a fully reducing

atmosphere to be achieved; on the basis of Tylecote's work[12], twelve times the diameter of the fuel size were required before a fully reducing atmosphere was achieved. Estimating a charcoal diameter of 20mm (a rough approximation based on charcoal impressions in smelting slag) means a radius of 0.24m around the tuyere would be insufficiently reducing. In many cases this would leave very little volume for the reduction process to proceed satisfactorily. If rich ores were used reduction could proceed more easily, resulting in less gangue, and hence far less slag.

The archaeological evidence for the geographical distribution and level of technology in Iron Age Britain is in conflict with the quality of some of the finished products and the documentary evidence provided by Roman writers. e.g. Caesar[60].

4.3 The Romano-British Period (Smelting Evidence)

The Roman Period induced a massive expansion of iron smelting (Figure 5, Vol II p210). The shaft furnace was predominantly used, although 'bowl-furnaces' have been found dated to this period. Major centres of production were established, or expanded from Iron Age industries. The main ones were the Weald (Kent/Sussex), the Forest of Dean (Gloucestershire), and Rockingham Forest (Northamptonshire).

Table 4.1 (p46) lists a series of sites and the number of 'bowl' and shaft furnaces, and Table 4.2 (p47) their date ranges. Both types appear to have been used throughout the Roman Period. Table 1 illustrates the southern bias of the information. but, more importantly, shows the two types of furnace were evenly

distributed. The evidence suggests a relative uniformity of dimensions of the shaft furnaces, i.e. an internal diameter of circa 0.30m, and a wall thickness of about 0.20m. The Ashwicken site[30] suggests that they may have had a height of about 1.5m, the tuyeres probably being about 0.30m above the base (cf. Levisham pl7), and pointed downwards (as in modern blast furnaces). The extent of the oxidation zone being dependent on the charcoal size and strength of the blast, means that with an internal diameter of 0.30m the reduction zone was in the vertical plane, i.e. the furnace had bands of differing oxidation/reduction zones varying with the height of the furnace. The shaft furnaces occurred singly or in groups, the latter being the industrial centres. *The output of these centres was massive*, the slag heap at the Wealden site of Beauport Park (Sussex)[24] has been estimated to have originally held upwards of 100,000 tons of slag.

TABLE 4.1   A SELECTION OF ROMANO-BRITISH FURNACES

Site Name	Number	of Furnaces
	Bowl Furnaces	Shaft Furnaces
Ariconium (Herefordshire)[61]	7	6
Ashwicken (Norfolk)[30]	0	6
Broadfields (Kent)[62]	0	36
Cantley (S. Yorkshire)[63]	1	0
Castleford (W. Yorkshire)[64]	1	0
Chester (Cheshire)[65]	2+	0
Dudswell (Hertfordshire)[66]	6	0.
Dymock (Gloucestershire)[67]	2+	0
Foxholes Farm (Hertfordshire)[68]	40	0
Hartfield (Sussex)[69]	1+	0
Holbeanwood (Sussex)[70]	0	4
Manchester (Lancashire)[69]	2+	0
Pickworth (Northamptonshire)[71]	0	2
Sacrewell (Northamptonshire)[69]	7	1
Wakerly (Northamptonshire)[33]	3	4
Whitwell (Leicestershire)[72]	0	1

TABLE 4.2   THE DATE RANGE OF ROMANO-BRITISH FURNACES

```
BC                          AD
50            50   100      200      300      400
 I    I    I    I    I    I    I    I    I    I

-
          _ _ _ _ _ _ _ _ _ _ARICONIUM
B
O                 _ _____ _ _ _CANTLEY
W
L                              _____ _ _ _CHESTER

                  _____DUDSWELL
F
U                    _ _ _____ _ _ _DYMOCK
R
N                              _____FOXHOLES
A
C           _____HARTFIELD
E
S              _____MANCHESTER

                              _____SACREWELL

          _____ _ _WAKERLY
-
```

```
50 BC   AD 50   100      200      300      400
 I    I    I    I    I    I    I    I    I    I

-
S              _____ARICONIUM
H
A           _____ASHWICKEN
F
T        _ _ _____ _ _ _ _BROADFIELDS

F              _ _ _____ _ _ _ _HOLBEANWOOD
U
R           _ _ _____ _ _PICKWORTH
N
A                         _____SACREWELL
C
E     _ _ _ _ _ _____ _ _WAKERLY
S
-                 _____WHITFIELD
```

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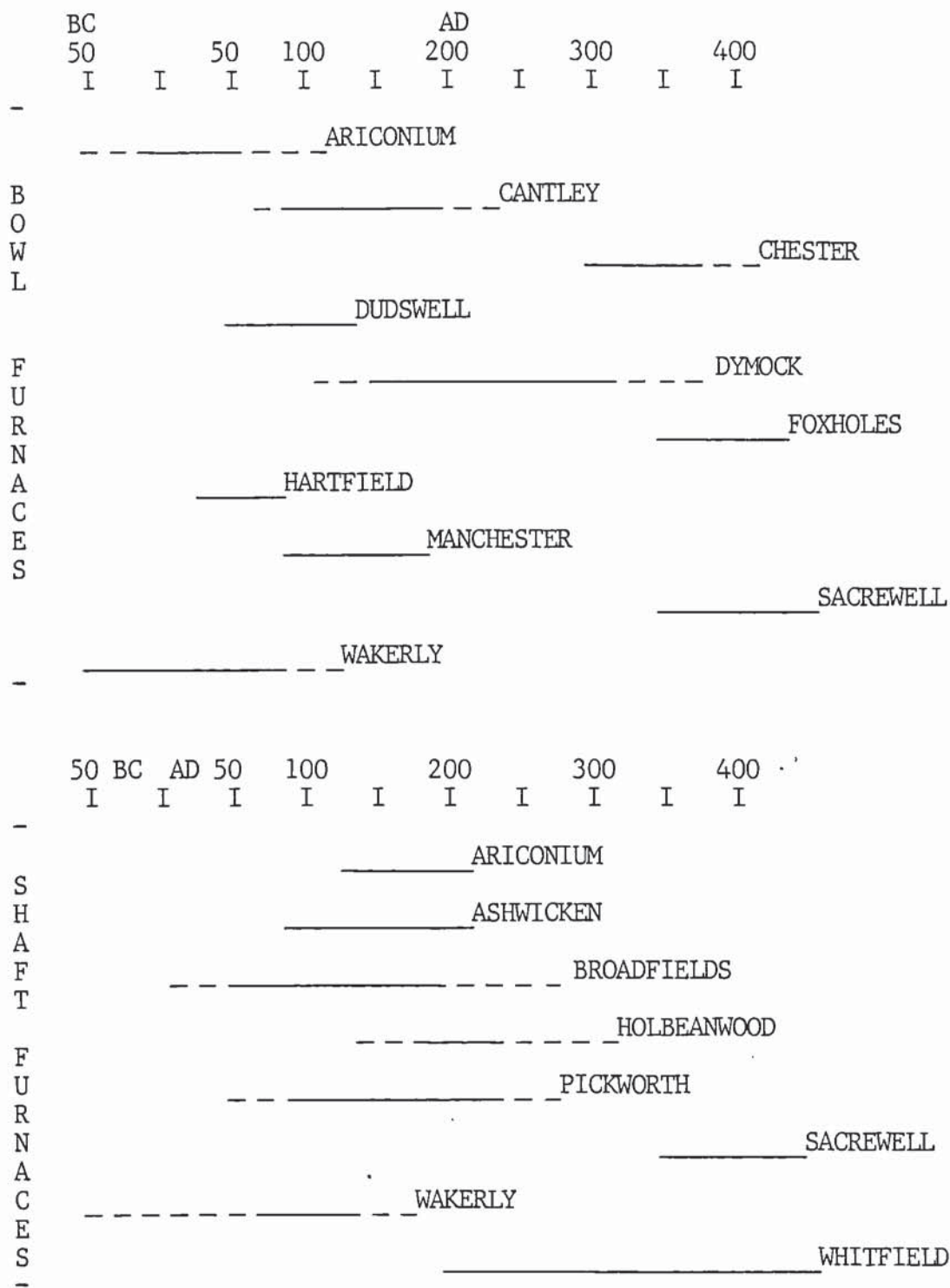
The 'bowl furnaces' have only been found outside the Weald. Their diameters varied considerably from c.0.5m up to 1.5m. The depth was dependent on the state of preservation, and very little superstructure survived, often less than 0.1m. There was, therefore, no indication as to the nature of the superstructure. One feature that has been noted both in Iron Age and Roman bowl furnaces was that there was often a basal layer of unconsumed charcoal several centimeters thick; this was not compatible with the use of free running slag, which would be expected to occupy the basal layer. It has also been noted that the bases showed no evidence of slag attack, which would have occurred at the slag/clay interface, although it was possible cleaning of the furnace after use removed the layer. This has also been observed in shaft furnaces, e.g. Levisham.

The continuing use of 'bowl furnaces' may indicate the continuity of local traditions supplying local needs. The industrial centres depended on the shaft furnace for mass production.

4.4 The Migration Period (Smelting Evidence)

The term Migration Period is used to refer to the period from the end of the Roman Period to the Medieval Period (5th - 11/12th Century). This is because different nomenclature is used in different parts of the British Isles. e.g. Anglo-Saxon. Anglian, and Viking.

The evidence from the period as a whole is insubstantial and confused. This is for two reasons: firstly it spans a period of 700 years and the dating evidence for many sites is very tentative. Secondly, different areas of the British Isles were

under different cultural influences at the same time. For example, late Anglo-Saxon Southern Britain equated with Anglo-Scandinavian Northern England. There is evidence of a major cultural change at the end of the Roman Period towards a kingship society, in which the documentary evidence indicates that the smith played an important role in society. As in the Iron Age the evidence is conflicting; the artefact evidence indicates a high degree of craftsmanship, yet the archaeological evidence (structural/slag) points to small isolated furnaces producing only for local needs. No furnaces have been found in the areas that were the major centres of production during the Roman Period.

Only five sites have produced furnace remains, none of any substance, Figure 6 (Vol II p211). The interpretation of iron-smelting technology therefore relies heavily on the interpretation of the slag evidence. This evidence suggests less reliance on the shaft furnace, which produced the classic tap slag, and greater use of a furnace that produced a more viscous slag tapped or raked into a pit in front of the furnace, e.g. Millbrook (p115).

The settlement site of Mucking (Essex) produced a large quantity of smelting slag, not only in the form of slag cakes probably associated with tapped or raked furnaces, but also other smelting slag types; the most distinct form was the slag block, each weighing twenty kilograms plus. The dating for these was not exact but they were believed to be Post-Roman. Examples of these blocks are known in other areas extending from the Humber[73] southwards around the east and south coasts as far as Romsey (Hants, Section 9.13 p131). They are thought to be a form of the slag pit or schlackenklotz type of furnace, in which the slag was

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retained within the furnace and allowed to fall into a pit below the furnace at the end of the smelt at one instant. The European distribution of this type covers Poland, North Germany, and Southern Scandinavia[20]. There is therefore a tendency to associate the arrival of this technology with the Anglo-Saxon immigrations of the 5th - 7th centuries.

Iron-smelting evidence derives from a few sites which are widely dispersed both spatially and temporally and indicate a variety of technologies in use during the Migration Period. This makes it impossible to identify any coherent development pattern of smelting technology. The most striking feature is the lack of evidence and its absence from the earlier, Roman centres of production.

4.5 The Medieval Period (Smelting Evidence)

The Norman Conquest and associated events can be regarded as the final phase of the Migration Period and the commencement of the Medieval Period. This is a political division. although it did introduce a period of greater political/economic stability, and see the rise of the power of the Monasteries. There was no technological change associated with the political change.

The most significant difference between the Migration and the Medieval Periods is in the survival of documents. This can be said to have started with the Domesday Book, although it provided little evidence for ironworking.

There is extensive documentary evidence for iron mining and smelting in monastic chartularies and manor court rolls. For example the West Yorkshire Survey[5] identified over 70 smelting

sites from a variety of documentary sources, but only a few have been located on the ground. Others have been found but cannot be traced in the documents. The distribution of sites plotted in Figure 7 (Vol II p212) is the evidence derived from excavated or surveyed sites, and does not include smelting (or smithing) sites referred to in documents.

All the furnaces excavated were tapped, most have been described as 'developed bowl furnaces', and were regarded as the typical medieval 'bloomery' furnaces. Exceptions were the furnaces found at Godmanchester (Huntingdonshire)[74] which were described as shaft furnaces.

This study examines only the slags associated with the direct process (see p19), and it was during the Medieval Period that the charcoal blast furnace was introduced. There is no archaeological evidence for its introduction, and the documentary evidence gives a date of 1496 for the first purpose-built blast furnace at Newbridge (Surrey)[24]. This technology rapidly spread and a blast furnace was built on the site of a previous Cistercian Monastic bloomery furnace at Rievaulx Abbey (North Yorkshire) in 1576. Probably by the 1600s the blast furnace was the dominant producer of iron in the Britain. As the evidence for the earliest blast furnace is documentary, it is feasible that the blast furnace may have been introduced earlier than 1496. In Sweden a blast furnace has been dated to the 13th Century[75], i.e. 200 years earlier than Newbridge. The Medieval Period saw the resurgence of centres of production, notably the Weald, Yorkshire and Forest of Dean.

4.6 Summary of Smelting Development

The development of early smelting technology appears to have
followed no step-wise growth. The Iron Age provides no firm
evidence for the earliest type of smelting furnace. The 'bowl'
furnaces offer no clue as to their method of operation. The
free-flowing tapped shaft furnace was present in Britain by the
Late Iron Age and is thought to have dominated the Roman Period,
in which centres of production were established. The 'bowl'
furnace continued in use, but was tapped, although the slag
appears to have been very viscous. In the Migration Period both
technologies continued, with the introduction of new ones. The
shaft furnace and 'developed bowl' furnace, both of which were
tapped, were used in the Medieval Period. The introduction of
the charcoal blast furnace caused the demise of the direct
bloomery furnace, except in remote areas.

Throughout the history of the direct process there may have
been six or more technologies used resulting in different types
of smelting slag.

4.7 The History of Smithing Technology

The evidence for the development of smithing technology
derives from a number of sources. The finished artefact provides
the best evidence for smithing techniques. although
archaeological and documentary sources also provide data. The
lack of a large corpus of artefact analyses, and the random
nature of many of the studies make it unreasonable to compare in
detail artefacts from different periods and localities. Also
the difference in preservation encountered influences the amount
of information retrievable from an object.

The most important development was the use of steel. It has been identified in objects of Iron Age date, and was used in the Roman Period, but heat treatments were rarely used. Its use in edged tools became widespread during the Migration Period, with the sophisticated application of heat treatments. The exploitation of steel and 'wrought iron' reached a peak in craftsmanship during the Late Migration Period (Viking Period), in the manufacture of pattern-welded tools and weapons. In the Medieval Period there was more widespread use of iron, and the craftsmanship declined slightly. Despite these variations in the exploitation of the metal the overall smithing techniques have remained unaltered since the earliest days of ironsmithing. The skill to bend, cut, fireweld etc. has always been required.

This continuity is reflected in the blacksmiths' tools recovered from archaeological contexts. The hoard from Waltham Abbey[19] contained five tongs, a sledge hammer, a file and a poker, a collection that could be seen in any modern smithy (Plate 6, Vol II p232). The only major change was the use of small portable anvils, (known from Roman and Viking Periods, e.g. from Coppergate, York (North Yorkshire)[76]), and the use of wood or stone as the anvil. A volcanic rock was probably used as an anvil at the Howe of Howe (Orkney)[37].

The smithing process required little in terms of hearth structure. The archaeological evidence indicates that the domestic hearth could be used if required, or a simple fire on the ground surface could suffice, leaving no trace in the archaeological record.

A significant question is the role of the smith in society, which was dependent on the nature of the society, urban or rural,

kingship or otherwise. The nature and status of the smith changed through the periods and appeared again to reach a peak during the Migration Period, where in the epic poetry of the time the smith held an important position in society.

CHAPTER 5

THE IRONWORKING RESIDUES

5.1 Introduction

The previous sections have shown that the structural evidence for ironworking is of variable quality and quantity. The nature of archaeology dictates that the majority of features are negative, and extant structures are the exception rather than the rule. This is clearly illustrated in the case of smelting furnaces, in which the shaft furnaces are only identifiable when they have been set into banks enabling part of the superstructure to survive. In the case of smithing hearths some must have been waist-high, thus making the chance of survival extremely remote. Therefore, heavy reliance must be placed on the residues associated with the smelting and smithing processes. The residues are the waste by-products of the processes and so, their composition will be dependent to a greater or lesser extent on the nature of the process. Thus, they provide an opportunity to interpret the conditions under which they were formed, and hence to understand the physical and chemical processes occurring in the smelting and smithing processes. Potentially they may also provide data for the identification of sources. These approaches will be considered in the forthcoming Sections.

The processes which were discussed in Section 2 have certain residues associated with them.

5.2 The Smelting Residues

The smelting process was the reduction of the ore to the metallic state. There were three major inputs: the ore, fuel, and furnace material. All three may be found on an excavated smelting site. The ore, either treated (e.g. roasted) or untreated, should be considered with some caution because it is possible that the ore had been discarded as unusable. The fuel (normally charcoal) provides information on wood type, charcoal size etc.. The in-situ furnace structure provides an opportunity for archaeomagnetic dating, and temperature studies. The output from the furnace was metal and waste products, the residues. Four residues can be associated with the smelting process: smelting slag, cinder, fuel ash slag, and furnace lining.

Smelting slag was the gangue material from the ore in the form of a predominantly crystalline silicate material. It occurred in a number of forms, most characteristically with a flowed lava-like morphology known as tap slag.

Cinder had a number of textures, but mostly comprised unliquefied slags, for example frits of unconsumed ore and charcoal or slag/furnace lining reactions.

Fuel ash slag was a high temperature reaction between silica and the ash from the fuel under oxidising conditions, e.g. in the tuyere zone. It was characteristically small (normally less than 50mm in length), composed of highly gassed shells of siliceous material, often vitrified.

Furnace lining consisted of fragments of the clay lining that had vitrified on the inner (hot) face, and fractured from the furnace wall. The material derived from the zone of highest

hot face temperature, the tuyere zone.

5.3 The Smithing Residues

Five residues were associated with the smithing process: smithing slag, hammer scale, cinder, fuel ash slag, and hearth lining.

Both (smithing) fuel ash slag and hearth lining were formed in the same manner as in smelting. In smithing hearths the atmosphere was predominantly oxidising and hence, more liable to form fuel ash slag than in the smelting furnace. Fuel ash slag and furnace/hearth lining were not restricted to the ironworking process, but may have been formed under similar conditions in other processes. Fuel ash slag has been found in large quantities on archaeological sites not associated with technological processes. For example the farming settlement site of Beckford (Worcestershire) (op. cit.) produced a large quantity of fuel ash slag that was distributed across the site, and could not be directly associated with the smithing slag that was found there. This material occurred in large lumps, up to fist-size, and was not necessarily vitrified. Probably, it derived from a reaction between fuel ash and the soil or sub-soil, and was, therefore, widespread on the site. It was possible that it derived from a single major conflagration, e.g. burning of a hut.

Fuel ash slag and furnace/hearth lining are non-diagnostic residues, i.e. they cannot be identified as having derived from the ironworking process, although this is normally done by association.

Smithing slag was the crystalline silicate slag formed in

the smithing hearth. It occurred characteristically as hearth bottoms, plano-convex accumulations of slag.

Cinder was smithing slag containing a higher silica content resulting from the more oxidising conditions that prevailed in the smithing hearth.

Hammer scale was the oxide/silicate scale that fractured from the surface of the iron being worked, due either to thermal shock or hammering.

5.4 The Application of the Residues to Archaeological Sites

The seven types of residue described in 5.2 and 5.3 are used as broad classes when sorting the residues from an archaeological site. It will be shown that the types do not have strict definitions, for example the silicate slag/cinder division cannot be defined by the percentage of any particular element or mineralogical texture. One site may have slag of a more cindery appearance than another and hence the differentiation between slag and cinder on each site would also differ.

The large quantities of residues encountered on archaeological sites restricts detailed analysis to a few selected samples. The selection is based on a number of factors: the variety of residues encountered, their temporal and spatial distribution, and the nature of the site e.g. urban or rural. Therefore, the initial 'on site' classification is based on the morphology of the residues, and confirmation made by detailed analyses of selected examples.

The residues are, by definition, waste material and hence become separated from the area of working, thrown away or

deposited in surrounding features that, although contemporary, are not directly associated with the activity, e.g. pits and ditches. The residues are not (very) susceptible to corrosion or degradation due to their chemical and mineral composition, and hence they survive essentially unaltered by weathering or burial. Therefore, on continuously occupied sites the residues are liable to redeposition, and hence, there may be a severe problem of residuality. The nature of the residues, particularly the smelting and smithing slags, are suitable materials for foundations, road or yard metalling. For example, a number of Roman roads in the Weald are constructed of smelting slag from the ironworking industry.

The site of the Roman villa/workshops at Amersham Mantles Green (Buckinghamshire) typifies the problem of residuality and redeposition. The site was first occupied in the early second century A.D., and finally abandoned in the late fourth. It was divided into eight phases (I -VIII). There were two periods of building construction on the site, Phases II and IV. Only a small area of the site was available for excavation. The spatial distribution showed the slag to be concentrated in one area of the site and indicated that the focus of the ironworking activity was close to but outside the area excavated (no ironworking features were identified). The phase distribution of the residues is shown in Figure 8 (Vol II p213), plotted as a percentage of the total of residues recovered, and Figure 9 (Vol II p214), plotted as a percentage of each type, i.e. total tap slag = 100%. These show smelting occurring in Phase I and III with residual quantities occurring in the other phases. Smithing also occurred in Phases I and III as well as later on in Phase VI. Residual quantities occurred in the other Phases. The

furnace/hearth lining is also plotted and this correlates with the smelting slag rather than the smithing slag. This is because of the larger quantity of lining present in a smelting furnace than in a smithing hearth; in this case a denser soft sandstone was used as part of the lining instead of the usual clay lining. The very low quantities of residues recovered from Phase II was due to the Phase being a period of a large timber posthole building. The features were, therefore, postholes which exclude the preservation of slag in this Phase. The Phase I smelting and smithing precedes the construction of the large timber building. The residues in Phase III are associated with cobbling layers. and also precede the construction of a stone building in Phase IV. The activity in Phase VI coincides with the demolition of the stone building. There is, therefore, a correlation between building/demolition and ironworking activity. The periods of ironworking activity are identified by their greater than background levels of residues recovered from the features dated to those phases. The difficulty with the site is to assess whether the quantities of smelting slag recovered from Phase III represent a separate period of smelting or are residual from Phase I. The near absence of all residues from Phase II hides any gradual decline in residue quantity as can be observed in the quantities of smithing slag in Phases III, IV, and V. The quantity, morphological, chemical, and mineral analyses of smelting slag from Phases I and II showed no significant differences. It can, therefore, be proposed that the smelting slag from Phase II is residual, although if there had been a second period of smelting activity and they had exploited the same ore source and used the same technology, differences would have been slight and lost in the level of heterogeneity observed in the analyses of slags.

The spatial and temporal distributions of the residues on a
site can identify areas and periods of ironworking, despite
residuality and the dispersal of slags into features contemporary
with, but not associated with, the ironworking activity.

The residues can be divided into two broad groups; first the
non-diagnostic residues, which are those that cannot be ascribed
to either the ironworking process in general, or to the smelting
or smithing process in particular. The second group are the
diagnostic residues which are the ones that are directly
attributable to the ironworking process. Section 6 discusses the
non-diagnostic residues and Section 7-12 the diagnostic residues.

CHAPTER 6

THE NON-DIAGNOSTIC RESIDUES

6.1 Introduction

The smelting and smithing processes produced two non-diagnostic residues, furnace/hearth lining and fuel ash slag. Also these residues may have been the products of other pyrotechnological processes. Their presence on a site is not, therefore, indicative of smelting or smithing having been practised on the site. It is necessary to give a general description of the two residues and stress certain aspects that may help to indicate their association with ironworking.

6.2 Fuel Ash Slag

In Section 5 fuel ash slag was described as a high temperature reaction product between the ash present in the fuel and silica. This reaction occurs at high temperature under oxidising conditions. Such conditions prevail in many technological furnaces, kilns, and hearths, as well as domestic hearths and fires and accidental/destructive fires. The characteristic features of fuel ash slag are its vesicularity (hence its low density), and its colour, which is generally grey-yellow. Higher iron oxide contents may produce other colours. Fuel ash slag may be subjected to very high temperatures and become vitrified, resulting in a further range of colours. Chemically it is predominantly silica, with minor concentrations of iron, calcium, and potassium oxides. X-Ray Diffraction Analysis of a sample identified only the presence of the mineral silica. Several d-spacing values were unidentified. The other oxides present formed either a glass phase or minerals that

comprised less than the minimum detectable limit of the technique, (5-10%?).

Fuel ash slag normally occurs in lumps less than 50mm in length, the average being 10 - 20mm. The Iron Age site of Beckford (Worcestershire) (op. cit.) produced 33.5 kg of fuel ash slag, the majority of which occurred as large lumps 50 - 100mm in diameter. It was widely distributed across the site. and the genesis was unknown, but thought to be either from one major conflagration, or derived from small (domestic?) fires. A similar form of fuel ash slag was recovered from the settlement/cemetery site of Wasperton (Warwickshire)[77]. It was deposited in a single feature, a pit, with no evidence of a wider distribution. This would indicate that it (and, therefore the Beckford material) derived from a single occurrence rather than several fires.

Fuel ash slag is commonly found in deposits of diagnostic slags, most often in association with smithing slag. It is rarely recovered in situ. The excavation of the Norse settlement on Birsay (Orkney) discovered a small ground level smithing hearth (op. cit.). The hearth fill consisted primarily of earth and charcoal with hammer scale and some smithing slag. Fuel ash slag was present and occurred on the periphery of the hearth fill, next to the clay wall of the hearth. There was no evidence in the hearth wall of a fixed tuyere mouth, and therefore the air blast was probably provided by a small pair of movable bellows which could be directed at any area of the hearth.

Fuel ash slag has not been recovered from the fills of smelting furnaces, but they have usually been cleaned out in

antiquity, and therefore it cannot be stated with any certainty as to whether fuel ash slag was generated by the smelting process. The smelting furnace was a dynamic system with respect to the smithing hearth, because the burden moves down the furnace. Formation of fuel ash slag may occur in the tuyere zones (oxidising conditions), and would remain unaltered in the early phase of working-up the furnace, during which time only fuel was burnt. The introduction of the iron ore and the subsequent formation of silicate slag would cause any fuel ash slag to be consumed by the silicate slag, since free iron oxide has great affinity for free silica. It is, therefore, likely that only very small quantities of fuel ash slag would have been generated during smelting.

Fuel ash slag does occur attached to pieces of furnace/ hearth lining, the silica of the lining having reacted with the ash from the fuel.

Fuel ash slag has a range of compositions, as judged by its appearance and density. Increasing iron oxide content gives rise to the formation of silicate slags, and the fuel ash slag becomes more cindery, until finally it becomes a silicate slag. There is no defined point at which a fuel ash slag becomes a cinder.

6.3 Furnace and Hearth Lining

In antiquity clay was one of the most utilised raw materials. Archaeological contexts indicate a misleading reliance on clay, since when fired it becomes durable, and other materials, notably the organic materials, wood, leather, etc. decay during burial. Clay was used to manufacture vessels in the form of pottery, from the crude neolithic pots to the

sophisticated wares of the Roman and Medieval periods, e.g. samian and stoneware. Clay was an important building material, e.g. wattle and daub. The survival of clay as a recognisable artefact, e.g. a pot or piece of daub, is dependent on it being fired to a sufficiently high temperature. Too low a firing will allow weathering and degradation to occur. Clay has been used as a basic building material for most technological furnaces, kilns, ovens, and hearths, although other materials may have been used or incorporated in the structure. Many furnaces etc. were often predominantly stone built, but luted and lined with clay, e.g. the furnace at Rotherfield/Minepit Wood in the Weald (Sussex)[78]. Other materials must also be considered as furnace and hearth building materials, for example, the possibility of stone/turf built furnace(s) from Steinfinnsstadir (Iceland)[7]. The residue evidence from Amersham Mantles Green showed the use of soft sandstone/mudstone as the furnace building material. In Britain the well-preserved iron smelting furnaces were built predominantly from clay; examples are known from the Weald, Norfolk (Ashwicken[30] and Scole[31]), Yorkshire (Levisham[21]), and Orkney (Howe of Howe[37], where only the base survived). Their preservation was not dependent on the degree of firing, but they were built into banks (except for Howe), which protected the lower part of the structure from damage, although the extant superstructure was destroyed.

Structural clay would have occurred in three forms, unfired/poorly fired clay, fired clay, and furnace/hearth lining. The first type would weather and degrade during burial, leaving little trace in the archaeological record. The fired clay, including daub, is normally burnt red (or grey, if reducing conditions prevailed), and reasonably hard, although it can be

easily abraded. These two forms are common finds when clay has been used for building purposes, but can only be recognised as such when wattle impressions are present.

Furnace or hearth lining is characterised by the hot face being vitrified. It is therefore associated with high temperature processes, principally pyrotechnological, although it may occur in domestic hearths. A section through one of the Bulwick furnaces (Plate 7, Vol II p233) shows the vitrified hot face degrades rapidly to well fired clay. The high temperature required for vitrification to occur (approximately 1200°C-1500°C) restricts the area of formation to the tuyere zone of the furnace or hearth. Therefore, the tuyere mouth only is preserved. The concept of a tuyere has become confused in archaeology. The commonest impression is that of a large cone of clay with the air passage running down the length. The only example known of this type is a Norse(?) steatite (soapstone) tuyere from Orkney, (Plate 8, Vol II p233)[79]. The tuyere that commonly survives in the archaeological record, is the tuyere mouth, which is a 10-20mm diameter hole through the furnace or hearth wall, or through the 'bellows protector' (see below).

The evidence of the well preserved furnaces provide some information as to the nature of the fired clay and hence the parts that are likely to survive in destroyed furnaces. Two examples have been closely studied in situ, -Levisham Moor and Scole. In the Levisham example two tuyeres survived approximately 0.3m above the base, in the furnace wall that was extant above the bank. They were inclined downwards at an angle of about 30° to the horizontal, and the tuyere holes were 10-20mm in diameter. The furnace had been re-lined at least once and there was slight vitrification around the tuyere mouths. There

was no evidence of slag attack or vitrification in the base of the furnace, which indicates that it had been efficiently cleaned out in preparation for re-use. The (assumed) slag attack and cleaning resulted in a concave profile to the inside of the furnace, Figure 10 (Vol II p215); this was the probable reason for the subsequent relining, and the original interpretation of the furnace as a 'domed bowl furnace'[21]. The clay wall was 100mm thick and uniformly well fired in the vertical plane, although it degraded from the internal face outwards.

The Scole furnace was very similar, but is dated to the Roman Period. The overall dimensions were the same as Levisham although less of the height survived and the tuyeres were absent. The clay lining was more heavily fired, and also showed degradation from the hot face outwards, it had also been relined and cleaned out.

The evidence of Levisham and Scole indicates a uniform firing at the base of the furnace. If they had been destroyed in antiquity or during burial the lining would survive only as large fragments of well-fired clay.

The structural remains of smithing hearths are more varied. Iron could be smithed either in a sophisticated hearth or (if necessary) in a simple hearth on the ground surface. Since the hearth is not required to maintain a high temperature and a reducing atmosphere, an enclosed refractory structure is not required. Thus even a sophisticated hearth can be built of stone with only the hearth base lined with clay. Plate 9 (Vol II p234) shows the smith's hearth on Sanday, Orkney, partially cleaned out; the base is clay and the tuyere mouth is visible. The localised temperature variation of the hearth results in

heterogeneous firing of the clay. The highest temperatures occur in the tuyere zone, which results in vitrification of the surrounding clay. The tuyere mouths from Hutton-le-Hole (Plate 5, Vol II p232) and the smithy on Sanday are similar to those recovered from archaeological sites.

The temporary hearths or domestic hearths used for smithing did not have a substantial structure, but the bellows would require insulation from the direct heat of the fire. In these cases 'bellow protectors' may have been used. Often triangular, 40-50mm thick, and up to 100mm in height with a transverse central hole, they were normally made of clay, although a steatite example is illustrated in "Iron and Man in Prehistoric Sweden"[21]. Bellows protectors (and hearth lining that includes a tuyere mouth) have been commonly mistaken for loom weights; the former may be distinguished by the vitrification on the hot face, or the evidence of above normal firing temperatures.

Furnace and hearth lining are particular forms of the fired clay structure, characterised by the vitrified hot face. It is also common to encounter adhering silicate slag, cinder or fuel ash slag. Plates 10a and 10b (Vol II p235) shows a hearth bottom with adhering lining (from Amersham Mantles Green excavation). These show a large volume of slag/lining reaction zone.

In general (vitrified) furnace/hearth lining probably derives from technological processes, rather than domestic hearths or kilns etc.. The lining rarely provides sufficient information to identify the process from which it derived, especially if found in isolation from other ironworking debris.

6.4 Summary

Fuel ash slag and furnace/hearth lining are treated as non-diagnostic slags, because they cannot be ascribed to ironworking in general, nor with any certainty to a particular process. They are normally ascribed to ironworking on the basis of association.

CHAPTER 7

ANALYTICAL METHODS

7.1 Methods of Analysis

Three types of analyses have been applied to the diagnostic slags. The first is the morphological description of the specimen, which includes overall appearance, dimensions, weight, colour, fracture, and the presence of foreign (non-slag) matter, e.g. pebbles, charcoal. The classification of a corpus of slags from a site relies on this method since only a few samples can be chemically or mineralogically analysed. Initial classification of all residues is based on the morphological study.

The second type of study is the preparation of specimens for microscopical studies. A thick section is cut from each sample using a diamond saw and mounted in conducting bakelite. They are ground on a succession of silicon carbide papers, and provided that the slags are well-formed and are not cindery and/or friable, a one micron polish finish can easily be achieved (using cloth pads and diamond paste). The standard metallurgical microscope is used to examine the microstructure which was evident without etching. The three major silicate-slag phases, iron silicate, iron oxide, and glass, are readily identified. The exact nature of the silicate cannot be determined. and other minerals may be present, distinct from the silicate, but not identifiable. e.g. hercynite. The texture and habit of the phases are indicative of the cooling rates, although other factors may influence crystallisation, for example, the presence of undissolved minerals such as forsterite ($2MgO.SiO_2$. m.pt. 1890^oC). The individual mineral percentage (volumetric percentage) is determined using the comparative technique of

Shvester, described by Terry and Chilingar[80] at a magnification of X100. Percentages are determined to +/- 5%, and vesicles are ignored in the volumetric determination. It is difficult to obtain satisfactory results for very vesicular specimens. Thus, the percentage values obtained for the silicate, glass and free iron oxide phase in a given field totalled 100%.

The third type of analysis is chemical and mineral analysis using a number of different techniques. Mineral identification of bulk samples can be obtained by X-ray diffraction (Cobalt excitation) of powdered samples or of the polished micro-specimen. This technique cannot provide information on the glassy phase, and will only detect the major minerals present.

7.2 Chemical Analysis

Previous workers have chemically analysed slags in two ways, firstly, an overall bulk analysis using Atomic Absorption, wet chemistry or wavelength dispersive X-ray fluorescence. Secondly, individual phases of the polished specimen are analysed by the Electron Microprobe to determine composition. A major influence when considering ancient slag analyses is that of heterogeneity, and how representative of the whole sample is a single bulk analysis? This, therefore, questions the relationship between individual phase analyses and the bulk analyses. To minimise the bulk/phase discrepancies the Scanning Electron Microscope with a Link Energy Dispersive System (E.D.S.) is used for both analyses. Bulk analyses are obtained using a raster scan at a magnification of X200, (giving an area of scan of approximately $0.25mm^2$), or if the sample is very vesicular a higher magnification is used. Individual phases are identified using the S.E.M. in the spot mode at an appropriate magnification. The E.D.S. system uses

calculations based on standard spectra, (normally pure element standards), obtained from spot analyses. To obtain a closer similarity between the sample and the standard spectra, a slag with a silicate phase of stoichiometric fayalite, (i.e. 70.5% FeO), confirmed by electron micro-probe analysis, is analysed and used as the iron and silicon standard spectra. To investigate any variation between bulk raster scan analyses and other methods of bulk analyses it is essential to obtain an homogeneous specimen which can be subdivided for independent analysis. This is not normally possible for slags, which are usually heterogeneous, but a fine grained smelting slag (D.I.S. see Section 9.15) was cut into six sections. Alternate specimens were powdered and analysed by an independent laboratory using Gravimetric and Atomic Absorption techniques, and the remainder mounted and analysed using the S.E.M.. The results are given in Table 7.1 (Vol I p73). The S.E.M. results are the mean of five bulk analyses of different areas of each sample. The results show close correspondence, the greatest difference being in the alumina contents.

Therefore, the bulk analyses obtained by the S.E.M. energy dispersive system can be accepted as representative, although it is noted that the system was primarily designed to obtain spot analyses of homogeneous phases, and not large areas containing segregated elements. e.g. iron oxide dendrites. The advantage of this method of analysis is that the bulk analysis can be related to the mineral structure, and that the phases within the area can also be analysed.

TABLE 7.1   ANALYSES OF DENSE IRON SILICATE SLAG BY S.E.M. (SAMPLES
2, 4 AND 6) AND INDEPENDENT CHEMICAL ANALYSES (SAMPLES
1, 3 AND 5).

	SAMPLE		NUMBER			
	1	2	3	4	5	6
Na_2O	0.06	0.3	0.06	0.1	0.06	0.3
MgO	0.13	0.1	0.12	0.1	0.12	0.1
Al_2O_3	2.46	2.3	2.57	2.1	2.59	2.0
SiO_2	26.80	23.5	26.70	26.6	27.82	25.9
P_2O_5	0.56	1.0	0.72	0.9	0.60	0.9
S	n.d	N.D	n.d	N.D	n.d	N.D
K_2O	0.13	0.2	0.14	0.6	0.14	0.3
CaO	0.43	0.5	0.45	0.6	0.46	0.5
TiO_2	n.d	N.D	n.d	N.D	n.d	N.D
V_2O_5	n.d	N.D	n.d	N.D	n.d	N.D
Cr_2O_6	n.d	N.D	n.d	N.D	n.d	N.D
MnO	0.05	N.D	0.05	N.D	0.05	N.D
FeO	68.1	71.3	68.4	68.5	68.1	68.7
CoO	n.d	N.D	n.d	N.D	n.d	N.D
NiO	n.d	N.D	n.d	N.D	n.d	N.D
Total	98.72	99.2	99.21	99.5	99.94	98.7

N.D - Not Detected;   n.d - Not Determined

The main purpose of this work is to establish criteria by
which smelting slags can be differentiated from smithing slags.
To use the chemical analyses to differentiate between the slag
types statistical techniques must be applied.   A number of
methods are commonly applied to similar problems, both within
archaeological sciences and in other disciplines. These include
regression analysis, discriminant analysis, and cluster analysis.

and their application is discussed in Section 13. An outline of discriminant and cluster analysis is given in Appendix 4.

7.3 Normative Mineral Calculation

The chemical analyses of areas (bulk analyses) or of individual phases can be converted to theoretical mineral assemblages. The method is termed the Normative Calculation (C.W.P. Calculation) and has been used extensively by geologists to classify igneous rocks on the basis of their (varying) normative mineral compositions. Thermodynamically different minerals are stable at different temperatures. Therefore, within a cooling liquid containing a number of oxides, there is a succession of mineral precipitations. The normative calculation determines the theoretical quantity of minerals formed from a given assemblage of liquid oxides in a predetermined sequence. The method does not imply that the minerals calculated will be present in the final mineral suite, since equilibrium conditions, perfect mixing etc. are required. Normative calculations have been applied to archaeological non-ferrous slags by Bachmann[81] and to ironworking slags, principally bloomery and blast furnace slags, by Kresten[82]. The latter used the technique to distinguish/classify the bloomery and the blast furnace slags, and has been used in the present study. Kresten (p.12) stressed the importance of analysing for Fe^{3+} and Fe^{2+}, except when appreciable amounts of free iron oxide were present. In these cases the Fe^{3+}/Fe^{2+} ratio would only effect the wustite/magnetite ratio, and not the amount of silicate calculated. The analytical technique used in this study could not determine the valency of the iron and therefore, the Fe^{3+} content was not calculated. The ferric iron content could have been determined by wet analysis,

but this would require a second sample which would be independant of the other analyses, and the Fe^{3+} may have derived from metallic iron inclusions or ferric-oxide hydrates, and therefore not relate to the normative mineral calculation. The majority of slags examined in this study contained excess iron oxide and therefore, the silicate calculation should not be affected. Significant quantities of Fe^{3+} could be detected by the failure of analyses to total 100%, and if needed, adjustments made to the analysis. Errors were detected in the computer programme provided by Kresten and these were corrected. A worked example is given in Appendix 1 and a listing of the computer programme in Appendix 2.

7.4 Ternary Phase Diagrams

The complex chemical compositions and mineral assemblages of early metal working slags have also been displayed and manipulated on ternary phase diagrams. The choice of which particular ternary diagram to use has been the subject of much discussion, e.g. Fells[op.cit.], since Morton and Wingrove[op.cit.] proposed the use of the wustite-silica-anorthite diagram in 1967. The use of ternary diagrams are clearly of value since slag mineralogy normally comprises three minerals, silicate, glass and free 'iron oxide (termed 'FEOX'). Therefore, an optical volumetric analysis of the different samples and, by grouping of the normative minerals into three phases, (silicate, glass and free iron oxide [FEOX], termed the ternary grouping), the bulk analyses could be plotted on to a ternary diagram. Thus, it is hoped that different slag types would plot in separate areas of the diagram.

The present study of slags has used conventional means, i.e.

the recording and measurement of attributes of the slags, e.g. colour, fracture, chemical composition, etc.. As the study progressed it was found that the heterogeneity or homogeneity of the slags needed to be assessed. Throughout previous analytical studies there has been a requirement to homogenise specimens prior to measurement of certain attributes: for example, the common practice of 'coning' powdered samples before bulk chemical analysis. There are problems associated with analysing archaeological artefacts, whether they be slags, metal artefacts or pottery. In particular, there is the requirement to take as small a sample as possible from the most unobtrusive place to avoid damaging what might be a rare artefact, and hence devaluing the object in monetary or aesthetic terms. Hence, many of the published studies have relied on the extraction of a small sample for analysis, and few have been able to take a sufficiently large sample to examine the variation across a specimen. It was, therefore, considered a probability that some slags may be more heterogeneous than others. In particular, it was thought that the smithing slags in general would be heterogeneous due to their method of formation, (see Section 10), while the smelting slags would be (relatively) homogeneous because they would have been fully liquid at some time in their formation.

Therefore, to investigate the relative homogeneity/ hetero-geneity of each sample five measurements of the volumetric analysis and five bulk analyses were taken from different areas of each sample. It was not considered practicable to take five different sections from each sample. To compare each set of five results they were plotted on to a ternary diagram. The bulk analyses were reduced to three phases by firstly, the use of the normative calculation to determine the theoretical mineral

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assemblage. Secondly, the minerals were grouped together into three phases in the following manner:-

Silicate Phase forsterite, tephroite, fayalite, enstatite, rhodonite, and ferrosilite.

Glass or Silicate Phase calcium silicate, wollastonite and hercynite

Glass Phase apatite, vivianite, ulvite. pyrrhotite, kalsilite, potassium silicate, nepheline, sodium silicate. anorthite, mullite, gehlenite, orthoclase, albite and quartz.

Iron Oxide Phase wustite

The distance between each of the plotted points was measured, this distance being termed the r-factor, (Figure 11 (Vol II p21b). The mean r-factor (r-mean), (and the standard deviation) for each sample was calculated. and this was treated as a relative measurement of homogeneity. To simplify the calculation the ternary co-ordinates were converted to X,Y, co-ordinates, and then the distance between each point was calculated.

The calculations are performed by the following formulae:

To convert ternary co-ordinates (Silicate A%, Glass B%, FEOX C%) to rectangular co-ordinates (X%, Y%).

$$Y = B\% * Cos30$$

$$X = (C\% + Y/Tan60)$$

To determine the distance (r) between two co-ordinates (X_1, Y_1) and (X_2, Y_2), (note r is always positive):

$$r\text{-factor} = \sqrt{(X_2 - X_1)^2 + (Y_2 - Y_1)^2}$$

The computer programmes to perform these calculations are given in Appendix 3. It should be noted that the sequence in

which the data is input into the 'Ternary" programme, (to convert ternary co-ordinates to X,Y co-ordinates), is crucial, and the strict sequence silicate%, glass% and iron oxide% was followed throughout. The volumetric r-factors are calculated only to two significant figures, because the phase percentage was measured to +/- 5%.

The normative calculation assumes equilibrium conditions to prevail. The rapid cooling of a slag emerging from temperatures of the order of $1100^{o}C$ into ambient temperatures clearly deviates significantly from equilibrium conditions. Therefore, the different slag types may be expected to differ from equilibrium conditions to varying extents. This variation would be expected to cause differences to be found between the theoretical phase composition, determined from the normative calculation, and the measured phase composition determined by the volumetric analysis. Therefore, the r-factor analysis method was applied to measure the differences between the volumetric and the normative (termed 'ternary') phase compositions, giving a volumetric/ternary r-factor.

Therefore, the analysis for each sample comprises five volumetric analyses and associated volumetric r-factors, five bulk analyses, the calculated normative mineral constituents, ternary groupings and ternary r-factors. The analyses include individual phase analyses, for which normative mineral constituents may be calculated. The volumetric and ternary analyses are compared using the volumetric/ternary r-factors.

CHAPTER 8

THE SMELTING SLAGS

8.1 Introduction

The smelting process (discussed in Section 2) can be summarised as the reduction of iron ore by (principally) carbon monoxide to metallic iron, with silicate slag as the main by-product. The process was carried out in a furnace, normally constructed of clay. The iron (or steel) conglomerates as a pasty lump, the bloom, and the liquid slag separates, forming a pool at the base of the furnace. The slag was normally removed (tapping) to avoid the level of slag reaching the tuyeres causing blockage and failure of the furnace. The method of removal varied with the different technologies which were employed at different periods in the archaeological record.

The study of the historical development of smelting technology has been impeded by the lack of suitable archaeological evidence, and the disproportionate distribution (both spatially and temporally) of dated sites; for example large numbers of Roman furnaces have been excavated in the Weald in Kent, but only seven Anglo-Saxon sites are known, none of which occur in the previous (Roman) centres of iron production.

The iron smelting evidence in the Iron Age is confused; the earliest slag (Sixth Century B.C.) is a form of tap slag from Farthingstone (Northamptonshire). In the Middle Iron Age, so-called 'bowl furnaces' have been identified. The shaft furnace, which produced the classic tap slag, was introduced into Britain towards the end of this period, according to the evidence currently available. This might be indicative of Belgic influences, corresponding to the introduction of the wheel in

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pottery technology. It is therefore tempting to argue for a general raising of industrial skills in a number of technologies. The Roman Period was dominated by the shaft furnace and mass production of iron in the major centres, e.g. the Weald and Forest of Dean, although small operations were carried out to supply local needs, e.g. Amersham Mantles Green.

It has been argued that a decline in technological skill accompanied the collapse of the Roman organisation in Britain in the Fifth Century A.D.. It is unlikely that the technological skill declined, although different technologies were introduced and mass production declined, and needs were met by local production.

Saxo-Norman and Medieval furnaces have been excavated, but the evidence is widely distributed and no coherent development can be determined. Extensive evidence of iron ore mining and smelting is found in the documents of the period, since the extraction and smelting rights were carefully controlled, and exploited principally by the monasteries, especially the Cistercians. The shaft and 'bowl' furnace technologies appear to have fused together in the form of the 'developed bowl' furnace.

The evidence of technological changes presented in Section 2 and 4, and summarised above, shows that there was no step-by-step, chronological development in iron-smelting technology. The overall impression is that a variety of technologies were introduced into Britain at various periods, that alternative technologies were in use in different areas at the same time. It was probably only in the Roman Period that one technology, the shaft furnace, became dominant in Roman Britain. Different technological traditions survived in many areas. There was also

the geographical factor, of the requirements of Upland Britain, north west of the Severn-Wash line, versus those of southern, Lowland Britain, south east of the Severn-Wash line. It can be argued that the lowland arable farmer had greater need of iron than his upland, pastoral, counterpart.

The archaeological evidence is disproportionately distributed between periods; for example there is little definite evidence, i.e. smelting slag, from the Iron Age, in contrast to the large numbers of Roman furnaces and slag heaps, which are known or have been excavated.

The variety of technologies, their temporal and spatial distributions, together with the discontinuity of evidence, inhibit any methodological approach to the study of smelting slags. Four systems of study can be considered; firstly the development approach in which the slags are examined in chronological sequence from primitive technologies through to high technologies. The difficulties arise in defining what is meant by 'primitive' and 'high' technologies. Various criteria have been used, e.g. furnace type, slag type, and efficiency, but no single definition can be applied exclusively to all technologies. Also the evidence shows that variations in technology are not temporal, and hence there is no real thread of development running through from the Iron Age to the Early Medieval Period.

The second type of study is the historical/temporal approach, which has the same faults as the developmental study, and also the weight of evidence is biased towards certain periods, and would therefore be difficult to provide a balanced approach.

The third method of study is the spatial or geographical approach in which the evidence from all periods in two or three particular localities would be examined. There is a trend in archaeology to discuss material culture, settlement patterns etc. in this way, because natural barriers, and environmental conditions were a controlling factor in the nature of the settlement and economy of a region. Ironworking technology was subject to the general technological level of the society in which it was practised, but also subject to more industrial factors, e.g. types of ore sources, fuel and furnace building material. Therefore, this method would be suitable to the study of ironworking technology, and Fells[9] followed this approach in general in her study of smelting slags and ores, by concentrating on two areas, Northamptonshire and the Weald. However, there are no suitable areas to compare in which there is sufficient available evidence of continuity; also there are some technologies that, at present, were restricted to specific areas.

The fourth method of study is the technological approach in which slags of similar morphology are loosely grouped together to form classes. This method does not provide a developmental, historical, or geographical theme, but uses data from sites of different periods and regions to illustrate the technological types. This can be seen as an advantage in illustrating the variety and variation, spatial and temporal, of iron smelting technologies that have been exploited within the archaeological record. This is, therefore, the method of study that has been employed here, but with some restrictions on interpretation.

The slags selected for study have been those examined during the author's work for the Historic Buildings and Monuments Commission (formerly Department of the Environment) Ancient

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Monuments Laboratory, which is restricted to English sites excavated under the auspices of H.B.M.C.. Additional material has been obtained through other contacts in areas of particular interest e.g. Orkney (Figure 12 Vol II p217). Although as wide a group as possible of material has been studied it cannot be claimed that all slag/technological types have been examined. Further, this work must be seen in the wider context of a relatively new science (that of archaeometallurgy and in particular the study of early ironworking), and the work of other researchers e.g. Fells[9] and Clough[83].

Smelting slags have been the subject of several studies, summarised recently by Fells[op.cit.]. The early work included investigations into the mechanisms of the smelting processes, e.g. Tylecote[12]. Later work e.g. by Morton and Wingrove[13] investigated the structure of smelting slags. Recent work has been directed at analysing the ore-slag relationship, e.g. Fells[op.cit.]. The relevance of earlier work will be referred to as appropriate.

The smelting residues have been divided into groups since they provide the main evidence of iron smelting on archaeological sites, and the occurrence of a well-preserved furnace structure is an additional bonus. Similarly smelting slags have been grouped together since their external morphology is a function of the method by which they were removed from (or remained in) the furnace. It is, therefore, argued that comparable methods of removal reflects a parity in technological level. It does not necessarily reflect similarities in overall furnace structure. Those slags that are tapped, and have the distinctive lava-like appearance, which are common in the Roman and Medieval Periods, must have been of similar viscosity within the furnace, and would

be removed, and allowed to cool in a comparable manner. This does not mean that the temperature profile within the furnace, nor the iron oxide, silica and alkali metal oxides in the slag, were the same, or that the height of the furnace or the number of bellows used were the same.

This approach is, therefore, a classification of slag, (and by implication of technology) but is not a classification of the ironworking process or furnace type. Nor does it imply an efficiency of the technology since the individual slags from a furnace or smelt will only show the efficiency of that particular smelt or furnace. Further, the efficiency of the smelt may be attributed to other factors, e.g. fuel and ore quality, the furnace structure and the skill of the smelter.

Smelting slags are divided into five groups. Firstly the classic tap slag which is distinguished by its characteristic lava-like morphology (Plate 11, Vol II p236), and is the most commonly identified smelting slag, to such an extent that often it has been regarded as the only smelting slag.

Secondly, the 'raked slag' which although it had clearly been liquid could not flow freely from the furnace and was therefore raked out (Plate 12, Vol II p236).

The third group includes the slag blocks or schlakenklotz, large blocks of slag weighing up to 50 kilograms (Plate 13, Vol II p237). Their distribution was originally confined to the continent but now has been identified in south and east England.

The fourth category is unique to one site in Britain. It is possibly a variant of Type 3, and is known as Dense Iron Silicate Slag (DIS). It is very fined grained and dense, and occurs in

small lumps up to 1 kilogram in weight.

The fifth group of smelting slags (not analysed in this study) is obtained from many furnaces, and includes furnace bottoms and clinker. The furnace bottom is slag that was left to cool within the furnace, possibly at the end of the smelt. The clinker contains fused masses of slag, partially consumed ore and charcoal again deriving from the end of the smelt.

8.2 The Chemical and Mineral Constitution of Smelting Slags

The chemical and mineral constitution of smelting slags has been discussed in detail by previous workers e.g. Fells[op.cit.] and Bachmann[84]. Chemically they comprise predominantly iron oxide and silica (totalling on average about 90%), and a small quantity of the alkali metal oxides (K_2O, CaO, Al_2O_3, and MgO), and other oxides may also be present e.g. MnO. Extensive studies have tried to establish a relationship between chemical composition and ore source but none has yet been successful. This is due to three reasons; firstly the failure to identify the exact ore source for a given furnace; secondly, the use of mixed ores, or the use of sources containing a variety of 'ferruginous ores', e.g. boulder clay; thirdly, the variation in chemical composition of ore sources. The mineral composition of smelting slags is varied Fells,[op.cit.] Bachmann.[op.cit] and is dependent on a number of factors, the presence of minor elements e.g. slags rich in CaO or Al_2O_3, the furnace conditions, and the cooling rate of the slag. Smelting slags normally consist of three phases: iron oxide, iron silicate, and a glassy phase. The iron oxide is normally present in the form of dendrites of wustite, or less commonly magnetite. The dendrites occur skeletally or as large rounded dendrites. Thin bands of iron oxide may occur in

tapped smelting slags, and were formed on the surface during cooling, and subsequently overlaid by a later tapping. These cooled surfaces usually contain magnetite rather than wustite. The quantity of free iron oxide is indicative of the efficiency of the furnace technology: the higher the free iron oxide content, the less efficient the furnace.

The iron silicate is normally fayalite ($2FeO.SiO_2$). but may also contain MnO (replacing FeO) and CaO, occurring as tephroite/gehlenite and calcium silicate respectively. Other minerals may be formed, e.g. hercynite — $FeOAl_2O_3$.

The remaining oxides precipitate in the glass phase, and hence the higher the percentage of alkali metal oxides the more glass phase is present.

The texture of the minerals is primarily dependent on the cooling conditions of the slag, and is, therefore discussed with individual specimens.

CHAPTER 9

SMELTING SLAG TYPES

9.1 The Tap Slags

Tap slag is the distinctive smelting slag. It is characterised by its flowed, ropey-like appearance. It has a fine crystalline fracture, is normally black in colour, and occurs in shapeless lumps, although it may have been tapped into channels or small pits and will take on their form when cooled, and hence may occur as slag cakes. Tap slag is associated with the shaft furnace in the Iron Age and the Roman Period, and with the 'developed bowl furnace'(or bloomery) of the Medieval Period. The shaft furnace from Scole (Norfolk) shows the two tap pits on either side of the tapping arch (Plate 14, Vol II P238), defined by their dark fill, and the feeders to each pit are indicated by the red staining of the sand, due to the heat of the molten slag.

The small shapeless tap slag lumps normally weigh less than 0.250 kg, but the slag cakes may exceed 1 kg. One exception is the massive block of tap slag in Norwich Castle Museum from the site of Hoveton (Norfolk) (Plate 15, VOL II P239). It measures 0.5m X 0.5m X 0.2m and weighs approximately 100 kg. Examination of the block shows that it was the accumulation of a number of individual tappings superimposed upon each other.

Three individual sites and one geographical area have been selected for study, they range from the Iron Age to the Medieval Period, and their geographical distribution is from the Chilterns to the North Yorkshire Moors (Figure 12, Vol II p217).

The Castledykes 'Camp" was a rectangular ditched-enclosure that has suffered destruction due to agriculture.   An excavation was carried out in 1959 ahead of further cultivation.   This excavation consisted of two trenches sectioning the ditch and outer bank; they revealed a timber-laced, stone-revetted rampart and a large flat-bottomed ditch.   There were only two diagnostic finds: a sherd of Iron Age pottery and a La Tene I brooch. Ironworking slag was recovered from the excavation but was not mentioned in the Interim Report (unpublished) or in the R.C.H.M. Volume on the area[85]. The slag was deposited in the local museum with the other finds. Recently the site has been re-assessed for publication[86], and was dated to the early part of the Iron Age. Fieldwalking has indicated that the slag was incorporated in the rampart construction; the slag recovered from the excavation was found in the primary fill of the ditch.

The slag recovered consisted of a single lump and several smaller pieces; also recovered were pieces of burnt stone, (possible ore?), and lumps of clay/stone that may have been part of the furnace structure. All the slag lumps showed the characteristic lava-like flowed surface, and the exaggerated appearance of the frozen flowed structures suggested a viscous slag. The slag pieces had been marked (accessioned) by the Museum, and could only be sectioned at an extremity, and no fracture surface could be prepared.

The limiting control of the sectioning resulted in the end of a flowed spur being removed for examination. The polished section showed an uncharacteristic microstructure. At low power

(100X) the structure appeared to be a glassy phase containing about 15% of a mineral that was not recognisable, and had no crystal form. This suggested a completely liquid fast cooling slag, and this was also endorsed by the spheroidal shape of the vesicles. At high power (X400+) (Plate 16, Vol II p240) the glassy phase resolved into a very fine dendritic structure, and a glassy phase in which the unidentified mineral had crystallised. This structure was probably due to the fact that the part sectioned was a small spur or tail of slag that would have cooled very quickly.

X-ray diffraction analysis of the polished specimen produced a pattern of strong fayalite peaks and a single quartz peak; no iron oxide peaks were present, (Table 9.2.1, Vol II p6).

The specimen was analysed on the S.E.M., bulk analyses were successfully obtained, but the fineness of the crystal structure meant that the spot analyses of the individual phases were contaminated by the surrounding glass, due to beam penetration. The bulk analyses and their normative mineral constituents are given in Tables 9.2.2 and 9.2.3 (Vol II p6/7). The analyses indicate a homogeneous composition throughout the specimen. This is illustrated by the S.E.M. micrograph and the iron and silicon X-Ray maps which show little segregation between the glass phase and the dendritic structure (Plates 17 - 20, Vol II p241). The normative constituents comprise mostly hercynite, orthoclase, ferrosilite and excess quartz. The X-ray diffraction results shown in Table 9.2.1 show the presence of quartz, and fayalite rather than quartz and ferrosilite, indicating that the fayalite did not saturate with silica to produce ferrosilite.

Spot analyses (and normative mineral composition) of the

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phase/inclusion noted in the optical analysis are given in Tables 9.2.2 and 9.2.3 (Vol II p6/7). It contains iron oxide (70-80%) and significant quantities of alumina (7-10%) with minor elements, principally titanium oxide, and is, therefore. presumably a high melting-point glass, since the excess iron oxide had not reacted with the excess silica in the matrix.

The mineral texture, bulk chemical composition and inclusion analysis are significantly different from the other slags, (smelting and smithing) that have been analysed in this work. The location of the section, on a spur, would account for the mineral structure due to rapid cooling. However, the bulk analysis, high silica low iron oxide content, suggest a very efficient smelting process and the use of a very rich ore that contained no manganese (for example see analyses of ironstone nodules from the ironstone junction band in Fells Table C4[9]).

The early date and the chemical and mineral constitution of the Farthingstone slag distinguish it both from the others analysed in this work and other published slag analyses.

Levisham Moor lies on the southern side of the North Yorkshire Moors (the Tabular Hills), at a height of about 200 metres above sea level.   It contains an extensive Late Iron Age settlement and field systems.   Selected areas were excavated between 1957 and 1978 by the Scarborough and District Archaeological Society[21].   The low-lying Enclosure D contained three iron-smelting furnaces cut into a clay bank, with a small slag heap 4.5 metres in diameter lying to the east.   The furnace was described as a 'bowl furnace' in the publication.   An opportunity was taken to re-examine the furnace in the summer of 1983, and it was re-interpreted as a shaft furnace (Figure 10, Vol II p215).   It had two tuyeres at right angles to each other, about 0.3 metres above the base of the furnace, and angled down at approximately 30 - 45 degrees.   The furnace was dated by the presence of Late Iron Age pottery in the Enclosure, and the overall date of the whole enclosure system.

There was a medieval slag heap in the valley bottom (Site J), and ironworking slag was also found in ditches within Enclosure A.   Analyses of some of these slags from Enclosure A (Table 9.3.1 Analyses 1 - 5, Vol II p8) and two samples from the Enclosure D smelting slag heap (Analyses 6 and 7) were published in the Report.   Sample 1 was believed to have been furnace/hearth lining, Sample 4 ore, Sample 5 partially reduced ore, and the remainder smelting slag.   These interpretations are reasonable, although the identification of Sample 5 was based on the presence of charcoal impressions, which are commonly found in viscous smelting slags.   There was no discussion of Samples 6 and 7 from

the furnace site, and the iron content had not been analysed. Sample 7 was probably a smelting slag sample, since the analysis is comparable to those obtained in the current study, except for the manganese oxide content. The low silica and high manganese oxide content of Sample 6 suggest some form of iron oxide waste. The lack of detailed morphological descriptions in the report, and the assumption that the slag was smelting slag must not exclude the possibility that some of the pieces were smithing slag.

Samples of slag were collected from the slag heap, and had a tap slag morphology, although they had not been as free-running as the typical tap slag. They had a fine crystalline fracture with few vesicles present, except near the upper cooling surface.

A sample from a cross-section of one of the lumps was examined in the usual manner.

The mineral texture was of two forms: firstly, massive silicate and massive glass with either rounded or fine dendritic iron oxide. Secondly, rounded iron oxide dendrites in massive silicate with a low glass content (Plate 21, Vol II p242). The volumetric analyses are shown in Table 9.3.2 (Vol II p9), with the mineral texture indicated, (2R for texture 2, and 1F for texture 1 with fine iron oxide dendrites, and 1R with rounded dendrites). These variations gave a high r-mean value (=16)

The bulk analyses (Table 9.3.3, Vol II p10) showed considerable variation, but were high in manganese oxide (average 8.3%), and a high iron plus manganese oxide to silica ratio (average 4.2:1, [fayalite = 2.3:1]). There was a low percentage of glass forming oxides .

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The phase analyses (Table 9.3.4, Vol II p11) identified the silicate as fayalite containing manganese oxide and a low lime content except for silicate 3, which was high in lime (14.3 %). The glass phases analysed were similar, high in alumina, silica and potassium oxide, and low in lime and iron oxide. The four iron oxide dendrites analysed contained low silica and alumina and high manganese oxide contents. The total (average 99.65%) and the absence of titanium oxide indicates the oxide to have been wustite.

The calculated normative mineral constituents of the bulk analyses (Table 9.3.5, Vol II p12) show that they comprised mostly silicate and iron oxide with only a low percentage of glass minerals present. The ternary groupings (Table 9.3.7, Vol II p14) showed wide variation, indicating sample heterogeneity, with a r-mean value of 19.7 and a high standard deviation (=13.5). The most deviant analysis was Analysis 1 and to a lesser extent Analysis 5.

The comparison between the volumetric and normative ternary groupings resulted in a high r-mean value (17.7) and a high standard deviation (10.7). The individual r-factors showed similarity and dis-similarity between volumetric and bulk analyses, e.g. V1 was similar to B2, and V5 was dis-similar to B1.

The normative calculations for the silicate phases (Table 9.3.6, Vol II p13) showed 2 and 3 to contain excess iron oxide. The lime rich silicate phase (3) was low in fayalite and high in calcium silicate. The glass phases were silica rich (orthoclase was calculated) and rich in kalsilite and potassium silicate.

The slag morphology indicated a viscous tap slag. The

analyses confirmed this by high r-mean values, indicating slag
heterogeneity, that would be in accordance with a viscous slag.

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9.4   AMERSHAM MANTLES GREEN BUCKINGHAMSHIRE (NGR SP947977)

The County of Buckinghamshire was one of the nine counties
listed by Tylecote as having no recognised ore sources (op.cit.).
There is now substantial evidence of smelting within the county,
e.g. at Missenden Abbey[88]. The site has already been described
(pp59-61), and both smelting and smithing slag was recovered, but
no ironworking structures were identified.

Three samples of smelting slag were selected for analysis;
AM714 and AM718 from Phase I and AM783 from Phase III.

9.4.1   Sample AM714

Sample AM714 derived from a context containing 43kg of
smelting slag. It had a typical tap slag morphology, a ropey
upper surface, black lustre, and fine grained fracture.

The mineral texture was typical of tap slags, silicate
laths, often dendritic, and fine dendrites of iron oxide in a
glassy matrix, which contained fine crystallites, probably
silicates (Plate 22, Vol II p243). The volumetric analysis is
given in Table 9.4.1 (Vol II p15), the specimen was homogeneous
as shown by the r-factors, (r-mean = 7, S.D. = 4).

The bulk analyses (Table 9.4.2, Vol II p16) showed high
manganese oxide contents, (average = 9.2%), and variable alkali
oxide percentages. These analyses also had high phosphorus
contents. The calculated normative mineral compositions (Table
9.4.3, Vol II p17) showed three of the analyses to be silica rich
(orthoclase being present); the fourth, Analysis 3 was balanced
i.e. neither rich in silica nor containing excess iron oxide.
This contrasts with the optical study which showed the presence

of free iron oxide. The ternary phase groupings are shown in Table 9.4.4 (Vol II p18); the calcium silicate was ascribed to the glass phase. The analyses indicate the sample to be homogeneous (r-mean = 8.3), although the standard deviation is high (S.D. = 5.0), which shows some deviation, caused by Analysis 3, which had a higher fayalite content and calculated no orthoclase.

The phase analyses (Table 9.4.2, Vol II p16) showed the silicate phase to be rich in manganese oxide, and contained some magnesia. The normative calculation (Table 9.4.3 Vol II p17) showed it to be fayalite/tephroite, but contained excess iron oxide (wustite = 1.0%). The glass phase was typical, containing the glass forming oxides, e.g. phosphorus. The normative mineral composition contained fayalite plus tephroite (53.0%), anorthite (20.4%), and kalsilite (12.7%). The iron oxide phase was exceptional because they were rich in alumina and titania; this gave normative mineral compositions containing hercynite, ulvite, and anorthite. The analysis of FEOX2 contained 10.5% fayalite. This shows the (analysed) 'iron oxide' dendrites to be alumina/titania rich spinels.

The comparison between the volumetric and normative ternary phase groupings (Table 9.4.4, Vol II p18) resulted in high r-factors. The r-mean value was 18.4, with a standard deviation of 7.2. Independently the volumetric and ternary analyses showed the specimens to have been homogeneous, but their comparison shows great deviation from equilibrium conditions during cooling. This is the expected result for tap slags.

9.4.2 Sample AM878

Sample AM878 was a typical tap slag similar in morphology to AM714. The cross-section showed that the slag lump was the result of a succession of tappings; the cross-section of each tapping being slightly different, e.g. in vesicularity. There were also distinct lines or bands delineating the separate tappings.

A cooling surface between two tappings, observed in the cross-section, was apparent in the polished micro-specimen as a band of iron oxide; probably magnetite or hematite (Plate 23, Vol II p244). The overall microstructure was of rounded iron oxide dendrites, iron silicate and a small amount of glass content. On either side of the cooling surface the texture varied in coarseness and the orientation of the iron oxide occurred ordered and disordered (Plate 24a and 24b, Vol II p244). The iron silicate occurred predominantly as laths, but was difficult to resolve due to the small amount of glass phase present. The specimen was treated as one sample, i.e. the areas on either side of the cooling surface were not analysed separately. The volumetric and r-factor analyses are given in Table 9.4.5 (Vol II p19). These show a high r-mean value, (11, S.D.=7), which was due to Analysis 3. If this is excluded then the r-mean value is reduced to a value of 7, (S.D. = 5).

The bulk analyses (Table 9.4.6, Vol II p20) show a high manganese oxide and phosphorus pentoxide content, and low alkali oxide content, which are compatible with the low glass phase observed in the optical study. The normative constituents (Table 9.4.8, Vol II p22) calculated an excess iron oxide content (mean

value = 40.8%) and low glass mineral content. This accords with the optical study. The r-factor analyses (Table 9.4.10, Vol II p24) show the bulk analyses to be very homogeneous (r-mean = 3.0 , S.D. = 2.1), Analysis 4 being the most divergent due to the lower silica content, resulting in lower fayalite and higher wustite contents.

The individual phase analyses (Table 9.4.7, Vol II p21) identify the silicate phases as fayalite. The normative compositions (Table 9.4.9, Vol II p23) contained significant percentages of tephroite, and were iron oxide rich. The presence of excess wustite in the silicate is not unexpected in slag that had a high percentage (40%) of free iron oxide in the volumetric analysis and in the normative mineral constituents of the bulk analyses. The glass phases analysed were very similar, being rich in phosphorus pentoxide and the alkali metal oxides. The resulting major normative mineral constituents were apatite, kalsilite, anorthite and fayalite. The first glass analysis was silica rich (orthoclase present), and the second contained excess iron oxide.

The iron oxide analyses are typical (unlike those from AM714), although they did contain a small amount of alumina and silica (less than 1.0%). There was a small percentage of manganese oxide present in the iron oxide (4.0%). The elemental percentages of iron plus manganese (FEOX1 = 73.6%, FEOX2 = 74.8%) were inconclusive, falling between the elemental percentages of wustite (77.7%) and magnetite (72.4%). This would indicate oxygen rich non-stoichiometric wustite, resulting from slight oxidation of the slag probably during tapping.

The comparison between the volumetric and ternary phase

between the two sets of data (r-mean = 9.4), although there was considerable variation (S.D. = 4.7). The r-mean value was less than that obtained for the volumetric analysis (Table 9.4.5, Vol II p19).

9.4.3   Sample AM783

Sample AM783 derived from Phase III of the site, and was analysed to try to determine whether the slag from this phase represented a second period of iron smelting activity or was residual Phase I material.

It had a typical tap slag morphology, and its mineral texture was the same as that of AM714; silicate laths in a glassy matrix containing very fine iron oxide dendrites. The volumetric analyses were also very similar (Table 9.4.11, Vol II p25), and gave a low r-mean value (= 5. S.D. = 3) indicating an homogeneous specimen.

The chemical bulk and phase analyses were also very similar (Table 9.4.12, Vol II p26), but contained a lower percentage of manganese oxide than either Samples AM714 or AM878. Sample AM783 differs from AM714 in the calculated normative mineral constituents, (Table 9.4.13, Vol II p27), which show the bulk analyses to be silica rich resulting in the presence of silica saturated minerals e.g. rhodonite in place of tephroite.   The silicate phase analysis identified it as fayalite, and there was slight excess of wustite, (0.3%). The glass phases analysed contained a high phosphorus pentoxide percentage, which gave high apatite contents in the normative constituents. The glass phase

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apatite contents in the normative constituents. The glass phase was also silica rich, rhodonite and ferrosilite being present; analysis Glass 1 contained excess silica (3.2%). The iron oxide phase was too fine to be analysed. The r-factor analyses (Table 9.4.14, Vol II p28) showed the bulk analyses to be very homogeneous (r-mean = 1.2 , S.D. = 0.8). The comparison between the volumetric and ternary phase analyses show a great deviation from equilibrium conditions, r-mean = 25.1, (S.D. = 3.2), which was due to the rapid cooling of the slag.

9.4.4 Summary

The analyses were inconclusive in determining whether the Phase III sample, (Sample AM783), derived from a separate smelting operation from the Phase I activity (Samples AM878 and AM714). It must be considered that if there had been a second period of smelting activity then the same ore source would have been exploited, and the same technology used. Therefore, the possibility of distinguishing the two activities, if they had occurred, is remote. This is further reduced when the differences observed in Samples AM714 and AM878 are considered.

The r-factor analyses of Samples AM714 and AM783 were similar, indicating homogeneity in the volumetric and bulk analyses, but showing considerable divergence from equilibrium conditions when the volumetric and normative ternary are compared. This is the expected result for tap slags which are removed from the furnace and cool very quickly. Sample AM878 was different, being iron oxide rich. This might be interpreted as the slag deriving from either an early or late stage in the smelting operation.

9.5 HOB HOLE, BAYSDALE BECK, NORTH YORKSHIRE (N.G.R. NZ644075)

Baysdale lies on the north side of the North Yorkshire Moors. The Cleveland Ironstone Formation, (Middle Lias), and the Dogger Ironstone Seam (Jurassic) are exposed in the Dale side. The site consisted of several slag heaps up to 1.2m high extending 100m along the beck side and probable associated building outlines. It was probably first noted by J.C. Atkinson in 1884[89], and listed by R.H. Hayes in his survey of North Yorkshire smelting sites[90]. It is one of the six sites excavated on the Moors, but has not yet been published[91]. The pottery dated it to the early 14th Century. Two smelting furnaces were found consisting of circular pits 0.5 m in diameter and 0.45 m deep. An oval area 2.0m in length was the tapping area.

The slag was typical smelting tap slag, having a flowed ropey morphology and fine crystalline fracture. A sample for analysis was cut from one of the slag lumps.

The mineral texture was broken silicate laths with secondary silicate crystallising from the glass, and fine iron oxide dendrites in a glassy matrix, which contained fine crystallites (Plate 25, Vol II p245). The secondary silicate was 5 - 10 % of the volume, but was included in the total silicate given in Table 9.5.1 (Vol II p29). The comparison of the volumetric analyses indicated an homogeneous sample (r-mean = 8.5), Analysis 1 being the most divergent.

The bulk analyses (Table 9.5.2, Vol II p30) were characterised by high magnesia, alumina, lime and phosphorus pentoxide. The magnesia may have derived from the magnesium carbonate present in the Cleveland ironstone and the other high

values may also have been dependent on the geology of the ores, although the alumina may be due to slag attack on the furnace lining.

The phase analyses (Table 9.5.3, Vol II p31) showed the expected distribution of oxides, the magnesia concentrated in the silicate phase, the alumina, phosphorus pentoxide, and lime in the glass. Two iron oxide analyses are given, the first totalled 96.9 % and there was a significant titanium content, which identified it as magnetite. The second was identified as wustite.

The normative mineral constituents of the bulk analyses (Table 9.5.4, Vol II p32) showed excess iron oxide present in 1, 2, and 4. Analyses 3 and 5 differed in containing calcium silicate. The high phosphorus contents formed apatite, and the magnesia, forsterite. The lime and alumina formed anorthite and gehlenite. The silicate was a forsterite-fayalite solid solution, and was silica rich. The calcium was concentrated in the glass as calcium silicate. The first glass analysis was silica rich (orthoclase present), the second was slightly silica deficient, gehlenite being calculated.

The bulk ternary groupings (Table 9.5.5, Vol II p33) showed homogeneity between the areas analysed, r-mean = 7.6, S.D.=3.0. The comparison between the volumetric and the analysed areas showed very little divergence from equilibrium (r-mean = 7.7, S.D.=3.8), which is uncharacteristic of tap slags. This was probably due to the lack of iron oxide in the slags.

The morphology and mineral texture of the slag indicated a rapidly cooled slag. The r-factor calculations of the volumetric analysis and ternary groupings gave low r-mean values, indicating

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homogeneity. The calculated normative mineral composition correlated well with the observed composition, indicated by the volumetric/ternary r-mean factor. The close correspondence is probably due to the low iron oxide content of the slags.

9.6   FARNDALE, NORTH YORKSHIRE

Farndale is one of the valleys cutting the North Yorkshire Moors on the south side with the Dogger Seam, Cleveland Ironstone and Ellerbeck Formation exposed in the valley side. Samples from two sites in the valley have been examined.

9.6.1   Oak Crag   (N.G.R. SE678962)

The slag heap lay in a bowl shaped hollow, measuring three metres by one metre, and was found during drainage work. There was no dating evidence recovered, nor was any furnace or hearth structure identified[90].

The slag had a typical tap slag morphology, ropey texture, black lustre, and a fine grained fracture.

The mineral texture was uniform, silicate laths and fine to globular iron oxide dendrites in a glassy matrix. There were also cooling surfaces identified by thin iron oxide bands (Plate 26, Vol II p245). The orientation and fineness of the laths varied between areas defined by the cooling surfaces. The volumetric analyses (Table 9.6.1, Vol II p34) were also uniform, the r-mean value being 6.5, (S.D.=4). The optical study indicated a free flowing, rapidly cooled slag.

The bulk analyses (Table 9.6.2, Vol II p35), were typical of fayalitic slags, containing high manganese oxide contents. The phase analyses were also typical (Table 9.6.3, Vol II p36), the manganese concentrated in the silicate phase, which contained a low lime content. The glass phase contained the expected alkali oxides. The two iron oxides analysed differed, the first was magnetite (total = 96.3 %, elemental iron plus manganese =

71.7 %), and the second contained significant silica and alumina contents, which may have derived from x-rays generated by the glassy matrix.

The normative mineral constituents (Table 9.6.4, Vol II p37) of the bulk analyses showed slight variation. Analyses 1, 4 and 5 were iron oxide saturated (wustite present), Analysis 2 was normative, and Analysis 3 silica rich (orthoclase present). Analyses 2 - 4 contained calcium silicate. The silicate was iron oxide rich fayalite/tephroite (Table 9.6.5 Vol II p38). The two glasses were consistent in the minerals present, but varied in their percentages, e.g. anorthite, and they were both silica rich (orthoclase present).

The normative ternary groupings (Table 9.6.6, Vol II p39) showed close correlation, indicating homogeneity (r-mean = 5.0, S.D.=2.1). The comparison between the volumetric and ternary analyses indicated divergence from equilibrium conditions (r-mean = 11.1, S.D.=4.9).

The morphology and mineral texture indicated a free flowed, fast cooled slag, and this was borne out by the ternary and ternary/volumetric r-factors. The volumetric and ternary r-means showed an homogeneous slag, but when compared showed divergence. The divergence resulted from the rapid freezing, which inhibited crystallisation of the silicate.

The site was an extant slag heap in the valley bottom. from which the sample was taken.

The slag had a typical tap slag morphology, ropey upper surface, black lustre, and fine grained texture.

The mineral texture was uniform, but was characterised by the absence of free iron oxide and the presence of a second silicate(?) phase. It occurred as pale grey veins in the major silicate laths, and occasionally as iron oxide-like fine skeletal dendrites. A glass phase and fine metallic inclusions were also present (Plate 27, Vol II p246). The percentage of the minor vein silicate was 5-10%, and was included in the silicate percentage in the volumetric analyes (Table 9.6.7, Vol II p40). This showed the sample to have been very homogeneous (r-mean = 5, S.D. = 4).

The bulk and phase analyses are shown in Table 9.6.8 (Vol II p41), the vein silicate was too fine to have been analysed. The bulk analyses were low in manganese oxide, potassium oxide and lime. The alumina and phosphorus pentoxide contents were high. The analyses confirmed the major silicate phase as fayalite; in which the magnesia and manganese oxide was concentrated. The glass phase showed the expected concentration of oxides, notably the phosphorus pentoxide.

The normative composition of the bulk analyses (Table 9.6.9, Vol II p42) showed Analyses 1 - 4 to be silica rich (orthoclase present) and Analyses 5 to contain excess iron oxide, (0.5%). The silicate phase (Table 9.6.9, Vol II p42) was also iron oxide rich, and the glass phase, silica rich. The r-factor analyses of

the ternary groupings (Table 9.6.10, Vol II p43) indicated an homogeneous composition (r-mean = 2.6, S.D. = 1.5). The comparison between the volumetric and the ternary analyses indicated close adherence to equilibrium conditions, (r-mean = 3.9, S.D = 3.4). This was probaly due to the low iron oxide content of the slag, and the absence of free iron oxide, (cf Baysdale p102). The mineral texture and the close correlation between the volumetric and ternary groupings distinguished the Park North tap slag from the other tap slags analysed.

9.6.3   Farndale Summary

The average bulk analyses of the slags from Oak Crag and Park North (Table 9.6.11, Vol II p44) show two significant differences; firstly the manganese oxide contents, (Oak Crag = 4.5%, and Park North = 0.2%), and secondly the alumina contents, (Oak Crag = 4.8%, Park North = 6.7%). The high alumina of the Park North analyses may have been the result of contamination of the slag by the furnace lining, but the low percentage of the other alkali oxides (potassium and calcium) would not support this argument. The difference in manganese oxide contents would indicate the use of two different ore sources, and the difference in alumina percentages may also result from the different ores.

The site lay next to Ouse Gill, a beck running into Bransdale. The site was listed by R.H. Hayes in his 1978 survey[90].

The slag was typical tap slag, ropey morphology, black lustre, and fine crystalline fracture.

The mineral texture was finely vesicular, with silicate laths in a glassy matrix. There was no free iron oxide present, but there were fine metallic inclusions (Plate 28, Vol II p246). The volumetric analyses (Table 9.7.1, Vol II p45) showed that the sample was very homogeneous (r-mean = 4, S.D.=5). The texture indicated that the slag had cooled rapidly.

The bulk analyses (Table 9.7.2, Vol II p46) were high in magnesia, alumina, lime, and phosphorus pentoxide. Manganese oxide was present but was less than 1.5 %. The magnesia and manganese oxide concentrated in the silicate, but the lime was contained in the glass phase.

The normative mineral calculation (Table 9.7.3, Vol II p47) showed the bulk analyses to be balanced, i.e. neither silica nor iron oxide rich, although gehlenite was present indicating the deficiency of silica and richness in lime and alumina. The normative mineral composition of the silicate phase was fayalite/forsterite, reflecting the magnesia content of the phase. A small amount of albite (sodium aluminium silicate $NaAlSi_3O_8$) was present. The first glass analysis was normative, and the dominant minerals were anorthite and fayalite. The second was similar except that the percentages of the minerals present were different. It was silica rich (orthoclase present), and

fayalite was absent.

The ternary groupings (Table 9.7.4, Vol II p48) gave a low r-mean value (5.3, S.D.=4.9) indicated homogeneity. The comparison between the volumetric and ternary groupings also gave a very low r-mean value, (4.7, S.D.=3.2). This indicated very close similarity between the observed and the theoretical structure. The rapid cooling suggested by the optical study would imply deviation from equilibrium conditions, and hence a high r-mean value for the volumetric-ternary data, as observed in other tap slags (e.g. Amersham AM783, p99)

The optical and chemical/normative analyses showed the slag to be a typical tap slag, although deviation between the volumetric and ternary groupings, indicated by the r-factors, may have been expected.

9.8 TAP SLAG SUMMARY

Nine specimens of tap slags from seven different sites have been analysed. The sample from Farthingstone was morphologically similar to the other tap slags but had a very different mineral texture and chemical composition. It is therefore excluded from the general summary, but relevant points will be brought in where useful.

The tap slags have the characteristic 'flowed, ropey surface' morphology. They are blue/black in colour, with a fine crystalline fracture. Vesicles tend to be small and concentrate at the surfaces. The lumps may be the accumulation of several successive tappings.

The mineral texture was varied, but was made up from either laths or euhedral (broken) laths; the Levisham sample was an exception, having massive silicate. A glass phase was always present, and the free iron oxide occurred either as fine dendrites, (Amersham, Baysdale, and Oak Crag), or as globular dendrites, (Levisham, and Oak Crag, which had both types present). Park North and Ousegill contained no free iron oxide.

The chemical composition of a slag sample is dependent on its genesis, (e.g. ore type in the case of smelting slags), not on its morphology or typology/classification. Therefore. the classification cannot relate directly to the slag composition, but the normative mineral composition and resultant ternary groupings and r-factor calculation are dependent on the composition. This summary offers a suitable opportunity to survey the compositions of the tap slags. The mean values (and standard deviations) for each oxide from each sample are given in

Table 9.8.1 (Vol II p49), and the mean values for all tap slag readings are given in Table 9.8.2 (Vol II p50). The variation from a single source can be observed in the analyses of the slags from Amersham Mantles Green, e.g. MnO content and, therefore, sourcing/grouping of slags on the basis of oxide content must be treated with caution. Further general comments can be made.

The most significant oxide was manganese, the overall mean value was 4.5%, (S.D.=3.3%), but there were three exceptions, Baysdale (mean=1.3%, S.D.=0.1%), Park North (mean=0.2%, S.D.=0.1%), and Ouse Gill (mean=1.2%, S.D.=0.1%). The Farthingstone sample was also low in manganese oxide, (mean<0.1%). The Baysdale and Ouse Gill sites were further distinguished by their magnesia contents (4.1% and 4.2% respectively, overall mean=1.4%), alumina, phosphorus pentoxide, potassium oxide, lime, titania, and iron oxide contents. This indicates that they exploited the same ore source, and the same technology. Park North, also a North Yorkshire site, was low in manganese oxide, similarly Oak Crag was high in potassium oxide and titania. The Levisham sample was very different from the other Yorkshire sites, particularly in having a very low alumina content, (mean=1.0%, S.D.=0.5%).

. The phase analyses reflect the bulk analyses, e.g. the Baysdale and Ouse Gill silicate were rich in magnesia, both bulk analyses were rich in lime but this did not concentrate in the silicate although the levels were slightly enhanced. One of the Levisham silicate analyses (Table 9.3.4 Vol II p11) was rich in lime although the bulk analyses contained average levels. The manganese oxide concentrates in the silicate phase as expected.

The glass phase analyses are more difficult to discuss,

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since they can vary greatly within a sample, and within a a glass field due to segregation. It is generally expected that the alkali oxides would concentrate in the glass phase, and that the lime percentage would be higher than the potassium oxide content. The Levisham glass analyses are contrary to the the last point, having very high potassium oxide and very low lime contents (Table 9.3.4, Vol II p11). The Levisham Glass alumina content is also very high, although the bulk analyses were exceptionally low in alumina. The North Yorkshire analyses (except Levisham) are distinguished by an above average titania percentage, (mean=0.7%, S.D.=0.5%).

The phase analyses of the free iron oxide are very varied, and their oxidation state is difficult to determine due to the presence of minor elements.

The volumetric, ternary, and volumetric/ternary r-mean values are given in Table 9.8.3 (Vol II p51), and plotted on Figure 13 (Vol II p218). The general trends as indicated by the overall mean values are low volumetric and ternary r-mean values (8 and 6.6 respectively), and high(er) volumetric/ternary r-mean values (12.2). The exceptions to this trend are Levisham, which has high values throughout, and Amersham, AM878, which has a high volumetric r-mean value. Amersham, AM714, has a lower volumetric value than ternary value. The volumetric/ternary value for Park North is lower than the volumetric factor. The ternary value for Ouse Gill is slightly higher than either other value.

The attributes of tap slags can therefore be summarised as their morphology, (flowed ropey surface, fracture etc.), the mineral texture, (silicate laths or euhedral laths), the presence of manganese oxide, low volumetric and ternary r-mean values and

a high volumetric/ternary r-mean value. However, these attributes may not relate exclusively to tap slags.

9.9   The Raked Slags

The Raked Slags were smelting slags that appear to have been
more viscous than Tap Slags.   Therefore, they do not have the
flowed, ropey morpholgy of Tap Slags.   They were probably raked
out, because of their higher viscosity, and were collected in a
pit in front of the furnace and, therefore, occur as slag cakes,
plano-convex accumulations of slag.   They also occur as randomly
shaped lumps without the plano-convex form.   These lumps often
include charcoal impressions, which indicate a charcoal size of
20mm across and 40mm long.   The raked slags are a form of tap
slag; it is unclear whether the higher viscosity was due to
chemical composition of the slag or to the furnace technology.

9.10   MILLBROOK, ASHDOWN FOREST, SUSSEX (N.G.R. TQ441296)

9.10.1 Introduction

The ironworking site at Millbrook, Ashdown Forest was discovered during pipe laying in 1980. It was excavated by the Wealden Iron Research Group and the report published in 1982[36] The site was dated archaeomagnetically and by Carbon-14 to A.D. 800-835. Three ironworking features were identified: two hearths and a furnace and a considerable quantity (unweighed) of slag and furnace/hearth lining. The furnace was a shallow pit, irregularly circular in plan, (approximately 1.00 X 0.95 m in diameter) and 0.32 m in depth. The bottom of the furnace was filled with charcoal and some slag overlain by collapsed lining. The furnace fill suggests that the slag did not penetrate to the base of the furnace, forming furnace bottoms, but was removed by tapping or raking out. Re-examination of the published evidence suggests that Hearth I may have been a tapping pit, and Hearth II a separate furnace complex.

Forty kilograms of slag were taken as a sample, none was found in situ due to the action of the bulldozers, although much of it derived from the associated slag heap. The slag occurred as either slag cakes or irregularly shaped lumps. There were 13 complete or near complete cakes (Table 9.10.1, Vol II p52). One was exceptionally large (300 X 250 X 150 mm, and weighed 5 kg). The remaining cakes varied in size with average dimensions of 160 X 100 X 50 mm. Some of them had a slight depression in the upper surface, and had a variation in texture from a flowed 'tap slag' appearance to an agglomerated texture. Some cakes had adhering fired clay/furnace lining. The slags had varying fine to coarse

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crystalline fracture dependent on the slag texture.

Two powdered samples of slag were analysed by X-ray diffraction. Fayalite was readily identified, but the remaining peaks could not be ascribed with certainty to any other minerals. The presence of magnetite was suspected and so the powder was separated using a weak magnet. The magnetic fraction gave a clear magnetite pattern, and wustite was present in the non-magnetic fraction. The magnetic fractions were 35.5% and 6.25% of the total weight for samples A and C.

Samples were chemically analysed by three methods, wet chemistry, wavelength dispersive X-ray fluorescence (X.R.F.), and S.E.M.

Samples A and C were analysed by wet chemistry (Table 9.10.2, Vol II p53). This method provided data not available from either of the other methods, having given ferrous and ferric iron content and carbon content (as CO_2). The carbon derived from charcoal inclusions in the slag.

The significant result was the high ferric iron content which would occur mineralogically as magnetite or hematite. This accords with the presence of the magnetic fraction of the powdered sample. The analyses were not very suitable for normative calculation because some of the oxides were not analysed, notably manganese and potassium; also the analysis of Sample A includes a high carbon content due to the presence of a charcoal inclusion. In the normative calculation the carbon content was ignored and the theoretical mineral composition determined using the iron oxide content as determined i.e. FeO and Fe_2O_3 and with all iron calculated as FeO (Table 9.10.3, Vol II p54). The determination of the glass phases (apatite,

pyhrotite, anorthite, and hercynite) was not greatly altered by the use of Fe_2O_3, but the silicate phase was enriched with silica, and free hematite was present.

The X.R.F analyses (from Fells[9]) are shown in Table 9.10.2 (Vol II p53). They do not total 100%, and it is assumed that the difference was due to the presence of magnetite. The analyses differ significantly, notably in their iron oxide to silica ratios, Sample D 1.52:1 ; Sample E 5.95:1. This was reflected in the normative mineral composition (Table 9.10.3, Vol II p54) in which they differed in the glass phase minerals (e.g. kalsilite and anorthite), and Sample E contained free iron oxide and was lower in silicate content.

Five samples were analysed by the standard S.E.M. and optical (volumetric) techniques.

9.10.2   Sample A

The volumetric analyses are shown in Table 9.10.4 (Vol II p55), the mineral texture was euhedral silicates tending to massive form and rounded iron oxide dendrites in a glassy matrix (Plate 29, Vol II p247). There was considerable variation in the volumetric phase percentages, and results in a high mean r-factor value, (mean r = 19, S.D.=10) indicating sample heterogeneity.

The bulk chemical and phase analyses are shown in Table 9.10.5 (Vol II p56). The bulk analyses were high in the glass forming oxides, and this accords with the optical study which contained on average more than 15% glass phase. The manganese oxide content was low for smelting slags that contain manganese. Only analysis B4 exceeded 100%: the low totals of the others

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indicate the presence of magnetite rather than wustite. The normative mineral compositions (Table 9.10.6, Vol II p57) indicate a variable composition: analyses B1, B2, and B4 were silica rich (orthoclase was present), whereas B5 contained free iron oxide. B3 was fayalitic. The normative composition also contained a high glass content (kalsilite and anorthite).

The phase analyses showed the silicate to have been fayalite containing a low concentration of calcium oxide. The glass phase was silica rich (orthoclase, albite and wollastonite were present in the normative calculation. Table 9.10.6, Vol II p57). The iron oxide analysis identified the phase as oxygen rich wustite (elemental Fe = 74.0%). A crystallite in the glass phase was also analysed, it was high in alumina and iron oxide, and was, therefore, hercynite containing excess iron oxide. Titania was also present (as ulvite). The titania preferentially concentrated in the hercynite crystallite rather than the magnetite dendrite, both are spinel structures and equal distribution could have been expected. The analysis of the glass phase was silica rich, hence the orthoclase present in the bulk analyses was ascribed to the glass phase in the ternary groupings (Table 9.10.7, Vol II p58). The r-factor calculation showed close similarity between analyses B1, B2 and B4, (all silica rich), and the greatest deviation for B5 (iron oxide rich). The latter caused a high mean r-factor (mean r = 11.7, S.D.=7.1).

The comparison between the volumetric and bulk phase analyses gave a high mean value (r-mean = 19.75, S.D.=7.4), that was equivalent to the value obtained for the Levisham and two of the Amersham samples (Table 9.8.3, Vol II p51). This indicated significant deviation from equilibrium conditions during the freezing of the cake.

The comparison between the wet chemical and S.E.M. normative phase compositions is shown in Table 9.10.8 (Vol II p59). The determined phases differ significantly when the Fe_2O_3 was included (r-mean = 31.0). The calculation showed that similar calculations, i.e. using FeO only, can be justifiably compared.

9.10.3   Sample C

Two samples (C-Area-A and C-Area-B) were analysed volumetrically (Table 9.10.9, Vol II p60). Both specimens had similar textures, silicate laths and rounded iron oxide dendrites and veins in a glassy matrix (Plate 30, Vol II p247). In some areas the silicate laths had grown to form massive silicate. The phase composition varied across the specimens indicated by the r-factors, (mean r-factors for Sample C-Area-A = 18 and C-Area-B = 13).

The bulk analyses of Sample C-Area-A only are shown in Table 9.10.10 (Vol II p61), they are distinguished by high calcium and manganese contents. The phase analyses (Table 9.10.11, Vol II p62) showed the expected segregation of magnesium and manganese in the silicate, and the aluminium, potassium and phosphorus in the glass. The high calcium percentages recorded in the bulk analyses were divided between the silicate and glass phases. The iron oxide analyses contained a significant manganese content. The analyses total approximately 100%, but they also contain a high titanium oxide percentage which has previously been suggested to indicate a spinel structure, i.e. magnetite.

The normative mineral compositions (Table 9.10.12, Vol II

p63) of the bulk analyses reflected the high calcium contents with the formation of calcium silicate, anorthite and gehlenite. They were broadly similar, but Analysis B4 was distinguished by having excess iron oxide present, and an absence of anorthite. The normative constituents of the silicate phases analysed were fayalitic (allowing for the manganese substitution) but were rich in iron oxide. The glass phases contained the same phases but differed slightly in the percentage of each mineral present.

To determine the three phase percentages from the bulk analyses the calcium silicate was apportioned in three ways (Table 9.10.13, Vol II p64/5). Firstly, it was apportioned to the silicate and glass phases in the ratio of the mean calcium silicate percentage found in the analysed phases (1:2.1 silicate:glass). Secondly, it was included in the glass phase only, and thirdly, in the silicate phase. The mean r-factor value was highest when ascribed to the glass phase only (r-mean = 16.4). The r-factor was influenced by bulk analysis B4, which contained excess iron oxide.

The volumetric analyses were compared with the three calculated normative phase percentages (Table 9.10.14, Vol II p66). This showed a better correlation when the volumetric analysis was compared with the three phase composition in which the calcium silicate was apportioned to the glass phase only (r-mean = 19.3).

The bulk analyses were compared with the wet chemical analysis (Table 9.10.15, Vol II p67), and showed closer correlation with the iron calculated as FeO only (as in Sample A).

9.10.4   Sample D

A single specimen was taken from slag cake D. The mineral texture was principally silicate, varying from small broken laths to massive form, in a glassy matrix with fine iron oxide dendrites. The volumetric phase percentages are shown in Table 9.10.16 (Vol II p68), the sample was homogeneous with an r-mean value of 9 (S.D.=7).   This value would be less than 5.0 if analysis 4 was excluded.

Five bulk analyses were measured (Table 9.10.17, Vol II p69), and were similar to those from Sample C, having high calcium and manganese oxide percentages.   They totalled 100% (within acceptable limits), and a reduced total due to the presence of ferric iron would not be expected due to the low free iron oxide content observed in the optical study.

The phase analyses of the silicate and glass correspond very closely with those obtained from Sample C.   The iron oxide dendrites were too fine to be accurately analysed.

The normative mineral composition of the bulk and phase analyses (Table 9.10.18, Vol II p70) were equitable with those from Sample C. The bulk minerals were very consistent, no analyses contained excess iron oxide.

The apportionment of the mineral calcium silicate to the silicate and glass ternary phases was carried out as in Sample C (Table 9.10.19, Vol II p71/2).   The calcium silicate ratio, silicate to glass, (1 :1.2) was lower than in Sample C .   R-factor analysis was only performed on the example with the calcium split between the silicate and glass phases, (this had a median value in Sample C). This confirmed the homogeneity of the

sample (r-mean = 4.7, S.D.=4.1).

The volumetric and normative ternary phase percentage comparison (Table 9.10.20, Vol II p73) also confirmed the relative homogeneity of the sample. The greatest correlation occurred between the volumetric analysis and the ternary grouping with the calcium silicate apportioned to the silicate phase only (r-mean=8.2, S.D.=3.6). The greatest deviation occurred with the calcium silicate apportioned to the glass phase only.

The mean of the bulk analyses and the normative mineral composition is shown with the X.R.F analysis and normative mineral composition in Table 9.10.21 (Vol II p74). The analyses were in good agreement, but the normative minerals differed partly due to the absence of a phosphorus figure in the X.R.F. analysis.

9.10.5   Sample E

A single specimen was diametrically cut from Slag Cake E. It had a similar mineral texture to Sample D except that it had a higher free iron oxide content which occurred as globular dendrites (Table 9.10.22, Vol II p75). The volumetric analyses were homogeneous, r-mean = 7, and would be lower if analyis 4 was excluded, (r-mean = 3).

Only two bulk analyses were obtained, and were very similar to those from Samples C and D, (Table 9.10.23, Vol II p76). The normative mineral composition of the bulk analyses are directly comparable to those from Samples C and D, being essentially fayalitic in composition with calcium silicate, forsterite, tephroite and gehlenite, (silica deficient anorthite), present

(Table 9.10.24, Vol II p77). The calcium silicate was divided between the silicate and glass phases in the ratio of the calcium silicate present in the analysed silicate and glass phases (1 : 0.77). The ternary groupings were similar (r= 3.0), (Table 9.10.25.1, Vol II p78), but diverged from the volumetric analyses, (r-mean = 14.7, S.D.=4.7). Closer correlation occurred between the ternary groupings and volumetric analysis 4, (the exceptional analysis only 10% glass). Allocation of all the calcium silicate to the glass phase gave a higher r-mean value (= 18.9, S.D.=5.0, Table 9.10.25.2, Vol II p78), and to the silicate phase a lower value, (r-mean=12.7, S.D.=3.8, Table 9.10.25.3, Vol II p79).

The silicate and glass phase analyses were similar to those of Samples C and D. The normative mineral compositions were also comparable; the silicate was iron oxide rich fayalite and the glass silica rich. The analysis of the iron oxide phase totalled less than 100% and contained a high titanium oxide content, and was identified as magnetite.

The mean S.E.M. and X.R.F. bulk analyses and their resultant normative constituents are given in Table 9.10.26 (Vol II p80). The X.R.F. analysis was high in iron oxide, the low total indicated the presence of ferric iron (as magnetite). The analysis indicated that the sample was mostly iron oxide and illustrates the dangers of accepting single bulk analyses of heterogeneous specimens.

9.10.6   Sample XX

Three samples (XX.1, XX.2 and XX.3) were prepared from a diametrically cut section, all were volumetrically analysed and only XX.3 was analysed by the S.E.M.

The silicate in all sections occurred in various forms, euhedral lath, lath and massive. The iron oxide dendrites were present as either fine or rounded globular dendrites (Plate 31 Vol II p248). The former tended to occur with the lath type silicate. The percentage of glass phase varied between the samples (Table 9.10.27, Vol II p81/2), XX.2 containing the least (average 19), and XX.1 the highest (average 29).

The r-factor analysis showed Samples XX.1 (r-mean=10, S.D.=4), and XX.3 (r-mean=9, S.D.=4) to be similar and more homegeneous than XX.2 (r-mean=18, S.D.=10).

The bulk analyses were similar to those of Samples C, D and E, having high calcium oxide contents, between four and five percent manganese oxide, and a slightly lower alumina content, (Table 9.10.28, Vol II p83).

The calculated normative mineral constituents of the bulk analyses show significant differences (Table 9.10.30, Vol II p85), although they were all silica deficient (gehlenite calculated). Bulk analyses 3 and 4 contain no anorthite or free iron oxide and lower gehlenite contents, this results from subtle differences in the oxide percentages, e.g. the slightly lower silica and alumina contents, and higher iron plus manganese oxides.

The phase analyses (Table 9.10.29, Vol II p84) showed the silicate phase to have been fayalite, with higher calcium oxide

and lower manganese oxide contents than in Samples C, D, and E. The two glasses analysed differed in all oxide contents, notably the iron and phosphorus oxide content. The normative constituents (Table 9.10.31, Vol II p86) of the silicate showed excess iron oxide present (as calculated in Samples C, D, and E). The constituents of Glass 1 and 2 reflected their chemical differences, Glass 2 contained a high apatite content and was silica rich (orthoclase present). Glass 1 was fayalitic/anorthitic.

Four iron oxide dendrites were analysed: all totalled less than 100%, and the presence of high titanium oxide contents indicated a spinel structure, i.e. magnetite. The elemental iron plus manganese percentage averaged 72.5, typical of magnetite.

The ternary grouping of the normative minerals was treated in the same manner as the previous samples. The silicate : glass ratio of the calcium silicate was 1 : 0.34. The mean r-factors (Table 9.10.32, Vol II p87-89), showed the closest correlation between the volumetric analyis and the ternary grouping when the calcium silicate was ascribed to the glass phase only (r-mean = 11.5, S.D.=5.2), and the greatest discrepancy when ascribed to the silicate phase (r-mean = 14.7, S.D.= 4.7). The closest individual correlation occurred between the volumetric ternaries and the ternaries for bulk analyses 3 and 4, which contained free iron oxide.

9.10.7   Comparison of the Millbrook Slags

Samples C, D, E and XX were similar volumetrically, chemically, and in normative mineral constituents and ternary groupings. They were characterised by high calcium and manganese oxide contents. This resulted in the normative calculation giving a high calcium silicate content. The phase analyses confirmed the presence of this mineral in both the glass phase and silicate phase, which was predominantly fayalitic, but was also iron oxide rich. The wet chemical analysis showed a high ferric iron content indicating the presence of magnetite. This was confirmed by X-ray diffraction, and the analysis of the iron oxide phase which showed high titanium oxide contents and normally totalled less than 100%. This phase also contained significant manganese oxide contents which would indicate strong reducing conditions, but the presence of the titanium oxide would also suggest the formation of the spinel structure of the iron oxide during the liquid phase. This sequence could be explained by strong reducing conditions in the reduction zone of the furnace and subsequent re-oxidation at the base of the furnace. (it is therefore probable that the tuyeres were low down at or close to the base of the furnace). The re-oxidation would lead to an increase in viscosity, and hence the agglomerated morphology of the slag cakes, rather than the free flowed nature of tap slag.

Sample A was atypical; it was low in calcium oxide and manganese oxide, and higher in alumina and potassium oxide. This difference could be explained in two ways: firstly, it represented a tapping of the furnace at a particular stage in the smelting cycle, probably the first or last tapping. The high alumina was derived from contamination by the clay of the furnace

lining. The second cause was that the slag cake was a smithing hearth bottom derived from the primary smithing process in which the raw bloom was refined, driving out the excess slag. This would result in a slag having some of the characteristics of the smelting slag (e.g. higher manganese oxide contents than typical smithing slag).

The smelting slag indicates a smelting process which was less efficient than the technology represented by tap slag. It was probable that re-oxidation took place resulting in oxidation of some of the metallic iron, the formation of magnetite, and high free iron oxide content in the volumetric analysis, and a more viscous slag, thus prohibiting the formation of free running tap slag.

9.11 Raked Slag Summary

The slag from Millbrook was selected as a typical raked slag sample.

The raked slag morphology lacks the characteristic ropey appearance of tap slags. It commonly occurs as slag cakes, plano-convex accumulations of slag, when it has been raked into a pit in-front of the furnace. Randomly shaped lumps of slag also occur. The most viscous slags include fossilised charcoal impressions.

The mineral texture of the silicate phase ranged from lath to massive, the euhedral form was the most common. The free iron oxide commonly occurred as rounded dendrites. The mean volumetric phase percentages are:-

Silicate	61%
Glass	24%
Feox	13%

The mean bulk analyses are shown in Table 9.10.33 (Vol II p90/1) and are characterised by the presence of manganese oxide, (cf. tap slags), and high lime. The exception was Sample MBRK A having less than 1% manganese oxide and 4% lime, and having a slightly higher alumina content. The high lime content in the bulk analyses resulted in concentration of this oxide in the silicate phase. The manganese oxide was also concentrated in the silicate phase. The glass phases were variable, and there was evidence for a significant number of the free iron oxide dendrites occurred as magnetite rather than wustite.

The calculated r-mean values were significantly higher

than those derived from the tap slags, the values being:-

	r-mean	S.D.
Volumetric	12	8
Ternary	9.6	7.2
Volumetric/Ternary	15.8	7.3

This indicates mineral and chemical heterogeneity and strong deviation from equilibrium conditions during cooling.

9.12 Slag Blocks

The 'Slag Block' or 'Schlackenklotz' technology has been investigated in Poland[20]. The theory proposes that a pit was dug and filled with combustible material, the furnace was built above and worked. The material in the pit did not burn during the smelting operation due to the absence of oxygen. The slag was supported by the material in the pit and allowed to build up in the furnace until a sufficient quantity of iron had been produced. Air was vented into the pit, the combustible material burnt, and the the slag dropped into the pit. The metallic iron was then removed and the furnace moved to above the next pit or destroyed. The questions raised concerning this theory will be discussed after the analysis.

The distribution of the slag block type slag in Britain was discussed earlier (p.50); they have been found as single specimens or from unstratified contexts at Mucking, Essex. Recent excavations in Romsey (Hants) have produced large quantities of complete and incomplete slag blocks.

9.13 ROMSEY, HANTS. (N.G.R. SU359321)

9.13.1 Introduction

Recent excavations[92] in the vicinty of the 10th Century Priory have produced 400 Kg. of complete or fragmented slag blocks. Other slag blocks were not recovered, but were noted in builders' trenches etc.. The greatest quantity (320 kg) was found on the Narrow Lane Site (excavated by the Test Valley Archaeological Trust); the slag occurred in a disturbed plough/garden soil, termed a 'black earth'. Discussions with the archaeologists suggest that they were not in-situ, i.e. in pits, but their concentration indicates that they originated from the area close to the Priory. The 'black earth' layer was disturbed but was Post-Roman; it is unlikely that they were produced after the building of the Priory and can, therefore, be dated to the 5-10th centuries.

The largest (complete) block weighed 40 kg and measured 400mm in diameter and 400mm in depth, it was a tapering U-shape in section, but it was not apparent which way up the slag cooled. A fragment of another block was taken for analysis, it weighed 3 kg and had broken from a block estimated to have similar dimensions to the one described above. It was fractured on the upper and basal surfaces, but the 'sides' were present, and had a 'tap or flowed' appearance with rivulets of slag present. In cross-section the slag was fined grained with no apparent cooling surfaces (iron oxide layers) present. There were small (<3mm in diameter) vesicles present throughout, but they were larger (5mm in length) close to the (side) outer surfaces. The block tapered, similar to the complete example, but the 'way-up' could not be determined.

A vertical section was cut from the block fragment, and two areas were mounted and examined. The first (Sample ROM3) was the central portion of the block, and the second (Sample ROM2) from closer to the side surface of the block.

9.13.2   Sample ROM3

The mineral texture was uniform, massive silicate and fine dendritic iron oxide, some of which was orientated, and a small quantity of glass (Plate 32, Vol II p249. The section was finely vesicular. The volumetric analyses (Table 9.13.1, Vol II p92) confirmed the uniformity of the section, and the r-mean value (9, S.D.=5) was of similar order to that obtained for the tap slags. The massive silicate indicates that the slag had cooled slowly, as would be expected for a large volume.

The bulk analyses (Table 9.13.2, Vol II p93) were fayalitic, with low manganese contents (cf. Baysdale analyses Table 9.5.2 Vol II p30), and low potassium oxide and lime contents. The alumina contents were high in relation to the percentage of the other alkali oxides.

The silicate phase analyses (Table 9.13.3, Vol II p94) confirmed the presence of fayalite, containing manganese oxide. The three glass phase analyses gave differing results, except in the high phosphorus pentoxide contents. Glass1 totalled only 77.2% and had a high silica and low iron oxide (wustite) contents. Glass2 also had a low total (74.1%) but was high in iron oxide (wustite) and low in silica (relative to Glass1), and was very low in the glass forming oxides, calcium and potassium Glass 3 totalled 103.4% and had a typical glass composition. The iron oxide analyses were similar, and were rich in titania

indicative of a spinel structure. The elemental iron percentages
(FEOX1=74.5%; FEOX2=73.8%; FEOX3=73.6%) indicate a composition
between magnetite and wustite.

The normative mineral constituents of the bulk analyses
(Table 9.13.4 Vol II p95) showed considerable variation, e.g. in
kalsilite, nepheline and anorthite contents. Analyses 3 differed
considerably, it was silica rich (orthoclase, enstatite, and
rhodonite calculated) and was low in 'glass' minerals.

The normative calculation of the fayalite (Table 9.13.5, Vol
II p96) showed SIL1 to have been iron oxide rich (wustite
calculated), and SIL2 silica rich (enstatite calculated). The
variation in the chemical composition of the glass phases was
reflected in the mineral composition, (the calculation normalised
the results, i.e. totalled 100%). Glasses 1 and 2 contained
excess silica (quartz calculated), and were rich in hercynite and
vivianite [$Fe_3(PO_4)_2$]. Glass 3 contained less silica (kalsilite
and fayalite calculated) but was still silica rich (orthoclase
calculated).

The normative ternary groupings of the bulk analyses (Table
9.13.6 Vol II p97) showed close correlation (r-mean=6.5;
S.D.=3.9), indicating homogeneity in composition. The comparison
between the volumetric study and the normative ternary analyses
indicated divergence from equilibrium conditions (r-mean=17.1;
S.D.=8.0), i.e. a rapid cool. These results are similar to those
obtained for tap slags, but this appears to conflict with,
firstly, the massive nature of the fayalite, which indicated a
slow cool. Secondly, the 'slag block' theory proposes cooling of
the slag in a pit below the furnace, which would have been heated
by the furnace above and would have induced a very slow cool.

9.13.3 Sample ROM2

The mineral texture of Sample ROM2 was the same as ROM3, (massive silicate and fine iron oxide dendrites in a glassy matrix). The volumetric fractions were similar to those obtained for Sample ROM3, (Table 9.13.7, Vol II p98), but showed greater variation as indicated by the r-factor analysis, r-mean=13, S.D.=5.

The bulk analyses (Table 9.13.8, Vol II p99) were similar to those obtained for Sample ROM3, with an average manganese oxide content of 1.3%, and was low in lime and potassium oxide. The analyses differed slightly in their alumina and silica contents, Sample ROM2 was lower in alumina (mean=4.5%), and higher in silica (mean=27.4%), (values for ROM3 were 5.4% and 26.7% respectively).

The silicate phase analyses (Table 9.13.9, Vol II p100) were fayalitic containing manganese oxide and magnesium oxide. The glass phase had a typical composition, but had a high sulphur content (1.0%). The iron oxide analyses contained less than 5% minor oxides, the titania content was high (0.8%), and the elemental iron percentage was close to the magnetite level, (93.3% and 94.4%).

The normative mineral constituents of the silicate phase analyses (Table 9.13.10, Vol II p101) showed them to be slightly silica rich (enstatite calculated). The glass phase was also silica rich (orthoclase, albite, ferrosilite, enstatite, and rhodonite were calculated).

The normative mineral constituents of the bulk analyses (Table 9.13.10, Vol II p101) shows Analyses 1 and 2 were iron

oxide rich (wustite calculated), the remainder were silica rich. (orthoclase etc. calculated). The ternary grouping and the r-factor analysis (Table 9.13.11, Vol II p102), indicate a very homogeneous composition (r—mean=1.5, S.D.=0.7). The comparison between the volumetric and ternary groupings resulted in a very high r—mean value (r—mean=16.3, S.D.=7.0), showing disparity between the two analyses, indicating deviation from equilibrium conditions during cooling.

9.13.4 Comparison Between Samples ROM3 and ROM2

The mineral textures of both samples were the same, (massive silicate with fine iron oxide dendrites in a glassy matrix). The mean volumetric percentages for the three phases are:

	SIL (S.D.)	GLASS (S.D.)	FEOX (S.D.)
ROM3	61 (8)	24 (5)	15 (3.5)
ROM2	70 (9)	17 (4.5)	13 (6)

The comparison between the volumetric analyses using the r-factor test (Table 9.13.12, Vol II p103) gives an r—mean value of 12, (S.D.=7), which is comparable to the individual r—mean values obtained for the samples (ROM3, r—mean=9, S.D.=5; ROM2, r—mean=13, S.D.=5). Thus, the heterogeneity between the samples is of a similar order to the heterogeneity within each sample.

Comparison between the chemical composition of the bulk samples and the phases can be assessed using the normative mineral compositions, the ternary groupings and resultant r-factor analyses. The silicate phases had similar normative mineral compositions, three of the analyses were silica rich, the fourth (Sample ROM3. SIL1, Table 9.13.5, Vol II p96) calculated

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excess wustite.   All the glass phases were silica rich, the ROM3 phases having a greater number of minerals calculated.   Overall four of the bulk analyses were silica rich, (ROM3 B3; ROM2 B3,B4,B5) the remainder calculated excess wustite.   The r-factor analysis for the comparison between the ternary groupings (Table 9.13.12,   Vol II p103), calculated an r-mean value = 7.0 (S.D.=4.6).   This   is   greater   than those   calculated   for   the individual ternary groupings,   but is of similar order   to   that obtained   for ROM3   (Table   9.13.6,   Vol II   p97,   r-mean=6.5, S.D.=3.9);   this   again   suggests   that   the   chemical heterogeneity/homogeneity   between   the samples is equivalent   to that   for   the individual samples.   The general   summary   can, therefore,   be   that the two samples were essentially   the   same. This   implies   full   miscibility and similar   cooling   conditions throughout the slag block.

9.14   The slag block theory

The analyses of the Romsey slag block shows a   predominantly fayalitic   slag   with a low glass content,   and a low   free   iron oxide content.   The low iron oxide content indicates an efficient process.   The   glass phase had a variable composition suggesting poor   mixing   in   the   liquid state   and/or   restrictions   on   the mobility of the glass oxides after formation of the fayalite.   If the slag had been retained in the fully liquid state while it was in   the   furnace prior to the burning of the material in the   pit and   slumping of   the slag into the pit,   complete   or   efficient mixing   would have occurred (dependent on slag   viscosity).   The massive   texture   of the fayalite indicates a slow   cooling   rate after crystallisation, and this would impede mixing of the (still liquid) glass,   resulting in varying glass composition.   Further,

the low percentage of glass present prohibited the formation of a continuous network of glass phase, restricting the diffusion of oxides.

The analyses of the slag block cannot confirm or refute the theory of block formation, since the results could equally be explained by tapping of the slag into a pit in front of the furnace, i.e. large slag cakes. This explanation has the advantage that the furnace could be continually worked to produce a greater quantity of iron, each slag block (cake) being removed when frozen, to allow further tappings. The section of the block analysed showed no cooling surfaces, therefore, the block was not formed by sequential tappings but by a single operation.

9.15 DENSE IRON SILICATE SLAG

The excavations at Mucking, (Essex)[93] produced 300 kg of residues distributed over a large area. They were classified into the usual groups, smelting slag, smithing slag/hearth bottoms, cinder, furnace/hearth lining, and fuel ash slag. The majority had morphologies typical of their group, but one class of slag was distinct. It was termed Dense Iron Silicate Slag (DIS), due to its apparent high density. The slag was fine grained with very few vesicles, hence its apparent high density. It was, therefore, classified as a smelting slag. It tended to occur in large lumps, greater than 500gms in weight, but with no characteristic form or shape, although some occurred cone shaped.

The sample analysed was that referred to in Section 7 (p72). It was a formless lump weighing about 400gms, but was clearly a broken fragment of a larger piece. It had the morphology described above.

The mineral texture was massive silicate and iron oxide dendrites with a glassy matrix (Plate 33, Vol II p249). The volumetric analyses of two sections (MUK5/2 and MUK5/4) are shown in Table 9.15.1 and 9.15.2 (Vol II p104/105). These show that each sample is reasonably homogenous (MUK5/2, r-mean=8, S.D.=5; MUK5/4, r-mean=6.5, S.D.=4). It was shown (Section 7, p73) that the bulk analyses from the different sections correlated closely. therefore, only the data from Sample MUK5/2 has been processed.

The bulk analyses of Sample MUK5/2 (Table 9.15.3, Vol II p106) were high in iron oxide and low in silica. Manganese oxide was only detected in Analysis 2 (0.1%), phosphorus pentoxide contents were high, lime and potassium oxide percentages were low. The silicate phase was very pure, the only significant

minor element present was phosphorus, which is uncharacteristic. The glass phase was typical except for the very low lime content. The iron oxide analyses were high in alumina and FEOX2 was relatively rich in titania; these both indicate the presence of a spinel structure and therefore, the oxide was probably present as oxygen rich wustite or magnetite.

The normative mineral calculation (Table 9.15.4, Vol II p107) showed the silicate to be fayalite with excess wustite present and a small proportion of minor elements. The glass phase was silica rich (orthoclase calculated), and the other major minerals being vivianite and kalsilite. The calculation applied to the bulk analyses showed them all to contain excess iron oxide, and to be predominantly fayalitic with vivianite. kalsilite and hercynite present. The ternary groupings and r-factor analysis (Table 9.15.5, Vol II p108) show homogeneity of the sample (r-mean=4.3, S.D.=2.3). The comparison between the volumetric analyses and the ternary groupings result in a high mean r-value (13.7, S.D.=5.9). The homogeneity indicated by the volumetric and the ternary r-factors and the heterogeneity indicated by the comparative r-factor suggests a fully liquid slag that cooled rapidly, but uniformly, resulting in divergence from equilibrium conditions. However, the mineral texture (massive silicate) indicated a slow cool. These results are similar to those obtained for the slag blocks and, therefore, a slow cooling rate must be accepted for the dense iron silicate.

CHAPTER 10

THE SMITHING SLAGS

10.1 Introduction

The smithing process (discussed in Section 2) is defined as the working of the metal. It, therefore, included primary smithing in which the unworked bloom of metal was removed from the smelting furnace, refined and consolidated. This process was carried out at the smelting site, and it was likely that in low-level iron production, i.e. one-off smelts, the furnace was re-used as the re-heating hearth. On sites where continual, 'industrial' production occurred, special re-heating hearths would have been constructed.

The secondary smithing process was the manufacture, and subsequent repair or alteration of artefacts. Secondary smithing included processes other than the fabrication activities of heating and hammering, notably heat treatments, (quenching and tempering), and possibly carburisation, (the introduction of carbon to produce steel). Heat treatments did not generate residues as a by-product. Carburisation would have required a sealed environment, and residues would have been generated, but would be unlikely to be recognised amongst the general smithing debris, e.g. 'oxide' scale and clay linings. No carburisation pits have been reported in the archaeological literature. The evidence for the use of heat treatments can only be obtained from analyses of the artefacts.

In discussing the residues the term smithing refers to the heating and hammering of the bloom or artefact, i.e. those activities generating by-products. Smithing was carried out in a

smithing hearth or forge. The process requires no elaborate hearth structure to maintain specific atmospheres, and could be carried out on the ground surface, in a suitable pit or hearth, including the domestic hearth.

The evidence of the smithing process from the different periods suggests a uniformity of fabrication techniques, that have changed little during the two millenia of ironworking. This indicates little reason for studying smithing slags, but, as will be shown, smithing and smelting slags can be similar in morphology, chemical and mineral composition. It is, therefore, of great importance to be able to distinguish between these slags in order to interpret the economic bases of early settlements and societies correctly.

10.2 Smithing Slag Types

There are four types of diagnostic residue associated with the smithing process:- hearth bottoms, smithing slag, hammer scale and finally cinder. Hearth bottoms are plano-convex accumulations of slag, while smithing slags are randomly shaped pieces, i.e. the hearth bottom is a particular form of smithing slag. The randomly shaped pieces of smithing slag were probably removed from the hearth before they fully developed into a hearth bottom. Cinder is smithing slag that contains a high silica content. Therefore, there is an increasing silica content between smithing slag (or hearth bottoms), to cinder to fuel ash slag, (a non-diagnostic residue). Hammer scale occurs in two forms: firstly, flake hammer scale is fragments of the oxidised or slagged surface of the metal that are removed during working. Secondly, spheroidal hammer scale consists of droplets of oxide or slag extruded during hammering (normally fire welding).

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10.3 Hearth Bottoms and Smithing Slag

Hearth bottoms and smithing slag are the commonly found forms of smithing residue. They were formed in the hearth during the heating of the iron. These slags are similar in morphology, chemical and mineral composition to smelting slags. They are formed by the accumulation of three components. Firstly, the iron oxide derived from the metal being worked, secondly, the 'flux' normally a 'sand', that was scattered on the metal to inhibit oxidation of the iron by the formation of a thin silicate film on the surface of the metal. Any excess slag that was not retained on the surface of the metal would drop off into the hearth. The third component was any slag that derived from the stringers within the iron being worked, that may have liquefied during the heating of the iron. This was only likely to contribute a very small amount to the total, but would be dependent on the quantity of slag inclusions in the metal. The very 'dirtiest' irons would have contributed a larger proportion to the total. The slags may also contain a proportion of foreign matter, e.g. pebbles, uncombined silica, charcoal and metallic iron.

Concentrations of slag to form a hearth bottom can only form in a localised zone for three reasons. Firstly, the smith could only achieve suitable conditions, i.e. temperature and atmosphere, in a restricted zone in front of the tuyere. Secondly, the greater proportion of smithing activity concerned small artefacts, knives, tools, etc.; large scale working was probably restricted to specialist smiths e.g. sword-smiths. Thirdly, the working of some larger pieces of iron, e.g. bar iron, could only be hammered, shaped, etc. in short lengths before the iron became too cold. It was, therefore, only

worthwhile to heat short lengths of the iron being worked.

Hearth bottoms are only a morphologically distinct form of smithing slag (they are chemically and mineralogically similar), and are only discussed separately where relevant, and therefore the term smithing slag refers to both types. These morphological differences are recorded by individually weighing the hearth bottoms, measuring the major and minor diameters and the depth. The true volume of a hearth bottom cannot be calculated from these readings, but an indication of the weight-to-size ratio can be determined, by plotting the weight against the mean diameter multiplied by the depth. The plot of the Millbrook smelting slag cakes and the Wharram Percy hearth bottoms is shown in Figure 14 (Vol II p219). This shows that in general the hearth bottoms and the slag cakes plot in different areas of the graph, but there is a region of overlap, and thus size alone cannot distinguish the two plano-convex accumulations of slag.

The absence of technological change in the smithing process throughout the period of study prohibits different methodological approaches to the study of smithing slags. Essentially an Iron Age specimen is no different from one dated to the Medieval Period.

Assuming the three-component model for the formation of smithing slags (above) and that the effect of the slag derived from the original stringers is insignificant, the composition of the slag will depend on:

      1) the quantity of iron oxide (scale) formed during
      heating.
      2) the quantity and type of flux used, e.g. whether a
      silica or a shell sand was used.

3) the type of smithing activity being carried out.

4) the hearth conditions.

1 The Iron Oxide Content

The iron oxide content will be dependent upon the temperature and time of heating, the efficiency of the fluxing and the availability of the silica to form fayalite. Higher temperatures and the absence of flux would result in large quantities of iron oxide being formed

2 The Flux

The nature of the flux will determine the minerals formed. Pure silica sand would result in fayalitic slags whereas shell sands would form lime rich slags. The geological location of the smithy would determine the level of the minor oxides present. The quantity of flux, in terms of the ratio between sand and iron oxide will determine the amount of free iron oxide present in the slag mineralogy.

3 The Hearth Conditions

Different hearth conditions, in particular temperature, will determine rates of diffusion and mineral formation of the slags. Smithing slags, especially hearth bottoms, will remain in the hearth for some considerable time, and would be subjected to re-heating to various temperatures under different atmospheric conditions. Therefore, mineralogical changes in the slags will occur after the formation of the slag; for example fayalite can form by solid state diffusion above 650°C.

The present study aims to distinguish smelting slags from

smithing slags. and to examine the variation in chemical and mineral content and mineralogical texture. The degree of variability in the conditions of formation of smithing slag and the treatments to which it may be subjected in the hearth after formation prohibits the association of individual samples with specific activities, such as simple forming or welding. Some general conclusions can be drawn; for example, the quantity of free iron oxide present would indicate the efficiency of the fluxing process, i.e. the higher the free iron oxide content the less efficient the fluxing was. Secondly the quantity of smithing slag on an archaeological site may indicate the level of the smithing activity, i.e. was there a full-time smithy in operation or was it just a low-level activity to satisfy occasional needs?

10.4 Hammer Scale

The term hammer scale has been applied to the macroscopic residues that have been found in association with smithing slags. The term has not been used in archaeological literature with the strict sense with which it is applied today, i.e. mill-scale. These residues were termed hammer scale because the archaeological particles were similar to those found around a modern smith's anvil. Hammer scale has been classified into two types, flake and spheroidal. The former is distinguishable by its similar form to modern scale. It has a metallic lustre. is often highly magnetic and measures up to 10mm across. It is believed to derive primarily from oxide and/or silicate scale formed on the iron. The oxide scale formed due to oxidation of the metal surface, and the silicate scale was a thin slag layer formed by the sand flux. It can be a constituent of smithing

slag when detached from the metal in the hearth, but it is found unaltered when it has parted from the iron due to either thermal shock (differential cooling rates), or physical separation by hammering.

The second type, spheroidal hammer scale, was a liquid that cooled in flight. It was formed by the rapid extrusion of either the liquid silicate slag or oxide during hammering. It forms the 'sparks' traditionally associated with blacksmithing. The spheroidal hammer scale may be distorted if it hits a surface prior to cooling, i.e. splatting.

The distribution of modern hammer scale in smithies has been examined. and concentrates, as expected. around the anvil. In antiquity it was unlikely to be re-deposited in secondary contexts, e.g. pits and ditches, as other ironworking residues were, and is, therefore, a very good indicator as to the area in which the smithing took place. Furthermore, it is the one residue that can be associated unequivocally with one particular ironworking process, primary and secondary smithing.

10.5 Cinder

Cinder is predominantly non-diagnostic. It is clear from archaeological evidence that cinder occurs in association with both smelting and smithing slags, although it may occur isolated from them. The evidence does suggest that it derives primarily from the smithing process. It is a highly siliceous slag, the silica being fused by iron oxide and or glass. The material has not been studied in detail, but a sample from Wharram Percy was sectioned and analysed in the usual manner.

The morphology of cinder is varied, but is usually randomly shaped with a fritted, 'cindery' appearance. In cross-section the slag was highly vesicular, which precludes the application of volumetric phase percentage analyses. The optical analysis showed a large phase fused by the second phase. Small area bulk analyses were obtained at magnifications greater than 500X, (Table 10.5.1, Vol II p109). These show variable composition, but are generally high in silica and low in iron oxide. The glass forming oxides are very variable, four of the analyses had CaO/K_2O ratios between (2.1-2.6) : 1 . Analysis 4 was distinguished by having a ratio of 4:1. The alumina content also showed considerable variation, 3.7-11.1%. The phosphorus pentoxide content was very low. The phase analyses confirm the presence of two phases, firstly the silica phase which formed the largest (by area) phase. The second phase, which was a glassy phase fusing the silica phases together, had a composition similar to glass phases analysed in smelting and smithing slags, but are characterised by very low (or absent) phosphorus pentoxide percentages. The normative compositions of the bulk analyses are given in Table 10.5.2 (Vol II p110). These show them to contain excess silica, (quartz was calculated), and the other minerals were silica saturated. The normative composition of the phases is shown in Table 10.5.3 (Vol II p111), and show them to be silica saturated. The major calculated minerals were orthoclase, wollastonite, ferrosilite and quartz. The silica phase was quartz, the glass phases were silica saturated, quartz being calculated in all three phases. The other minerals calculated are the same as those in the bulk analyses.

The iron content of the cinder does suggest that the cinder derives from the ironworking process, rather than from any other

pyrotechnological process.

10.6 Smithing Slags- Previous Work

Smithing slags have not been studied in any detail, and have only been mentioned with respect to smelting slags. Tylecote mentioned them only briefly[4]. Sperl[94], Bachmann[84], and Kresten[82] studied them in slightly more detail, but came to no firm conclusions. The most recent evidence was presented at the Comite Pour La Siderurgie Ancienne de l'UISPP 1984 Belfast Symposium[92]. At that Conference Sperl proposed a number of attributes for the identification of smithing slags. These included morphology, a high glass content, and the presence of unaltered quartz, and a reversal of the $FeO:SiO_2$ ratio from approximately 2:1 for smelting slags to 1:2 for smithing slags. These analyses correspond more closely with the present work's category of 'cinder'.

There is no corpus of identified smithing slag analyses for reference purposes and therefore, comparisons with other data is not possible. Further, except for Sperl's comments there are no other detailed descriptions or definitions.

10.7   The Chemical and Mineral Composition of Smithing Slags

The chemical and mineral composition of smithing slags is essentially the same as that of the smelting slags (Section 9). The major oxides present are silica and iron oxide, with varying amounts of the lesser oxides, alumina, lime, etc.. It therefore, follows that the mineral composition is also the same, iron silicate, free iron oxide, (wustite or magnetite), and a glass phase.

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The genesis of smithing slag suggests that the chemical and mineral content of the slag may vary within a single specimen. Smithing slags, unlike smelting slags, are formed intermittently and hence the component ratios may vary. Therefore. it is possible that there is a higher heterogeneity factor for smithing slags.

The methods of analyses are those used for the smelting slags. The variation in formation gives no basis for prior classification of the smithing slags. Therefore, a number of samples from different sites have been analysed, and the data must be regarded as a random selection. Analyses of hammer scale has also been included as a final group.

11.1 BECKFORD, WORCESTERSHIRE. (N.G.R. SO984364)

11.1.1 Introduction

The Beckford site provided evidence of occupation from the Mesolithic through to the Medieval Period[48]. The main period of settlement was during the Middle Iron Age until the end of the Roman Period. It was a rural settlement with timber buildings and an extensive field system. There was evidence for iron smithing during the Middle Iron Age, in the form of slags, but there were no identified smithing hearths or structures. The slag occurred in secondary contexts, e.g. pits and ditches, that were functional at the time of the smithing activity. The total quantity of slag recovered from these contexts was 4.13 kg. This was interpreted as intermittent smithing rather than the residue of a full-time smithy. A small quantity of slag occurred in Romano-British and later contexts but was probably residual. Two samples were examined from the Iron Age and two from the Romano-British Periods, and one from an unstratified layer.

The slag had an agglomerated morphology and occurred predominantly in small lumps. A small number of hearth bottoms were recorded and their dimensions are given in Table 11.1.1 (Vol II p112).

Five Samples (BEK 1 - 5), were fully analysed and other ones were only optically examined. The contexts and dating of the five samples are given in Table 11.1.2 (Vol II p112).

11.1.2   Sample BEK1   (Context 4831)

Sample BEK1 was a typically random shaped smithing lump weighing 105 grammes. The volumetric phase percentages are given in Table 11.1.3 (Vol II p113). It contained 40 - 60 % of silicate in lath and massive form, with 30 - 50 % of globular iron oxide dendrites which were orientated. The glassy matrix comprised 10 % of the total (Plate 34. Vol II p250). The r-factor analyses showed a relatively heterogeneous sample, the overall r-mean value was low (10) , but the standard deviation was high (8), and the individual r-factors were very variable (0.0 - 20.0).

Only four bulk chemical analyses were obtained and are shown in Table 11.1.4 (Vol II p114). There was a low percentage of alkali metal oxides; phosphorus and sulphur were absent. and they were rich in iron oxide. Only the silicate phase was analysed and was shown to be fayalitic with very low concentrations of other oxides present.

The normative mineral composition (Table 11.1.5. Vol II p115), showed the bulk analyses to have been iron oxide rich with a low concentration of glass forming minerals present. This accorded with the optical study, the ternary groupings (Table 11.1.6, Vol II p116), were very homogeneous (r-mean=4.1, S.D.=2.0), and showed close similarity with the volumetric analyses (r-mean=7.5, S.D.=6.4). This shows the specimen to be relatively homogeneous.

The chemical analyses show that it was comprised of silica and excess iron oxide, resulting in a predominantly fayalitic phase with free iron oxide present. Such analyses would result from simple smithing using sand as a flux. The excess iron oxide

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suggests that the fluxing was not fully effective and the iron being smithed suffered oxidation.

11.1.3 Sample BEK2 (Context 65370)

Sample BEK2 was morphologically the same as BEK1. The optical analyses showed very low glass phase (0-2%) and varying percentages of silicate and iron oxide present (Table 11.1.7, Vol II p117). The silicate phase occurred mostly in massive form and the iron oxide as rounded globular dendrites. There was some lath silicate present in areas of greater glass content (Plate 35, Vol II p250). The r-factor analysis indicated an homogeneous volumetric mineral composition (r-mean=8, S.D.=6). The bulk analyses (Table 11.1.8, Vol II p118) showed a high iron oxide content, and average percentages of the glass forming oxides. Phosphorus, sulphur, and titanium were present in significant concentrations. The bulk normative mineral constituents indicated a high glass content (average 18%, Table 11.1.9, Vol II p119), and the presence of free iron oxide. The calculated r-factor (Table 11.1.11, Vol II p121) of the bulk analyses showed a variation in the mineral composition of the areas analysed (r-mean = 23.1, S.D.=17.1). Hence there was a high discrepancy between the observed (Volumetric) and the calculated (Ternary) mineral compositions (r-mean=23.4, S.D.=8.1).

The silicate phase analyses (Table 11.1.8, Vol II p118) and normative compositions (Table 11.1.9, Vol II p119) showed it to be impure, containing 11.6% of oxides other than iron and silicon, resulting in 13.3% of normative glass minerals in the phase. This partly explains the discrepancy between the observed and calculated mineral compositions. The glass phase was silica

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rich, orthoclase being calculated as well as fayalite and calcium silicate, with the major glass minerals being kalsilite and anorthite. The glass phase contained high titania and had an average phosphorus pentoxide content. Six iron oxide dendrites were analysed (Table 11.1.10, Vol II p120); they all contained high alumina plus silica contents. These values are unusual and indicate a small amount of hercynite present in the phase, and possible substitution of Fe^{3+} with Al^{3+}; wustite is non-stoichiometric and would allow higher oxidation states than Fe^{2+}.

The analyses indicate a complex mineral structure, both the silicate and iron oxide phases contain significant amounts of alkali oxides. The glass phase was silica rich. This suggests the use of an impure silica sand as the flux.

11.1.4 Sample BEK3 (Context 74119)

Sample BEK3 was a morphologically typical smithing lump weighing 25gms. The volumetric phase composition (Table 11.1.12, Vol II p122) shows approximate equal quantities of silicate and free iron oxide with 10% glass phase present (except analysis 2). The silicate was massive and the oxide occurred as globular dendrites and were orientated in some areas (Plate 36, Vol II p251). The r-factor analysis indicated sample heterogeneity (r-mean=11, S.D.=5).

The bulk chemical analyses (Table 11.1.13, Vol II p123) were similar to those of BEK1 having very low alkali oxide contents, and no phosphorus or sulphur present, being predominantly iron oxide and silica. The normative calculations (Table 11.1.14, Vol II p124) show excess iron oxide (33 - 60%) with fayalite as the other major mineral. The mean r-factors for the normative

ternary groupings (Table 11.1.15, Vol II p125) indicate chemical heterogeneity (r-mean=10.9, S.D.=7.4). The value for the volumetric/ternary analyses (r-mean = 12.5, S.D.=5.8) indicate considerable deviation from equilibrium conditions during cooling.

The phase analyses indicate the silicate to be a pure fayalite, and the iron oxide was magnetite, (elemental iron = 71.9%)

The analyses show a fayalitic slag containing excess iron oxide, occurring as either magnetite or wustite. Like BEK1 it was formed from iron oxide with a pure silica sand as flux.

11.1.5 Sample BEK4 [Context 65726]

Sample BEK4 was a hearth bottom weighing 75gms, and measuring 60 X 50 X 30mm. Typically plano-convex with an agglomerated appearance. The mineral texture was varied; the silica was present in massive and lath form, and the iron oxide as either fine skeletal dendrites or as larger globular dendrites. Some dendrites were orientated (Plate 37, Vol II p251). The glassy matrix ranged from 20 - 35 percent; the larger percentage occurred in association with the lath silicate rather than the massive form. Fine (= 1 - 5mm) inclusions of metallic iron were present. The variation in the mineral texture gave a high mean r-factor (r-mean = 14, S.D.=8, Table 11.1.16, Vol II p126).

The bulk analyses (Table 11.1.17, Vol II p27) were similar to those of BEK2 (Table 11.1.8, Vol II p118), except in the silica content which is higher in BEK4. This was reflected in

the normative mineral constituents which result in lower free iron oxide and higher fayalitic content (Table 11.1.19, Vol II p129) than calculated in Sample BEK2 (Table 11.1.9, Vol II p119). The r-factor for the normative ternary groupings (Table 11.1.22, Vol II p132) shows good agreement (r-mean = 7.3, S.D.=4.9) except for analysis 2, which derives from lower iron oxide and higher silica contents. The comparison between the observed and the calculated mineral composition gave a mean r-factor of 13.1 (S.D.=6.9), indicating a large deviation from equilibrium conditions.

The phase analyses of the silicate phase (Table 11.1.18, Vol II p128) show it was an iron rich fayalite, (with a normative composition containing 3.5 and 29.7 percent wustite (Table 11.1.20, Vol II p130)). The glass phase was silica rich giving normative calcium silicate, fayalite and orthoclase the other major normative mineral present was kalsilite. Six iron oxide dendrites were analysed (Table 11.1.21, Vol II p131); they differ slightly from the iron oxide dendrites analysed in Sample BEK2 (Table 11.1.10, Vol II p120), containing only minor levels of alumina (mean BEK4=0.6%, BEK2=1.4%). They contain higher levels of titanium oxide (average content 0.4%). This would suggest that the oxide was magnetite, or a low iron containing wustite, as indicated by the elemental analyses.

The analyses show a typical fayalite/iron oxide smithing slag, containing average contents of the alkali oxides.

11.1.6 Sample BEK5 [65635]

Sample BEK5 was a typical plano-convex hearth bottom weighing 30gms, measuring 55 X 50 X 30mm. The volumetric phase

composition is shown in Table 11.1.23 (Vol II p133). The silicate occurred as laths merging to massive form, and the iron oxide as rounded globular dendrites (Plate 38, Vol II p252). The r-factor analysis indicated a relatively homogeneous mineral texture (r-mean=10, S.D.=4).

The bulk analyses (Table 11.1.24, Vol II p134) were similar to those from Sample BEK4 (Table 11.1.17, Vol II p127) and BEK2 (Table 11.1.8, Vol II p118) in having average alkali oxide contents, but differ in higher phosphorus pentoxide contents (average 0.8%). The normative mineral composition (Table 11.1.25, Vol II p135) showed excess iron oxide. The mean r-factor (r-mean = 12.9, S.D.=7.7 Table 11.1.28, Vol II p138) for the normative ternary groupings shows high variation between the areas analysed; and for the comparison between the observed and the calculated phases, the mean r-factor (r-mean = 11.0) suggests divergence from equilibrium conditions, and the individual r-factors showed great divergence (Standard Deviation = 5.5).

The individual phase analyses and resulting normative compositions (Tables 11.1.24, Vol II p134 and 11.1.26, Vol II p136), show the silicate to be fayalite containing excess iron oxide, and a high lime content. The glass phase was silica rich, forming calcium silicate, fayalite, and orthoclase. The iron oxide phase analyses (Table 11.1.27, Vol II p137) were similar to those from Sample BEK4 (Table 11.1.21, Vol II p131), the titanium oxide percentages were lower, and indicate the phase to be wustite.

11.1.7   Beckford Summary

The slag lumps and hearth bottoms were morphologically
similar.   Their mineral texture varied between samples and
within samples.   Chemically they formed two groups. Samples BEK1
and BEK3 were low in all minor oxides (alkali oxides, phosphorus
pentoxide etc.), and hence composed mostly of fayalite, and free
iron oxide.   The second group (BEK2, BEK4, and BEK5), contained a
more typical suite of oxides, in particular the alkali oxides.
The normative mineral compositions reflect these differences
between the two groups.   In all samples the silicate phase was
fayalitic, BEK2 and BEK3 being silica rich, BEK4 and BEK5 wustite
rich, and BEK1 normative fayalite.   Only the glass phase in the
group 2 samples was analysed, in all cases it was silica rich.
Detailed analyses were made of the iron oxide phase in group 2
samples.   Those in Sample BEK2 were atypical due to a high minor
oxide content, but all the oxides contained a significant titania
content; those with the highest content indicated that they were
present as magnetite rather than wustite.

11.2   WHARRAM PERCY, NORTH HUMBERSIDE. (N.G.R. SE858642)

The Deserted Medieval Village of Wharram Percy has been the subject of detailed archaeological study since the 1950s. Recently an Anglo-Saxon smithy (Sites 59 and 76) has been excavated[96]. It was identified by the large quantity of slag recovered (91 kg) and several hearth or hearth-like structures. The slag was concentrated within a single property (defined by ditches and/or lines of stake holes). The smithy is the subject of further study. The classification of the residues recovered are given in Table 11.2.1 (Vol II p139). The tap slag was a single piece and can be considered intrusive. The 'ore' was a ferruginous stone and could have occurred either naturally or could have been finely ground and used as a flux during the smithing. The smithing slag and hearth bottoms had a typical morphology. The hearth bottoms had mean values of:- weight 300gms; mean diameter 80mm; depth 29mm. Analysis of a soil sample from one of the 'hearth contexts' contained flake and spheroidal hammer scale, (for the analyses of scale from Southampton see Chapter 12). Two samples of smithing slag from the same context were selected for analysis (WP1 and WP2).

Both specimens had typical smithing slag morphology, having an agglomerated appearance, randomly shaped and coarsely vesicular, with a coarse grained fracture that contained charcoal inclusions.

The volumetric phase compositions and the calculated r-test values for each sample are given in Tables 11.2.2 (Vol II p139) and 11.2.3 (Vol II p140), together with the calculated r-values between the samples. The microstructure of WP1 contained silicate laths which, in parts, became massive, surrounded by a

glassy phase containing fine crystallites of a third phase. There was no free iron oxide present, but there were inclusions of metallic iron. Sample WP2 had a similar mineral texture, but also contained fine dendrites of iron oxide (Plate 39. Vol II p253). The low free iron oxide content of both specimens is unusual; this indicates heavy fluxing of the metal being worked. Sample WP1 was homogeneous (r-mean=6, S.D.=4). due in part to the absence of free iron oxide. Sample WP2 was more heterogeneous (r-mean=9, S.D.=7), due mostly to the variation in the glass phase percentage. The volumetric analyses of both samples was compared using r-factors. This showed the samples to be texturally different, (r-mean=11, S.D.=4.5).

The bulk analyses of both samples are given in Tables 11.2.4 (Vol II p141) and 11.2.6 (Vol II p143). and the calculated normative constituents in Tables 11.2.5 (Vol II p142) and 11.2.7 (Vol II p144). The analysis of Sample WP1 showed a low iron oxide content and the normative calculation results in an iron oxide deficiency (silica rich) by the formation of orthoclase. This accords with the optical study which showed no free iron oxide present. The basic oxides (Al, P, K, and Ca) all show considerable variation. The analyses and calculation of Sample WP2 shows an excess of iron oxide in all but one of the bulk analyses. The normative constituents are grouped into silicates, iron oxide and glass (Table 11.2.8. Vol II p145. and 11.2.9. Vol II p146) and the subsequent r-factor calculated. The results for Sample WP1 show it to be extremely heterogeneous. (r-mean=16.1, S.D.=11.7. The absence of (calculated) free iron oxide normally results in a low r-factor. In this case, the calculation of high values shows great variation in the silicate and glass percentages, and hence variation in the bulk chemical

composition. The results for Sample WP2 indicate sample homogeneity, (r-mean=7.5, S.D.=2.6). The ternary groupings from each sample were also compared using r-factor analysis (Table 11.2.10, Vol II p147). This also indicated substantial differences in chemical composition between the samples (r-mean=12.6, S.D.=8.9). The normative constituent ternary groupings are compared with the volumetric phase compositions in Tables 11.2.8 (WP1) and 11.2.9 (WP2) (Vol II p145/6). In both samples the results showed strong deviation from equilibrium conditions. The deviation was less for Sample WP1 (r-mean=11.0, S.D.=7.4), and greater for Sample WP2 (r-mean=4.5, S.D.=6.9), which contrasts with the individual set's of volumetric and ternary r-factors which showed greater sample heterogeneity in Sample WP1.

The individual phase analyses for both samples are shown in Table 11.2.11 (Vol II p148), and the normative constituents in Table 11.2.12 (Vol II p149). The WP1 silicate analysis identifies the phase as fayalite, which the normative calculation shows was deficient in iron oxide due to the formation of silica rich minerals:- enstatite, rhodonite, and ferrosilite. The calculations also show the glass phase is silica saturated due to the formation of orthoclase. The WP2 silicate phase was also fayalitic, but with excess iron oxide is present. The analyses of the oxide phase show that it was magnetite (or possibly hematite) rather than wustite; the metallic iron content was 68.4% which is below that of the hematite value of 70%. but the analysis contained 4.5% of other oxides, this would give a corrected metallic iron content of 71%, i.e. close to the magnetite value of 72%. All the analyses of the glass phase also indicate excess silica present (formation of orthoclase etc.). The analyses show very high phosphorus pentoxide percentages in

WP1 and lower values in WP2.

Wharram Percy Summary

The slag was morphologically identified as smithing slag. The analyses show three characteristics. Firstly a significant discrepancy between the observed and the calculated ternary groupings. Secondly the bulk and phase analyses show deficiencies in iron oxide, deviating from the theoretical fayalitic iron oxide content of 70%. The third characteristic is the presence of high phosphorus contents in Sample WP1 and its above average content in WP2, specifically in the silicate phase.

11.3 BROUGH OF BIRSAY, ORKNEY. (N.G.R. HY239284)

11.3.1 Introduction

The Brough of Birsay is a tidal island lying off the north-west coast of Mainland Orkney. The Brough and adjacent Mainland region was the major settlement on Orkney during the Early Norse Period. Recent excavations on the Brough[40] (Figure 15, Vol II p220) identified Pictish (Pre-Norse) and Norse buildings. There was evidence of smithing activity throughout the period of occupation. On Site IX in the Pictish Period two hearths were excavated that could be confidently described as smiths' hearths. The first example was a sub-rectangular clay-lined hearth (0.6m by 0.5m) containing slag, charcoal, and hammer scale, with a stake hole in the base of the hearth on the northern side. The second hearth (Feature 0282) was more substantial, u-shaped in form with an ash-pit at the south-east end. The clay lining of the hearth was burnt grey indicating reducing conditions and there was no evidence of slag attack of the lining itself. The hearth fill consisted of charcoal, slag, and hammer scale. The smithing activity continued into the Early Norse Period, evidenced by the presence of smithing slag and a third hearth. No smithing slag was directly associated with this hearth, which was also clay lined, but cinder was present in the fill. The hearth was oval in shape with a stake hole in the base. The hearth was assumed to be associated with the continuing smithing activity, but was not used as a forge; other interpretations were considered, e.g. a carburising pit, but no firm conclusions were reached. The three hearths were further distinguished by the absence of peat charcoal in the hearth fills which was present in all other domestic hearths. Further evidence of smaller scale smithing was present on Site VII in the

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Pre-Norse Period; slag was associated with a hearth that contained domestic debris.

Smithing slag was recovered from the Early, Mid, and Late Norse Phases. The greatest density of ironworking residues (from all periods) was recovered from Site IX during the Late Norse Phase; although domestic hearths were present, no specific ironworking hearths were identified.

Samples from Pictish (BIR1395) and Late Norse (BIR1296) contexts on Site VII were analysed. These analyses formed part of a larger programme of analysis of slag from the excavations[40].

11.3.2   Sample BIR1395

BIR1395 was a small randomly shaped slag lump, with an agglomerated texture. The volumetric phase mineral composition is shown in Table 11.3.1 (Vol II p150); the silicate occurred as broken laths and in equiaxed form. There was a low free iron oxide content in fine dendritic form, some of which was cubic (Plate 40, Vol II p254). Fine crystallites occurred in the glassy phase. The sample was relatively homogeneous, (r-mean = 8, S.D.= 5).

The bulk analyses are shown in Table 11.3.2 (Vol II p151), they show high silica and low iron iron oxide contents. The sodium oxide content was considerably higher than those observed from other sites, this probably derived from the coastal location of the site, and the availability of kelp for fuel. The normative mineral constituents showed a silica rich slag, resulting in the absence of free iron oxide and the calculation of orthoclase and albite (Table 11.3.3, Vol II p152). The r-factor analysis showed the slag to be very homogeneous, (r-

mean=2.2 S.D.=1.4, Table 11.3.4, Vol II p153). The comparison between the optical and mineral composition showed a very large discrepancy (r-mean = 22.6, S.D.= 5.9). The individual phase analyses showed the silicate to have been silica rich fayalite and the glass to have also been silica rich: fayalite, orthoclase, and albite were present. The iron oxide phase was too fine to be analysed.

The analyses showed that the sample was silica rich, and there was significant discrepancy between the observed and calculated mineral ternary groupings. This indicated significant deviation from equilibrium conditions, although the individual volumetric and bulk chemical analyses showed homogeneity between the areas analysed.

11.3.3   Sample BIR1296

Sample BIR1296 was morphologically similar to Sample BIR1395. The mineral texture was also similar: broken and whole silicate laths, with dendritic iron oxide in a glassy matrix (Plate 41, Vol II p254). The volumetric phase analyses were uniform (Table 11.3.5, Vol II p154, r-mean = 7, S.D.= 4).

The bulk chemical analyses (Table 11.3.6, Vol II p155) were analagous to those of BIR1395 (Table 11.3.2, Vol II p151), with a high silica and sodium oxide contents. The normative calculations resulted in a broadly similar mineral composition, but differing substantially in the nepheline content (mean content for BIR1395 = 2.8%, and for BIR1296 = 5.5%), and albite content (mean value for BIR1395 = 7.6%, and for BIR1296 = 0.2%). These result from the higher silica content present in BIR1395, giving the saturated sodium-aluminium silicate, albite, rather

than the lower silica content nepheline present in BIR1296. The r-factor calculations for the BIR1296 bulk analyses (Table 11.3.9, Vol II p158), were also very similar to those of BIR1395, and showed chemical homogeneity (r-mean=3.5, S.D.=3.0), and a large discrepancy between the observed and calculated ternary groupings, (r-mean = 30.3, S.D.= 5.4).

The phase analyses and subsequent normative calculations (Tables 11.3.7, Vol II p156 and 11.3.8, Vol II p157) showed the silicate phase was fayalite, but with excess iron oxide present. The glass phase was richer in silica than that of BIR1395. The iron oxide phase analyses indicated the presence of two oxide forms. The first analysis (FEOX1) was typical of other non-stoichiometric wustite analyses, containing a significant silica content, and with an elemental iron content of 74.1%. The other two analyses were distinguished by a low elemental iron content (69.5% and 70.9%), and high titanium oxide contents (1.7% and 2.9%). This indicates the dendrites were magnetite rather than wustite, the titanium oxide concentrating in the magnetite spinel structure.

11.3.4 <u>Summary</u>

The analyses of both samples were very similar. They diverge from the equilibrium conditions, the optical analyses showed a low free iron oxide content, but the normative calculations indicated a silica rich composition. The samples were rich in sodium due to the coastal location of the site. The samples were dated to two distinct phases, Pre-Norse and Late Norse, but the analyses indicated no change in smithing techniques. This is of significance as regards the question of

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whether the Norse influence resulted from invasion or a more gradual peaceful settlement. The evidence of the slag analyses accords with other archaeological evidence indicating a gradual assimilation of cultures rather than violent overthrow.

11.4   AMERSHAM MANTLES GREEN (SMITHING SLAG), BUCKINGHAMSHIRE

11.4.1   Introduction

The distribution of the slag has already been described (Section 5.4 p58 - 61), and the smelting slag discussed (Section 9.4 p95 - 100). Three samples of smithing slag were selected for analysis. Sample AM783 derived from the large deposit of smithing slag in Phase III which had been re-utilised as cobbling. Sample AM661 derived from a floor level in Phase IV. Sample AM716 derived from the Phase VI smithing activity.

11.4.2   Sample AM783

Sample AM783 was a typical smithing slag lump, having an agglomerated morphology, coarse fracture, and very vesicular in parts.

Two mineral textures were observed, firstly approximately equal quantities of free iron oxide dendrites and euhedral/massive silicate in a glassy matrix, (Plate 42, Vol II p255); analyses 1 and 2 in the volumetric analyses, Table 11.4.1. Vol II p159). Secondly iron oxide dendrites (90%) in a glassy matrix. The overall mineral composition can be regarded as iron oxide rich. The r-factor analysis reflects the two distinct mineral textures; volumetric analyses 1 and 2 (silicate/iron oxide/glass) were similar, r-factor=10. The remaining analyses are the same (FEOX=90%), hence r-factor=0. The comparison between the two mineral textures results in a high mean r-factor value and standard deviation (r-mean=30 S.D.=24).

The areas selected for chemical bulk analyses (Table 11.4.2, Vol II p160), were predominantly the areas of silicate/iron

oxide/glass. Analysis 4 totalled only 69.6% indicating the presence of hydrated iron oxides due to corrosion. The analyses were rich in iron oxide (mean=64.0%), and low in manganese oxide (mean=0.1%). The alkali oxides varied slightly between the analyses. The phosphorus pentoxide percentage was low. Bulk Analysis 5 had a relatively high percentage of titania present, indicating the presence of magnetite.

The silicate analyses were analogous (Table 11.4.3, Vol II p161) and showed them to have been fayalite with small percentages of magnesia and lime present. The glass phases differed, Glass 1 was typically rich in the alkali oxides; Glass 2 was similar to Glass 1 in alumina and silica contents, but was rich in soda, high in titania, and low in phosphorus pentoxide, potassium oxide, and lime; the difference being made up of iron oxide, the mineral composition of the glass is difficult to determine since conversion of the iron oxide to hematite does not cause the total to approach 100%. A similar difficulty is encountered in the FEOX 2 analysis, which is rich in alumina, silica and titania. FEOX 1 contained 71.4% elemental iron and was therefore magnetite.

A spheroidal inclusion was also analysed (Table 11.4.3, Vol II p161, 'Incl') although the total exceeded 105% (limit of acceptable analyses) it was clearly a silica grain, probably the sand used in the fluxing of the metal during smithing. It was unexpected to find unaltered silica grains in a slag containing a very high excess iron oxide content.

The normative calculations of the bulk analyses (Table 11.4.4, Vol II p162) reflect the iron oxide rich composition observed in the optical study, and the variation in composition.

particularly in the amount of fayalite calculated. The calcium silicate (calculated in Analyses 1, 3, and 4) was ascribed to the glass phase in the ternary groupings (Table 11.4.6, Vol II p164). Both silicates analysed were silica rich fayalite (wollastonite and enstatite calculated) (Table 11.4.5, Vol II p163). The normative results of the glass phase reflect the differences in chemical composition, but both were silica rich (orthoclase calculated in Glass1, and ferrosilite, albite, and orthoclase in Glass2). The FEOX2 analysis was calculated to contain fayalite (35.3%), hercynite (3.0%), and ulvite (2.0%).

The r-factor analysis of the normative ternary groupings (Table 11.4.6, Vol II p164) resulted in an equivalent r-mean factor (24.8, S.D.=17.2) to the volumetric analyses (r-mean=30, S.D.=24), indicating heterogeneity of the specimen. The comparison between the volumetric analyses and ternary groupings gave a very high mean r-factor value (r-mean=47.4, S.D.=20.7), showing strong deviation from equilibrium conditions.

11.4.3 Sample AM661

Sample AM661 was a typical smithing slag lump. The mineral texture was silicate laths tending to massive form with globular iron oxide dendrites in a glassy matrix. The volumetric analysis (Table 11.4.7 Vol II p165) showed variation in the percentage of the phases present, and this was reflected in the r-factor analyses, (r-mean=20, S.D.=10). This showed the sample to be heterogeneous.

The bulk analyses (Table 11.4.8, Vol II p166) were typical fayalitic slag analyses, except for a slightly low iron oxide content. The phase analyses (Table 11.4.9, Vol II p167) showed

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the silicate to be fayalite containing some magnesia and lime. The two glasses analysed differed significantly; the first was silica rich containing a high alumina content, and the potassium oxide content exceeded the lime content. The second glass phase contained approximately equal amounts of silica and iron oxide. The lime and the potassium oxide content were greater than in Glass1, and the lime exceeded the potassium. The alumina content was lower than Glass1. Both glasses contained equal amounts of phosphorus pentoxide. The Glass1 analysis did not total 100%, a feature of silica rich glassses. The iron oxide analyses contained minor percentages of alumina, silica, and titania, the latter indicative of a spinel structure, although the analyses totalled greater than 99%.

The normative mineral calculation of the bulk analyses (Table 11.4.10, Vol II p168) showed Analyses 2-5 to be iron oxide rich. Analysis 1 was slightly silica deficient, since gehlenite was calculated as well as anorthite. The normative calculation showed the silicate phase to be silica rich fayalite (wollastonite and enstatite calculated). The Glass1 analyses contained excess silica (quartz calculated), less than 13% of the minerals were not silica rich. The high potassium oxide content was reflected in the presence of albite. Glass2 was fayalitic and silica rich (orthoclase calculated).

The r-factor analyses (Table 11.4.11, Vol II p169) of the bulk analyses reflected the difference in Analysis 1, but the overall resulted in a low mean r-factor (4.3, S.D.=2.1), indicating homogeneous composition (comparable to tap slag analyses). The comparison between the volumetric and ternary analyses showed high heterogeneity (r-mean=33.2, S.D.=13.9) indicating strong deviation from equilibrium conditions.

11.4.4 Sample AM716

Sample AM716 had a typical morphology; in cross-section it was coarsely vesicular, and had a coarse crystalline fracture. It had a variable mineral texture, the silicate ranged from small laths to massive form (Plate 43, Vol II p255), the iron oxide occurred as fine dendrites in the glass to large rounded globular dendrites. The volumetric analysis (Table 11.4.12, Vol II p170) showed considerable variation in the quantity of the phases present; silicate 50-80%, glass 10-30%, FEOX 5-20%. This resulted in high r-factor values, r-mean=15, (S.D.=9), indicating sample heterogeneity.

The bulk analyses (Table 11.4.13, Vol II p171) showed some variation in the iron oxide and minor oxide contents. Analyses 1,2 and 5 contained relatively high phosphorus pentoxide contents.

Two silicate phases were analysed (Table 11.4.14, Vol II p172) and were typical fayalite containing some lime. The glass phases analysed were of two types, Glass1 and Glass3 were rich in alumina, silica and potassium oxide. Glass2 was distinguished by lower alumina, silica, and potassium oxide, but was rich in phosphorus pentoxide, lime, and iron oxide. The iron oxide analysis contained silica (1.2%) and 0.6% titania, it totalled 99.8%, and was therefore wustite rather than magnetite.

The normative mineral determination of the bulk analyses (Table 11.4.15, Vol II p173) showed them to be silica rich (orthoclase calculated in all analyses, and with some albite in Analyses 4 and 5). The silicate phase (Table 11.4.16, Vol II p174) was silica rich fayalite (wollastonite present due to the lime content). The normative mineral composition of the glass

analyses reflected the chemical differences; Glasses 1 and 3 were principally kalsilite/orthoclase, due to the high potassium oxide contents. Glass2 had a more varied mineral composition, apatite, anorthite, fayalite, and orthoclase calculated. All the glasses were silica rich.

The ternary groupings of the bulk analyses (Table 11.4.17, Vol II p175) and r-factor determination indicated an homogeneous specimen, (r-mean=8.8, S.D.=6.0), Analysis 4 gave the highest r-factor values. The ternary groupings differed from the volumetric analyses in the absence of free iron oxide. the analyses being silica rich. This generated a relatively high mean r-factor, (r-mean=14.6 S.D.=6.1), indicating a significant deviation from equilibrium conditions.

11.4.5 Summary of Samples AM783, AM661, AND AM716

The three samples all showed typical smithing slag morphology, an agglomerated appearance, coarse fracture, and contained vesicles throughout or in parts. The mineral textures were also similar; the silicate occurred in forms ranging from lath to massive, and the iron oxide from skeletal to globular dendrites, in a glassy matrix.

The volumetric analyses varied within specimens and between samples. It was most apparent between AM783 (upto 90% iron oxide) and AM716 (upto 80% silicate). The r-mean values were all high, indicating sample heterogeneity.

Sample	r-mean	S.D.
AM783	30	24
AM661	20	10
AM716	15	9

The bulk analyses also varied within, and between specimens. but were typical fayalitic slag analyses. The Amersham smithing slags were not characterised by any particular oxide content. They were all very low in manganese oxide, which is typical of smithing slags in general.

The phase analyses confirmed the silicate as fayalite; AM783 and AM661 contained some magnesia and lime, and AM716 lime only. The glass phases all varied greatly in composition and no oxide or oxide group was consistent in all the analyses. The iron oxide phases all contained about 1% silica, and the dendrites in AM661 and AM716 contained >0.5% titania.

The normative mineral composition of the bulk analyses showed Samples AM783 and AM661 to contain excess iron oxide, (except AM661, Analysis 1), and AM716 to be silica rich (orthoclase calculated). The normative calculation applied to the silicate phase confirmed the identification as fayalite, all were silica rich, wollastonite being calculated in preference to calcium silicate; enstatite (silica rich forsterite) was calculated in Samples AM783 and AM661. The glass phases were also silica rich, (orthoclase calculated in all analyses, and albite in one analyses in each sample).

The r-factor analyses of the ternary groupings showed great variation; Sample AM783 was very heterogeneous, the high mean r-factor (24.8, S.D.=17.2) being caused by Analysis 4. Sample AM716 had a median r-mean value (8.8, S.D.=6.0), and AM661 a low

value (4.3, S.D.=2.1) comparable with tap slag.

The comparison between the volumetric analyses and the ternary groupings all gave high r-mean values. This indicates deviation from equilibrium conditions for all specimens.

VOLUMETRIC/TERNARY MEAN 'r-factors'

Sample	r-mean	S.D.
AM783	47.4	20.7
AM661	33.2	13.9
AM716	14.6	6.1

11.5   HEYBRIDGE, ESSEX. (N.G.R. TL85020823)

11.5.1 Introduction

Excavations in Heybridge revealed Roman and Anglo-Saxon deposits[97]. The former included a probable pottery kiln, associated with which was a large deposit of smithing slag, (6.695 kg, 44% of the total recovered from the site). Smithing slag was also recovered from the later Saxon layers, but it was not possible to ascertain (on archaeological grounds) whether it was residual slag from the Roman smithing activity, or represented a later smithing operation. Two samples were analysed from the Roman levels (Samples HEYA8 and HEY119), and one from the Saxon deposits (Sample HEYA64).

11.5.2   Sample HEYA8

Sample HEYA8 was a typical smithing slag lump, having an agglomerated morphology, coarse crystalline fracture, and was heavily vesicular.

The section displayed a varied mineral texture, the silicate occurred as laths, broken (euhedral) laths, and in massive form. The iron oxide occurred as rounded dendrites, and a glassy matrix was present, which in some areas was two phased (Plate 44, Vol II p256). The volumetric analysis is given in Table 11.5.1 (Vol II p176), and this also shows some variation. The heterogeneity is reflected in the calculated r-values. (r-mean=13, S.D.=8)

The bulk analyses (Table 11.5.2, Vol II p177) showed some variation in all the major and minor oxides present, Analysis 3 being the most deviant. The analyses were very typical of fayalitic slags, but were high in phosphorus, (mean value=1.0%,

S.D.=0.5). The manganese oxide content in Analysis 1 was slightly high (0.3%). The silicate analysis confirmed the presence of fayalite, rich in magnesia and lime. The glass phase analysis was also rich in lime, but contained no (significant) amount of potassium oxide., and could be regarded as a lime rich fayalite. The iron oxide phase contained low levels of minor elements, and the elemental iron percentage was 74.7%, indicative of wustite rather than magnetite.

The normative mineral composition (Table 11.5.3, Vol II p178) of the silicate analysis show it to be silica rich (wollastonite and enstatite calculated), and the glass phase to contain fayalite and calcium silicate with excess iron oxide.

The bulk normative constituents show considerable variation as indicated by the bulk analyses. Analyses 1, 4, and 5 calculated excess iron oxide, and Analyses 2 and 3 were silica rich, (orthoclase calculated). The r-factor analyses (Table 11.5.4, Vol II p179) gives a high mean value but with a low standard deviation (r-mean=14.3, S.D.=5.7) indicating a heterogeneous chemical composition. The comparison between the volumetric analyses and the ternary normative composition results in a very high r-mean value, (24.3, S.D.=9.6). The most significant difference is that the normative ternary groupings estimate much higher silicate content (mean=73.4%) than was observed in the volumetric study (mean=49.0%). The corresponding normative glass and free iron oxide are lower than the observed values. This indicates substantial deviation from equilibrium conditions during cooling.

11.5.3 Sample HEY119

Sample HEY119 was an incompletely formed hearth bottom, measuring less than 80mm in diameter, and 20mm deep. It had an agglomerated appearance, coarse/fine fracture, and was heavily vesicular. In the prepared section two mineral textures were apparent, and occurred in two distinct areas of the section. The interface between the areas was possibly a cooling surface. The largest area contained silicate laths and a glassy matrix with no free iron oxide present except in a few areas when it occurred as very fine dendrites (Plate 45, Vol II p256). In the second area the silicate became euhedral and/or massive and large rounded iron oxide dendrites and veins of glass were present. The volumetric analysis is shown in Table 11.5.5 (Vol II p180). The first area was distinguished by the absence of, or a low content of, free iron oxide, and was richer in the glass phase than the second area. The r-factor analysis gave a similar r-mean value as for HEYA8, (r-mean=13, S.D.=6). The highest r-factors confirming the difference between the two areas, i.e. Analyses 1-3 and Analyses 4 and 5.

The bulk analyses (Table 11.5.6, Vol II p181) were characterised by high silica, phosphorus pentoxide, and lime percentages, conversely the iron oxide content was low. The manganese oxide content was variable, but had a high mean value (0.3%, S.D.=0.2). Bulk Analyses 5 differed significantly from the other four, being rich in silica and alumina and low in iron oxide. The silicate contained magnesia and lime, and a slightly enhanced manganese oxide content (0.5%). The glass phase analyses were similar to that of HEYA8, rich in lime, but differed in having significant alumina and phosphorus pentoxide contents. No free iron oxide was analysed.

The normative mineral calculation of the silicate analysis (Table 11.5.7, Vol II p182) showed it to be fayalitic with some forsterite present and containing excess iron oxide, (wustite calculated). Both calculations on the glassy phase analyses showed them to be silica rich (e.g. orthoclase and wollastonite calculated).

All the bulk analyses were silica rich, (orthoclase and wollastonite calculated). The calculation for Analysis 5 contained excess silica, quartz being calculated, and differed from Analyses 1-4. The r-factor analyses (Table 11.5.8, Vol II p183) resulted in high mean and standard deviation values (r-mean=11.8, S.D.=11.5). These result from Analysis 5; if this is excluded the r-mean value is reduced (r-mean=3.0, S.D.=1.8).

The comparison between the volumetric and the bulk analyses generated a mean value similar to the volumetric and the bulk r-mean values (r-mean=13.1, S.D.=9.8). The high mean value derives from the atypical bulk analyses (Bulk Analysis 5), and the two volumetric analyses from the second area (Volumetric Analyses 4 and 5).

The results from the r-tests comfirm the sample's heterogeneity and the deviation from equilibrium conditions during cooling.

11.5.4 Sample HEY64

Sample HEY64 derived from the Anglo-Saxon deposits. It was a smithing slag lump with a typical morphology; agglomerated appearance, coarse fracture and heavily vesicular.

The mineral texture was vesicular, the free iron oxide occurred mostly as fine dendrites, the silicate as laths, euhedral laths, and in massive form. A glassy matrix was present (Plate 46, Vol II p257). The volumetric analyses are shown in Table 11.5.9 (Vol II p184), and indicate a homogenous specimen, despite variations in texture, (r-mean=5, S.D.=4).

The bulk analyses (Table 11.5.10, Vol II p185) were similar to those obtained for Sample HEYA8 (Table 11.5.2, Vol II p177), except they were lower in iron oxide (mean value=53.0%), and higher in lime content, (mean value=7.3%). The silicate analysis was also similar to that obtained in Sample HEYA8, significant magnesia and lime contents being present. The glass phase analysis was rich in silica and iron oxide, and contained significant percentages of alumina, phosphorus pentoxide, potassium oxide, and lime. The iron oxide contained low levels of minor elements, notably titania (0.5%). The elemental iron percentage (73.3) indicates the presence of magnetite.

The normative mineral constituents of the silicate phase (Table 11.5.11, Vol II p186) was predominantly fayalite (88.5%), but was silica rich, (wollastonite calculated), forsterite, calcium silicate, and wollastonite was also calculated to absorb the lime and magnesia contents in the analysis. The constituents of the glass phase was also silica rich, the predominant minerals being fayalite and orthoclase.

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The normative constituents of Bulk Analyses 1-4 were silica rich, (orthoclase calculated), and Analysis 5 calculated excess wustite. The analyses were all predominantly fayalitic with significant preportions of apatite, kalsilite, calcium silicate, and orthoclase or wustite. To determine the ternary groupings (Table 11.5.12, Vol II p187) the calcium silicate was apportioned to the glass and silicate phases in the ratio 2.4:1, (glass:silicate) determined from the ratio of the calcium silicate determined in the analysed phases ((4.7:2.3, glass:silicate) The resulting r-factor calculations gave a low mean value (r-mean=5.9, S.D.=2.65), indicative of a homogenous composition. The comparison between the volumetric and bulk analyses resulted in a high mean r-value (r-mean=14.9, S.D.=3.6). This shows deviation from equilibrium conditions during cooling.

11.5.5 Summary of the Heybridge Slags

The morphology and mineral texture of the Heybridge slags were typical of smithing slags. The bulk analyses showed variation within specimens and between specimens. The most significant aspect of the bulk analyses was the high mean manganese oxide contents (overall mean of the three specimens=0.25%, S.D.=0.1). There was no apparent significant difference between the two Roman specimens and the Anglo-Saxon sample.

11.6 WETWANG SLACK, NORTH HUMBERSIDE (N.G.R. SE946607)

11.6.1 Introduction

Excavations have been carried out in advance of gravel extraction in Garton/Wetwang Slack[49]; the name change is due to the crossing of the Garton/Wetwang Parish Boundary. The excavations have concentrated in the slack (valley) bottom and have uncovered extensive Iron Age and Romano-British complexes, notably cemeteries, including chariot burials. A sampling excavation was also undertaken on an Iron Age/Romano-British farmstead on the wold top. A small quantity of intrusive smithing slag was found in the excavations in the slack, but a large deposit (4.3 kg) of smithing slag was recovered from a single section of the boundary ditch. Close to this deposit, inside the boundary ditch, was a four-post structure, enclosing a burnt area, that can be tentatively proposed as a smithy. A sample of the slag from the ditch was selected for analysis.

11.6.2 Analysis

Two samples were selected for analysis: WWS501/1 was a small hearth bottom with dimensions of: weight 90gms; major diameter 70mm; minor diameter 50mm; depth 25mm. The second sample (WWS501/2) was a typical smithing slag lump weighing less than 60gms, with a typical smithing slag morphology.

Sample WWS501/1 had a varying silicate texture, lath, euhedral/broken lath and massive form. The free iron oxide occurred as rounded globular dendrites and a glassy matrix was present. The section was vesicular and fine metallic inclusions occurred at the rims of some of the larger vesicles. Some of the iron oxide became massive due to subsequent

oxidation/hydroxation. The iron oxide dendrites contained small vesicles/cracks, and there were a few large silica inclusions. The volumetric analysis (Table 11.6.1, Vol II p188) indicated a heterogeneous mineral texture, (r-mean=14, S.D.=6.5).

Sample WWS501/2 had a similar mineral texture to WWS501/1, but contained a second phase that may have been segregation within the primary silicate phase, a fourth phase e.g. hercynite or a second glassy phase (Plate 47, Vol II p257). The volumetric analysis (Table 11.6.2, Vol II p189) shows greater variation, notably in the free iron oxide content. The r-factor analysis shows greater heterogeneity (r-mean=19, S.D.=10) than Sample WWS501/1.

The bulk and phase analyses for Sample WWS501/1 is shown in Table 11.6.3 (Vol II p190). The bulk analyses were low in silica (mean=20.0%), contained no phosphorus (except Analysis 4). Analyses 1, 2, and 3 contained high sulphur contents. The alumina contents in all the analyses were high (mean=6.5%). Analyses 4 and 5 had low totals, and were low in silica, but did contain high titania contents. indicative of the presence of magnetite or hematite.

The silicate phase analysis was typical of fayalite containing a small percentage of lime. The glass phase was typically rich in the alkali oxides. and was low in phosphorus pentoxide, corresponding to the low values recorded in the bulk analyses. The iron oxide analysis contained minor oxides, was low in titania. and the elemental iron percentage was 73.5%. indicative of iron deficient wustite rather than magnetite.

The normative mineral composition of the silicate phase

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(Table 11.6.4, Vol II p191) was fayalite with minor percentages of other minerals. It was very close to being 'normative' in composition there being no silica rich phases or excess iron oxide, although the calculation of gehlenite is indicative of slight silica deficiency. The glass phase was silica rich (orthoclase calculated), the major components being kalsilite, anorthite, calcium silicate, fayalite and orthoclase.

The normative mineral composition of the bulk analyses all calculated excess iron oxide, which accords with the volumetric study. The major calculated constituent was fayalite, and anorthite the major glass phase in Bulk Analyses 1-3, and hercynite in Analyses 4 and 5. The ternary grouping and r-factor calculations are shown in Table 11.6.5 (Vol II p192), these confirm the differences noted for Bulk Analyses 4 and 5. The r-factor calculation resulted in a low r-mean value, (5.85), and standard deviation (2.9), indicating a homogeneous chemical composition. The comparison between the volumetric and the ternary phase percentages resulted in a high mean value (r-mean=11.2, S.D.=6.4), which indicates a strong deviation from equilibrium conditions.

The analysis has shown that the smithing slag from Wetwang Slack had a very typical mineral and chemical composition, although it did have a high alumina content. The slag was composed mostly of silica and iron oxide, giving a mineral texture of fayalite and free iron oxide.

11.7 SMITHING SLAG SUMMARY

The smithing slags have two forms: firstly the diagnostic hearth bottom, and secondly the randomly shaped smithing slag. The morphology varies; commonly smithing slag has an agglomerated appearance, but may have flowed surfaces. The fracture is normally coarse and vesicular. The cross-section is vesicular and often contains non-slag inclusions, normally silica.

The mineral texture of smithing slags (i.e. hearth bottoms and smithing slags), is very varied. The results from all specimens are summarised in Table 11.7.1 (Vol II p193). The silicate ranges through lath, euhedral (broken) lath, and massive. The massive form was the commonest, 13 of the 16 samples included some massive silicate. although often in association with euhedral laths. The iron oxide was normally in the form of rounded globular dendrites; in some samples free iron oxide was absent or in very low concentrations, e.g. Wharram Percy WP1 and WP2. The overall mean volumetric percentages and standard deviations were:

	Mean	S.D.
Silicate	53%	16%
Glass	23%	12%
Iron Oxide (FEOX)	24%	20%

The high standard deviations indicate the strong variation observed in the mineral texture of smithing slags.

The bulk analyses are summarised in Table 11.7.2 (Vol II p194 - 198). They are very variable but several points can be made. The most significant attribute of the analyses is the low manganese oxide contents, mean <0.1%. The Birsay analyses are distinguished by their high soda and alumina contents. The

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Wetwang Slack slag was characterised by high alumina and sulphur percentages, and low potassium oxide contents. The Wharram Percy slags differ from the mean values in their high phosphorus, potassium, lime and chromium oxide contents. The Beckford slags show considerable variation between each sample, e.g. the alumina content was high in samples 2 and 4, and low in sample 3. The Amersham samples analyses were generally within one standard deviation of the mean oxide values; the exceptions were sample 716, (high phosphorus and lime contents); sample 661 was also rich in lime. The Heybridge slags showed some variation between samples but there were some general trends, e.g. all the samples had a significant manganese oxide content (but less than 0.3%), and were high in phosphorus pentoxide and potassium oxide. The cobalt and nickel oxide contents divide the smithing slags into two groups, those containing these oxides (Birsay, Amersham, and Wetwang Slack) and those without (Beckford, and Wharram Percy). The Heybridge slags show mixed results, Sample HeyA64 contained these oxides, but they were absent in Hey119, and HeyA8 contained nickel oxide only.

The phase analyses show that the majority of the silicate (fayalite) contains greater than 1.5% magnesia, and 1.5% lime, although the bulk analyses are low in these oxides. The glass phases analysed showed very mixed compositions, for example the lime content is normally greater than the potassium oxide content, but in several examples, e.g. Beckford Sample Bek5 (Table 11.1.24, Vol II p134), and Wharram Percy Sample WP2 (Table 11.2.11, Vol II p148), this relationship is reversed. The iron oxide phase also shows great variation in the concentration of the minor oxides, alumina, silica, titania. Hence the exact oxide state is difficult to determine, but it is reasonable to conclude

that smithing slags contain both magnetite and wustite as free iron oxide.

The volumetric, ternary and volumetric/ternary r-mean values are given in Table 11.7.3 (Vol II p199), and plotted on Figure 16 (Vol II pp221-224). The overall mean values (Figure 19, Vol II p227) show a low volumetric and ternary values and a high volumetric/ternary value. This indicates that the samples have homogeneous mineral textures and chemical compositions, but that there was considerable deviation from equilibrium conditions during cooling. The deviation from equilibrium conditions is further confirmed by the presence of silica inclusions. The overall mean values can be summarised as:-

Ternary Mean < Volumetric Ternary <<< Volumetric/Ternary Mean

The wide variation observed in the volumetric, bulk and phase analyses is also present in the r-mean values. Thus smithing slags from Wetwang Slack (WWS501/1), Beckford (BEK1 and BEK4) and Heybridge (HEY119) have a lower volumetric/ternary r-mean value than volumetric value. The Amersham sample AM783 had very high r-mean values.

The attributes of smithing slags can, therefore, be summarised as. their morphology, (the plano-convex form of the hearth bottoms, an agglomerated texture), the mineral texture, (massive silicate and rounded iron oxide dendrites), the presence of unaltered silica inclusions, the absence/low content of manganese oxide, low ternary and volumetric mean r-values and high mean volumetric/ternary values. These attributes may not relate exclusively to smithing slags.

11.8   Formation of Smithing Slags

In Section 10.3 (p142-145) a model was proposed for the formation of smithing slags.   This can now be re-examined in the light of the slag analyses.

It was proposed that smithing slag was formed from three components. Firstly, the iron oxide from the iron being worked, secondly, the sand applied to inhibit oxidation, and thirdly, and as a minor contribution, the slag component of the iron being worked.   It was further suggested that the slag formation was dependent on four conditions. Firstly, the composition was oxide (scale) formed during heating.   Secondly, the quantity and type of flux used.   Thirdly, the type of smithing activity being carried out, and fourthly the hearth conditions.

The analyses would support the three-component model, particularly the minor part played by the slag inclusions present in the metal. The four conditions are clearly inter-related, but it was apparent that some slags were iron oxide rich, and contained high percentages of free iron oxide, e.g. Amersham Sample AM783, while others contained little or no free iron oxide, (Wharram Percy Sample WP1). The amount of free iron oxide present in the slag being dependent on the quantity of scale formed, the amount of flux used and the hearth conditions.   The latter may have been dependent on the type of operation being carried out.   The type of flux used clearly influenced the composition of the Birsay slag which was high in soda.

It is therefore reasonable to accept the three-component model and the four conditions as a working hypothesis of smithing slag formation.

CHAPTER 12

ANALYSIS OF HAMMER SCALE

12.1 Introduction

Two forms of hammer scale were outlined in Section 10.4 (p145-146). They have not been discussed in detail before, and therefore samples of flake and spheroidal scale from Wharram Percy were examined and some from the Anglo-Saxon smithy site at Hamwih (Southampton) were analysed. The latter material was recovered from the wet sieving of soil samples, during recovery of environmental samples.

12.2 Flake Hammer Scale

The flake hammer scale occurred as flat flakes less than 10mm across, and less than 0.5mm in thickness. The majority of fragments were magnetic. Low powered microscopical study showed that the majority of flat surfaces were smooth with a metallic lustre. The surface of a sample from Wharram Percy was cleaned in dilute hydrochloric acid. This showed a network structure of grains fused together (Plate 48, Vol II p258). The prepared surface confirmed the structure; iron oxide grains fused by a network of glass or silicate phase, evidenced by the silica X-Ray distribution map (Plate 49a and 49b, Vol II p258). The Hamwih flake hammer scale was mounted and prepared in the usual manner. The specimens were vesicular (Plate 50, Vol II p259). The analysis of five samples are shown in Tables 12.2.1-4 (Vol II pp200-203). Due to the vesicularity of the samples, area bulk analyses were difficult to obtain. The high free iron oxide content described above is reflected in the analyses.

The first bulk analysis was similar to that of a silicate

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slag. The second bulk analysis of Sample HS3 (Table 12.2.1, Vol II p200) was more typical of a scale analysis, being dominated by the iron oxide content. Both bulk analyses contained high phosphorus pentoxide contents, which were not detected in the subsequent phase analyses and, therefore, probably derived from the presence of a small quantity of phosphorus rich glass. The phase fusing the free iron oxide had a fayalitic composition rather than a glassy one. The iron oxide contained a low percentage of silica and alumina. The normative composition of the bulk analyses (Table 12.2.2, Vol II p201), showed them both to be rich in fayalite, which would not seem to accord with the optical study. The silicate phase contained less than 5% of other minerals indicating the use of a pure silica sand as a flux.

The bulk analysis of Sample HS5 (Table 12.2.1, Vol II p200) was similar to that of HS3, but contained less silica, and no phosphorus pentoxide, but magnesia was present, as well as a small quantity of manganese oxide. The silicate had a more varied composition, magnesia and lime being present. The iron oxide phase contained less than 1% of silica or alumina. The normative composition (Table 12.2.2, Vol II p201) of the bulk analysis contained over 60% wustite, and the silicate contained approximately 5% of other minerals.

Sample HS6 was more vesicular than the other samples and had a cindery appearance. The microstructure was massive silicate with small quantities of free iron oxide and glass present. Consequently the bulk analysis (Table 12.2.3, Vol II p202) was similar to that of a smithing or smelting slag. The silicate of the rim (SIL1), had a fayalitic composition but

contained 1.7% alumina. A silica particle in the fragmented 'cindery' region was analysed (SIL2) and was a pure silica sand inclusion. The silicate in the same area was also analysed (SIL3), it was rich in silica and contained a high alumina content and 1.2% potassium oxide, this analysis is closer to a silicate slag glass phase analysis. The normative mineral constituents (Table 12.2.4, Vol II p203) show the bulk analysis to be predominantly fayalitic with a small amount of excess wustite present. The rim silicate (SIL1) was also slightly wustite rich (0.2% calculated) and contained less than 6% of other minerals. The silicate in the 'cindery' region was silica rich, ferrosilite being calculated. Sample HS6 was not typical of the other scale samples analysed, being silica rich, containing very low quantities of free iron oxide.

Sample HS7 had a typical microstructure of globular iron oxide grains fused by a silicate or glass phase. Two of the bulk analyses obtained totalled less than 100%, indicative of the presence of some magnetite (Table 12.2.3, Vol II p202). The samples contained low alumina contents, and no significant quantities of lime or potassium oxide. The silicate phase was not of fayalitic type, being low in silica, but with some alumina present. The iron oxide phase analysed contained 1% silica, but no significant alumina content, and was wustite rather than magnetite. The normative mineral composition calculated that Bulk1 contained over 50% wustite, and Bulk2 and Bulk3 over 50% fayalite (Table 12.2.4, Vol II p203). The silicate phase was wustite rich (32.8% calculated), and contained less than 4% of minerals other than fayalite and wustite.

The analysis has shown that flake hammer scale was normally formed from iron oxide fused by silicate. The silicate

phase was usually slightly iron oxide rich, wustite being calculated. Sample HS6 was untypical, being silica rich, with silica particles present in one area.

12.3 Spheroidal Hammer Scale

Spheroidal hammer scale occurs as small balls of slag normally less than 5mm in diameter. It is blue/grey to black in colour, often with a metallic lustre, and usually strongly magnetic. The balls may not be perfectly rounded and have either protrusions and tails or flattened surfaces present. Three samples were analysed; they were mounted and ground down to obtain approximately a half section.

Sample HS1 was not perfectly spheroidal, but was 'banana shaped' in cross-section. The section showed it to be formed by a skin of slag, 1mm thick, enclosing a void (Plate 51 Vol II p259). The microstructure was the same as the flake hammer scale, being globular iron oxide grains fused by a silicate or glass phase [cf. flake hammer scale and a spheroidal example from Wharram Percy (Plates 52a and 52b, Vol II p260)]. It was not suitable for bulk area analysis, and therefore spot analyses were made at low magnification. The analyses (Table 12.3.1, Vol II p204) show that the scale is very clean, comprising iron oxide and silica, with less than 2% other oxides present. The normative mineral constituents are, therefore, predominantly fayalite and wustite (total 98.1%), (Table 12.3.2, Vol II p205).

Sample HS2 was circular in cross-section and was a slag skin enveloping a void (Plate 53, Vol II p260). The microstructure of the rim was globular iron oxide grains fused by silicate or glass. Two bulk analyses were obtained (RIM1 and RIM2 Table

12.3.1, Vol II p204) and were predominantly iron oxide with some silica present, and less than 25% of other oxides. The oxide grain boundary phase (SIL) was not of fayalitic type, being rich in iron oxide. The iron oxide grain contained less than 2.5% of other oxides. The normative mineral constituents (Table 12.3.2, Vol II p205) of the bulk analyses were wustite and fayalite. The grain boundary phase had principal normative constituents of fayalite and wustite.

Sample HS8 was a small spheroid and was solid throughout. It had the typical microstructure, rounded grains of iron oxide fused by silica or glass. The bulk analysis (Table 12.3.1, Vol II p204) was similar to that of HS2, except it had a higher alumina percentage. The grain boundary phase had a composition approaching that of fayalite, but was richer in silica and contained significant levels of alumina, potassium oxide and lime. The iron oxide phase contained 2.4% of other oxides and did not total 100%, but did not have a magnetite composition, and was, therefore, low elemental iron wustite. The normative calculation of the bulk analyses (Table 12.3.2, Vol II p205) was dominated by wustite and fayalite. The boundary phase was silica rich, orthoclase, ferrosilite etc. being calculated.

Spheroidal hammer scale is normally a hollow sphere of slag. It has a similar microstructure to the flake hammer scale, grains of iron oxide with a grain boundary silicate phase. The composition of the silicate is different to that of the flake silicate, having a lower silica percentage in sample HS1 and HS2 and being silica rich in HS8.

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12.4 Hammer Scale Summary

The two forms of hammer scale have a similar microstructure and chemical composition. They are formed by the fusion of particles or grains of iron oxide by a silicate grain boundary phase. The composition accords with the theory of simple fusion of flux (sand) and iron oxide scale.

CHAPTER 13

DISCUSSION. DISTINGUISHING SMELTING SLAGS FROM SMITHING SLAGS

13.1 Introduction

The purpose of the present work was to describe the residues, in particular slags, derived from the smelting and smithing processes, and to establish criteria by which smelting slags may be distinguished from smithing slags (pl8). It is aimed to discuss the different analytical methods in turn, and use this sequence to arrive at slag identification.

Iron has been utilised, to varying degrees, by different societies since its introduction into Britain c.700 B.C.. The smelting of iron was not restricted to specific geological areas, because of the widespread occurrence of iron ores. Despite this it is believed that most slags arise from the smithing operation, i.e. a single unit of smelted iron could be recycled through the smithing hearth many times. Thus, it is assumed that the majority of slag deposits are derived from the smithing process. It is, therefore, the purpose of the analysis sequence to identify the smelting slags from the smithing slags

13.2 The Archaeological Evidence

It has been shown that difficulties arise in correctly identifying and interpreting archaeological structures and features associated with the ironworking process. In particular a conflict between archaeology, per se, which is a below ground discipline, and ironworking which utilised above ground structures, ie. furnaces and waist-high smithing hearths. It is more likely to find slag deposited in features/contexts that were contemporary with, rather than associated with, the ironworking

process. Therefore, it places heavy reliance upon interpretation of the ironworking residues.

The quantity of slag is indicative of the process; large slag heaps or concentrated deposits are expected to derive from the smelting process. It must be remembered that associated with smelting must be some primary smithing and probably some secondary smithing activity, e.g. Amersham Mantles Green. The excavations at Six-Dials, Southampton, uncovered part of Anglo-Saxon Southampton (Hamwih) and included large quantities of slag (500 kg), probably it was all derived from two smithies. Therefore, large spatially and temporally concentrated quantities (100+? kg) of slag are not necessarily indicative of the smelting process.

The recovery of hammer scale from archaeological deposits is evidence of ironworking activity having been practised in the close vicinity, since it was not subject to re-deposition, as other residues were, e.g. use as hard core. The presence of hammer scale is normally interpreted as indicative of smithing, although very recent iron smelting experiments have generated morphologically similar material[98].

13.3 Slag Morphology

The morphological examination of the residues is the basis of all slag classification, since it is impossible to do detailed analyses of large quantities of slag. The morphologically distinct smelting slags are: tap slags, furnace slag or furnace bottoms, slag blocks or schlackenklotz, the Dense Iron Silicate Slags. Smelting slags that are not easily distinguished from smithing slags are the raked slags and slag cakes. The latter

may be distinguished if the slag feeder is still attached, but normally this is liable to have been broken off.

13.4 Mineral Texture

Three phases are encountered in slag mineralogy; silicate, free iron oxide and a 'glassy' phase. The silicate occurs in three forms, lath, euhedral (or broken lath), and massive form. The iron oxide occurs in dendrite form, but varies in degree of fineness or coarseness, i.e. true fine dendritic form to large rounded globular dendrites. The glassy phase forms the slag matrix. The texture of the slag is, therefore, dependent on the form of the silicate and iron oxide phases. The shape of the iron oxide relates to the quantity of free iron oxide present; the lower the percentage, the more dendritic the mineral form. The factors influencing the form of the silicate have not been determined. The gradation from lath to massive is related to the rate of cooling of the slag, i.e. laths are indicative of fast cooling. Donaldson[99,100] investigated the morphological changes of olivines subjected to different cooling rates and varying degrees of undercooling. The experiments produced lath structures but no massive olivine, and showed that with slow cooling rates (0.5-7°C/hr) polyhedral and euhedral crystals were produced. At faster rates the crystals became elongated and formed laths (40-300 $^{\circ}$C/hr). The effect of super-cooling was examined by isothermal crystallisation and this showed that the greater the degree of super-cooling the more elongated the crystals became. Slags differ significantly from the olivines Donaldson studied by having abundant nuclei to induce crystallisation. Therefore, super-cooling should not play a role in silicate formation in slags.

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Evidence from the slags shows that the tap slags have lath structures, sometimes euhedral (the exception is the Levisham sample [p.92], which had massive silicate, but was also different in other ways). This would accord with rapid cooling and, perhaps, some degree of super-cooling. The raked slags from Millbrook show a range of mineral textures, but were generally either lath and/or euhedral, although there was some massive silicate present in three of the five samples. The slag block had massive silicate, which was expected from a large mass of slag that would cool slowly. The dense iron silicate also had massive silicate which indicated a very slow cool, hence the slag might be a form of the slag block type. The majority of the smithing slags had mixed mineral textures; these ranged from lath to massive, indicating variations of cooling rate within the samples or differences in composition that might affect crystallisation. There is, therefore, no diagnostic form of mineral texture that can be associated with either smelting or smithing slags and, in particular, as an aid to distinguishing the raked slags from the smithing slags. This is clearly demonstrated by the optical and S.E.M. micrographs (Plates 16-47, Vol II pp240-257). The tap slags, and slag blocks (previously identified on morphological criteria), had the textures expected.

13.5 Volumetric Phase Analysis

To aid this discussion a summary of the mean and standard deviations of all the volumetric analyses, (excluding Farthingstone) are given together in Table 13.1 (Vol I p198). These show that the smelting slags have a slightly greater silicate phase percentage and lower free iron oxide phase percentage than the smithing slags. The high standard deviations

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for all values preclude the use of volumetric phase percentages as a method of discriminating between smelting and smithing slags. For example, the smithing slag sample from Wharram Percy (WP1) contained no free iron oxide, and the smelting slags from Millbrook contained up to 35% free iron oxide. The smithing slags have a wider range of phase percentages as indicated by the standard deviations. This makes differentiation of the slag types more difficult, and all the slag types overlap.

TABLE 13.1 VOLUMETRIC PHASE PERCENTAGES, MEAN VALUES AND STANDARD DEVIATIONS

	SILICATE PHASE		GLASS PHASE		IRON OXIDE PHASE	
	MEAN	S.D	MEAN	S.D.	MEAN	S.D.
SMELTING SLAGS						
Tap Slags	61	9	27	11	12	13
Raked Slags	61	13	24	8	15	9
Slag Blocks	65.5	10	20.5	6	14	5
OVERALL VALUES	61	11	25	10	14	10
SMITHING SLAGS	53	16	23	12	24	20

The r-mean values (as a measure of homogeneity and heterogeneity) are summarised in Table 13.2 (Vol I p199), these show that the overall r-mean value for the smelting slags is slightly lower than that obtained for the overall smithing r-mean value, but they are within one standard deviation of each other. The r-mean values for the different types of smelting slags show that the tap slags and slag blocks are more homogeneous than the smithing slags. It also shows the similarity between the raked slags and the smithing slags (observed in the morphological study).

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TABLE 13.2 VOLUMETRIC r-mean VALUES

	r-mean	S.D.
SMELTING SLAGS		
Tap Slags	8	6
Raked Slags	12	7.5
Slag Block	11	5
D.I.S.	8	5
OVERALL SMELTING VALUE	10	7
OVERALL SMITHING VALUE	12	10

The results of the optical study clearly show that this method alone cannot distinguish smelting slags from smithing slags.

13.6 Bulk Chemical Analysis

Bulk chemical analysis has been the most common method of analysis for classification and/or sourcing of material. The particular problems of bulk analysing slags have been discussed and the evidence of many of the five analyses obtained from a single specimen has shown that the composition can vary within a specimen. Hence bulk analyses obtained by other methods, e.g. powdering of the sample and X.R.F. analysis, are meaningless since they cannot be associated readily with a specific mineral texture. Therefore, the heterogeneity of the slags must be examined by multiple analysis and, it was apparent that a slag classification could not be based on a single bulk analyses. The heterogeneity of the slag analyses is confirmed by standard deviations for each sample, e.g. see Table 11.7.2 (Vol II pp194-198), and the overall smelting values and smithing values. (Table

13.4, Vol I p202).

A simplistic approach to classification can be obtained by the regression analysis of oxides or ratios of oxides. In order to select suitable oxides for plotting, an assessment of genesis of the oxides must be made, and in the smelting process the relative partitioning of the oxides between the slag and the metal must be assessed. The oxides present in smelting slags derived from three sources; ore, fuel ash and furnace lining. Those in smithing slags from flux, (usually sand), the metal, fuel ash, and hearth lining. The oxides associated with each source are listed in Table 13.3 (Vol I p201). The minor oxides, e.g. vanadium, titanium etc., were present in quantities equivalent to the minimum detectable limit of the analytical system used. The metallic oxides of possible interest that may have been present only in the ore, e.g. cobalt, would have been reduced and concentrated into the metallic iron. The table clearly shows that the potentially useful oxides (except perhaps manganese) are not derived from a single unique source, and therefore, cannot be used in simple regression analysis.

TABLE 13.3   SOURCES OF OXIDES IN THE SMELTING AND SMITHING PROCESS

+   Present

++   High Percentage

	SMELTING			SMITHING			
	Ore	Fuel Ash	Furnace Lining	Metal	Flux	Fuel Ash	Hearth Lining
Na_2O	+	+	+		+	+	+
MgO	+	+	+		+	+	+
Al_2O_3	++	+	++		+	+	++
SiO_2	++	+	++		++	+	++
P_2O_5	+	+		+		+	
S	+	+			+		
K_2O	+	+	+		+	+	+
CaO	+	+	++		+	+	++
TiO_2	+	+			+	+	
V_2O_5	+	+			+	+	
Cr_2O_6	+	+			+	+	
MnO	++*						
FeO	++	+	+	++	+	+	+
CoO	+	+			+	+	
NiO	+	+			+	+	

*   MnO may or may not be present in significant quantities in an ore.

TABLE 13.4 MEAN BULK ANALYSES (Weight Percent)

	SMELTING SLAGS		SMITHING SLAGS		OVERALL MEANS	
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
Na_2O	0.2	0.2	0.4	0.5	0.3	0.4
MgO	1.0	1.3	0.4	0.3	0.7	1.0
Al_2O_3	5.5	2.6	3.7	1.7	4.6	2.3
SiO_2	28.4	6.0	25.8	8.0	27.1	7.2
P_2O_5	1.0	0.6	0.8	0.9	0.9	0.7
S	0.1	0.1	0.1	0.1	0.1	0.1
K_2O	1.5	0.8	1.7	0.9	1.6	0.9
CaO	5.1	4.7	3.6	2.4	4.3	3.8
TiO_2	0.4	0.2	0.2	0.1	0.3	0.2
V_2O_5	0.0	0.0	0.0	0.0	0.0	0.0
Cr_2O_6	0.0	0.0	0.1	0.1	0.0	0.0
MnO	3.4	3.0	0.1	0.1	1.7	2.6
FeO	53.1	10.3	61.9	10.8	57.6	1 1.4
CoO	0.2	0.2	0.1	0.2	0.2	0.2
NiO	0.1	0.1	0.1	0.1	0.1	0.1

The .overall results (Table 13.4, above) do suggest that manganese oxide can be used to identify smelting slags. Detailed study of all the results show that manganese oxide is present in the majority of smelting slags (7 out of the 10 sites sampled). The samples from the following sites contained manganese oxide at a level less than 0.5%: Farthingstone, Park North. and Mucking. Farthingstone and Park North were classified as smelting slags on the basis of their morphology. The Mucking slag was only classified as a smelting slag on the basis of its fine grained

texture and density and some doubt must be raised about this classification. These slags provide an opportunity to investigate the possibility of distinguishing the non-manganese oxide bearing smelting slags from the smithing slags. Unfortunately, the analyses do not display any consistent difference from either the other smelting slags or the smithing slags.

The analyses of the smithing slags show that the samples from Heybridge have the highest overall mean manganese oxide value (0.2%), and sample AM661 from Amersham Mantles Green contained 0.3% manganese oxide. Therefore, the presence of manganese oxide at levels greater than the 0.5% can be used to identify a smelting slag.

Levels of less than 0.5% or the absence of manganese oxide cannot be used to confirm or refute the slag as a smithing slag or smelting slag without other data being available.

Due to the difficulties outlined above, sophisticated statistical techniques were applied to attempt to distinguish the slag types. The bulk analyses were analysed using Discriminant[101] and Clustan Analysis[102] (see Appendix 4). Discriminant Analysis was applied to distinguish between the smelting and smithing slags. This discriminated on the basis of manganese oxide, alumina, and soda (the three highest Wilks Lambda values). It therefore re-classed smelting slag bulk chemical analyses Park North number 5, Romsey sample 2 number 2, and Mucking 5 numbers 1, 2, 4, and 5 as smithing type analyses. It also reclassed smithing slag analyses Wetwang Slack numbers 4 and 5, and Heybridge 119 number 4 as smelting slags. The discriminant analysis would, therefore, appear to be reasonably

successful. Only in one case was the sample changed in type. In all other cases the majority of analyses were as originally typed and, thus the sample remained as first classified. This is further evidence of the difficulty of distinguishing between smelting and smithing slags.

Clustan Analysis was used to determine independent groupings, and ultimately to achieve two separate groups. If the Clustan Analysis was to be totally successful one group would be formed by the smelting slag analyses and the second group by the smithing slag analyses. The dendrogram (Ward's Method) is shown in Figure 17 (Vol II p225), and clearly illustrates the two major difficulties of slag analyses: firstly, the variability in the five bulk analyses for each sample. For example the analyses of sample MBRKA (Millbrook A, Clustan Numbers [C.N.'s] 45-49) are not grouped together. Further, five samples were analysed from Millbrook (Samples MBRK A, (C.N.'s 45-49) MBRK C,(C.N.'s 50-53), MBRK D,(C.N.'s 54-58), MBRK E, (C.N.'s 59-60), MBRK XX,(C.N.'s 61-65)) and are widely scattered throughout the dendrogram. The converse of variability, i.e. homogeneity, is shown by the analyses of the Wetwang Slack smithing slag, (C.N.'s 142-146), which are grouped together.

The second feature of analyses of smithing and smelting slags is the difficulty encountered in distinguishing the two slag types. The independent Clustan Analysis cannot distinguish between the two types. Using the 'Rules Procedure' the number of significant clusters are determined, and the analysis showed five clusters to be significant (at the 3.1 level of significance), but what is important is the final grouping of two clusters which resulted from the amalgamation of the previous groups. The

listing of the final groupings are given in Table 13.5 (Vol I pp206/7), this gives the five to two cluster groupings obtained by the Relocate Method, and the final two clusters obtained by Ward's Method (as shown in the dendrogram). This shows that the two sets of two clusters from each method (Ward and Relocate) do not contain the same set of bulk analyses. The second Ward cluster is the same as the fifth group obtained by the Relocate results on five groupings. Discriminant analysis was applied to each of the final groupings to determine which were the most significant oxides in the Clustan groupings. The summary table (Table 13.6, Vol I p208) shows that manganese oxide played no significant role and that the groupings were determined on the basis of different oxide groupings, although phosphorus pentoxide and magnesia were important in both clusters. The Relocate Method was more successful than the Ward Method but clearly failed to distinguish between smelting and smithing slags on the basis of bulk chemical analysis. The inability of statistical techniques to distinguish successfully the different types of slag confirms the variability and heterogeneity of smelting and smithing slags, which derive from the different sources of the oxides present in the slags.

TABLE 13.5   BULK ANALYSES CLUSTER GROUPINGS
5-2 CLUSTERS BY RELOCATE METHOD, 2 CLUSTERS BY WARD'S METHOD
CN= CLUSTER NUMBER; RELOCATE=RELOCATE GROUPS
W= WARD'S METHOD GROUPS

Sample	CN	5	4	3	2	W	Sample	CN	5	4	3	2	W
FARTH1	1	2	2	1	1	0	MBRKD2	55	1	1	1	1	0
FARTH2	2	2	2	1	1	0	MBRKD3	56	1	1	1	1	0
FARTH3	3	2	2	1	1	0	MBRKD4	57	5	4	3	1	2
FARTH4	4	2	2	1	1	0	MBRKD5	58	1	1	1	1	0
FARTH5	5	2	2	1	1	0	MBRKE1	59	1	1	1	1	0
LEV1	6	3	3	2	2	0	MBRKE2	60	1	1	1	1	0
LEV2	7	1	1	2	2	0	MBRKXX1	61	1	1	1	1	0
LEV3	8	1	1	2	2	0	MBRKXX2	62	1	1	1	1	0
LEV4	9	1	1	2	2	0	MBRKXX3	63	1	1	1	1	0
LEV5	10	3	3	2	2	0	MBRKXX4	64	1	1	1	1	0
AMG141	11	1	1	1	1	0	MBRKXX5	65	1	1	1	1	0
AMG142	12	1	1	2	2	0	ROM3.1	66	3	3	2	2	0
AMG143	13	1	1	1	1	0	ROM3.2	67	3	3	1	2	0
AMG144	14	1	1	1	1	0	ROM3.3	68	3	3	2	2	0
AMG781	15	3	3	2	2	0	ROM3.4	69	3	3	1	2	0
AMG782	16	3	3	2	2	0	ROM3.5	70	3	3	1	2	0
AMG783	17	3	3	2	2	0	ROM2.1	71	3	3	2	2	0
AMG784	18	3	3	2	2	0	ROM2.2	72	3	3	2	2	0
AMG785	19	3	3	2	2	0	ROM2.3	73	3	3	2	2	0
AMG831	20	1	1	1	2	0	ROM2.4	74	3	3	2	2	0
AMG832	21	3	1	1	2	0	ROM2.5	75	3	3	2	2	0
AMG833	22	1	1	1	2	0	MUK51	76	4	3	2	2	0
AMG834	23	1	1	1	2	0	MUK52	77	3	3	2	2	0
AMG835	24	1	1	1	2	0	MUK53	78	3	3	2	2	0
BAY1	25	5	4	3	1	2	MUK54	79	3	3	2	2	0
BAY2	26	5	4	3	1	2	MUK55	80	3	3	2	2	0
BAY3	27	5	4	3	1	2	BEK11	81	4	3	2	2	0
BAY4	28	5	4	3	1	2	BEK12	82	4	3	2	2	0
BAY5	29	5	4	3	1	2	BEK13	83	4	3	2	2	0
OAK1	30	1	1	1	2	0	BEK14	84	4	3	2	2	0
OAK2	31	1	1	1	2	0	BEK21	85	4	3	2	2	0
OAK3	32	1	1	1	1	0	BEK22	86	4	3	2	2	0
OAK4	33	1	1	1	2	0	BEK23	87	4	3	2	2	0
OAK5	34	1	1	1	2	0	BEK24	88	4	3	2	2	0
PARK1	35	3	3	1	2	0	BEK25	89	4	3	2	2	0
PARK2	36	2	2	1	2	0	BEK31	90	4	3	2	2	0
PARK3	37	3	3	1	2	0	BEK32	91	4	3	2	2	0
PARK4	38	2	2	1	2	0	BEK33	92	4	3	2	2	0
PARK5	39	2	2	1	2	0	BEK34	93	4	3	2	2	0
OUSE1	40	5	4	3	1	2	BEK35	94	4	3	2	2	0
OUSE2	41	5	4	3	1	2	BEK36	95	4	3	2	2	0
OUSE3	42	5	4	3	1	2	BEK41	96	4	3	2	2	0
OUSE4	43	5	4	3	1	2	BEK42	97	2	2	1	2	0
OUSE5	44	5	4	3	1	2	BEK43	98	3	3	2	2	0
MBRKA1	45	2	2	1	1	0	BEK44	99	4	3	2	2	0
MBRKA2	46	2	2	1	1	0	BEK45	100	4	3	2	2	0
MBRKA3	47	3	2	1	2	0	BEK46	101	4	3	2	2	0
MBRKA4	48	2	2	1	1	0	BEK51	102	4	2	1	2	0
MBRKA5	49	3	2	1	2	0	BEK52	103	4	3	2	2	0
MBRKC1	50	1	1	1	1	0	BEK53	104	4	3	2	2	0
MBRKC2	51	1	1	1	2	0	BEK54	105	4	3	2	2	0
MBRKC3	52	1	1	1	1	0	BEK55	106	4	3	2	2	0
MBRKC4	53	1	1	2	1	0							
MBRKD1	54	1	1	1	1	0							

TABLE 13.5 (CONT.) BULK ANALYSES CLUSTER GROUPINGS

		RELOCATE				W
Sample	CN	5	4	3	2	
WP11	107	2	2	3	1	0
WP12	108	4	3	2	2	0
WP13	109	2	2	1	1	0
WP14	110	2	2	1	1	0
WP15	111	4	3	2	2	0
WP21	112	4	3	2	2	0
WP22	113	4	2	3	2	0
WP23	114	2	2	1	1	0
WP24	115	4	2	2	2	0
WP25	116	4	3	2	2	0
BIR961	117	2	2	1	2	0
BIR962	118	2	2	1	2	0
BIR963	119	2	2	1	2	0
BIR964	120	2	2	1	2	0
BIR965	121	2	2	1	2	0
BIR951	122	2	2	1	2	0
BIR952	123	2	2	1	2	0
BIR953	124	2	2	1	2	0
BIR954	125	2	2	1	2	0
BIR955	126	2	2	1	1	0
AMSM83 1	127	3	3	2	2	0
AMSM83 2	128	3	3	2	2	0
AMSM83 3	129	3	3	2	2	0
AMSM83 4	130	3	3	2	2	0
AMSM83 5	131	3	3	1	2	0
AMSM61 1	132	3	3	1	2	0
AMSM61 2	133	3	3	1	2	0
AMSM61 3	134	3	2	1	2	0
AMSM61 4	135	2	2	1	2	0
AMSM61 5	136	3	3	1	2	0
AMSM16 1	137	2	2	1	1	0
AMSM16 2	138	2	2	1	2	0
AMSM16 3	139	2	2	1	2	0
AMSM16 4	140	3	3	2	2	0
AMSM16 5	141	2	2	1	1	0
WWS1	142	3	3	2	2	0
WWS2	143	3	3	2	2	0
WWS3	144	3	3	2	2	0
WWS4	145	3	3	2	2	0
WWS5	146	3	3	2	2	0
HEYA64 1	147	2	2	1	1	0
HEYA64 2	148	2	2	1	1	0
HEYA64 3	149	2	2	1	1	0
HEYA64 4	150	2	2	1	2	0
HEYA64 5	151	3	3	1	2	0
HEY119 1	152	2	2	1	1	0
HEY119 2	153	2	2	1	1	0
HEY119 3	154	2	2	1	1	0
HEY119 4	155	2	2	1	1	0
HEY119 5	156	2	2	1	1	0
HEYA81	157	4	3	2	2	0
HEYA82	158	2	2	1	2	0
HEYA83	159	2	2	1	1	0
HEYA84	160	3	3	2	2	0
HEYA85	161	4	3	2	2	0

TABLE 13.6   DISCRIMINANT ANALYSIS SUMMARY TABLE   BULK ANALYSES

SUMMARY TABLE

STEP	ACTION ENTERED	ACTION REMOVED	VARS IN	WILKS LAMBDA	SIG.	LABEL
1	P		1	.722177	0	
2	MG		2	.592298	.0000	
3	SI		3	.509080	0	
4	CO		4	.499398	.0000	
5	CR		5	.494235	0	
6	TI		6	.488869	.0000	
7	FE		7	.484872	0	
8	NI		8	.481423	.0000	
9	CA		9	.477912	0	
10	AL		10	.473634	.0000	
11	NA		11	.470394	0	
12	K		12	.466752	.0000	
13		TI	11	.469089	0	

CLASSIFICATION FUNCTION COEFFICIENTS
(FISHER*S LINEAR DISCRIMINANT FUNCTIONS)

GP1   =   0   1

	0	1
NA	6.747346	5.714053
MG	5.856512	4.033578
AL	12.31416	11.81893
SI	7.488755	7.645632
P	3.907182	7.578693
K	-.7065386	.1193900E-01
CA	10.82971	10.46099
CR	17.45022	12.03087
FE	8.755185	8.567619
CO	43.11230	39.63349
NI	55.01948	51.56398
(CONSTANT)	-419.5017	-413.6201

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13.7 Phase Analyses

In general smelting and smithing slags comprised three
phases: silicate, free iron oxide, and a glassy phase. In most
specimens each phase was analysed.

13.7.1 The Silicate Phase

The mean and standard deviations of the silicate phase
analyses for the smelting slags, smithing slags, and the overall
means are given in Table 13.7 (Vol I p210). The bulk analyses
showed the presence of manganese oxide in the majority of
smelting slags. In accordance with theory, the manganese oxide
concentrated in the silicate phase. High lime values were
present in both smelting and smithing slags, although extremely
high values (>10%) were only present in some smelting slag
silicates. Discriminant and Clustan analyses were performed on
the analyses. The summary of the discriminant analysis (Table
13.8, Vol I p211) showed the most important oxides were
manganese, magnesium, and nickel. This analysis caused some
silicates to be re-classified; these were Park North, and Mucking
(manganese oxide <0.5%), and Romsey 3.1 and 2.2. No smithing
slag silicates were re-classified as smelting slag silicates.
The Clustan analysis did not distinguish between smelting and
smithing silicates. Both sets of groupings obtained by the Ward
and Relocate Method were the same. The analysis of silicate Bek2
was the only member of the second group, hence the three group
level was used. This grouped 14 of the 24 smelting slag silicate
analyses together, those ascribed to the second group were:-
AMG783, OAK1, OAK2, PARK, MBRKA, ROM3.1, ROM3.2, ROM2.1, ROM2.2,
MUK.
This second group included all the smithing silicate analyses

except BEK2 which was the sole member of Group 3.

Thus it may be concluded that the analysis of the silicate phase cannot distinguish smelting slags from smithing slags. The expected segregation was found for specific oxides into the silicate phase.

TABLE 13.7 MEAN AND STANDARD DEVIATIONS OF SILICATE PHASE ANALYSES
(Weight Percent)

	SMELTING SLAGS		SMITHING SLAGS		OVERALL VALUES	
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
Na_2O	0.2	0.2	0.2	0.2	0.2	0.2
MgO	2.7	4.1	1.1	0.8	2.0	3.2
Al_2O_3	0.2	0.2	0.3	0.9	0.3	0.6
SiO_2	29.7	1.4	29.3	2.2	29.5	1.8
P_2O_5	0.2	0.3	0.4	0.6	0.3	0.4
S	0.0	0.0	0.0	0.1	0.0	0.0
K_2O	0.0	0.1	0.1	0.4	0.1	0.2
CaO	3.8	5.4	1.9	1.3	2.9	4.1
TiO_2	0.0	0.0	0.0	0.1	0.0	0.1
V_2O_5	0.0	0.0	0.0	0.0	0.0	0.0
Cr_2O_6	0.0	0.0	0.0	0.0	0.0	0.0
MnO	6.0	4.2	0.2	0.2	3.4	4.3
FeO	57.2	8.4	66.5	3.3	61.5	8.0
CoO	0.2	0.2	0.1	0.2	0.1	0.2
NiO	0.2	0.1	0.1	0.1	0.1	0.1

SUMMARY TABLE

STEP	ACTION ENTERED REMOVED	VARS IN	WILKS LAMBDA	SIG.	LABEL
1	MN	1	.525145	.0000	
2	MG	2	.465428	.0000	
3	NI	3	.417151	.0000	
4	CO	4	.401149	.0000	
5	CA	5	.385504	.0000	
6	P	6	.379040	.0000	

CLASSIFICATION FUNCTION COEFFICIENTS
(FISHER*S LINEAR DISCRIMINANT FUNCTIONS)

TYPE =	1	2
MG	.5027529	.1063500
P	1.577752	2.910090
CA	.3898680	.2199097
MN	.7824824	.4825290E-01
CO	8.800289	5.187049
NI	19.85612	11.76570
(CONSTANT)	-7.136629	-2.429689

13.7.2 The Glass Phase

The analyses of the glass phases proved difficult to obtain satisfactory results, indicated by the failure to achieve consistent totals within 5% of 100%. Assessment of the results suggests three reasons for these poor results. Firstly, the phase may become bevelled during polishing, and, due to the restricted area of the phase, a non-flat area may have been analysed. This, therefore, disturbs the geometry of the analytical system and inaccuracies may result in the analysis. The second difficulty in glass phase analysis is the migration or 'boiling off' of certain elements, notably potassium, due to the heat generated by the electron beam. The third factor is that the phase may be rich in oxygen; the results are calculated stoichiometrically and therefore would total less than 100%. Therefore, glass phase analysis would not be a reliable method of distinguishing smelting from smithing slags, unless there was a clear-cut distinction.

The means and standard deviations of the smelting, smithing, and the overall values are given in Table 13.9 (Vol I p213). Manganese oxide had significantly different mean values for smelting and smithing slags. The glasses were generally high in alumina and silica, but had considerable variation in the other major oxide contents, e.g. lime, potassium and iron oxides, as indicated by the standard deviations. The smithing slag did not show greater variation in composition than the smelting slags.

TABLE 13.9 MEANS AND STANDARD DEVIATIONS OF GLASS PHASE ANALYSES
(Weight Percent)

| | SMELTING SLAG | | SMITHING SLAG | | OVERALL VALUES | |
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
Na_2O	0.5	0.3	1.0	0.8	0.7	0.6
MgO	0.1	0.1	0.0	0.1	0.1	0.1
Al_2O_3	14.4	4.7	10.7	4.8	12.6	5.1
SiO_2	33.8	8.7	40.6	8.3	37.1	9.1
P_2O_5	3.7	2.5	3.0	3.0	3.4	2.8
S	0.6	0.7	0.3	0.3	0.5	0.6
K_2O	6.5	5.4	7.6	5.0	7.0	5.2
CaO	12.1	6.7	10.8	7.2	11.5	6.9
TiO_2	0.6	0.4	0.4	0.3	0.5	0.4
V_2O_5	0.0	0.0	0.0	0.0	0.0	0.0
Cr_2O_6	0.0	0.0	0.1	0.2	0.0	0.1
MnO	1.3	1.3	0.1	0.1	0.7	1.1
FeO	24.3	11.1	24.3	10.9	24.3	1 0.9
CoO	0.1	0.1	0.0	0.1	0.1	0.1
NiO	0.1	0.1	0.0	0.1	0.0	0.1

13.7.3 The Iron Oxide Phase

The amount of free iron oxide present in a slag is indicative of the efficiency of both the smelting and smithing process. It is also indicative of the oxygen fugacity, since the oxide may occur as either wustite, magnetite, or (less likely) hematite. However, the oxides may also be subjected to post-formation oxidation. The cubic form of the oxide mineral is characteristic of magnetite, but most oxides occurred as rounded/globular dendrites and could not be identified by their

form. It was also difficult to determine the oxidation state from the chemical phase analyses because of the presence of minor levels of other oxides and the non-stoichiometry of wustite. The presence of high levels of titania is probably indicative of a spinel structure, i.e. magnetite, and this is sometimes associated with higher levels of alumina. Although the mean titania value (Table 13.10, Vol I p215) was higher for smelting slags. the variation was such that spinel structures were not more common in smelting slags than smithing slags. The iron oxide dendrites in smelting slags contained higher manganese oxide contents, reflecting the bulk analyses. There was no other diagnostic difference between the oxides from the two types of slag.

TABLE 13.10 MEAN AND STANDARD DEVIATIONS OF FEOX PHASE ANALYSES
(Weight Percent)

| | SMELTING SLAG | | SMITHING SLAG | | OVERALL VALUE | |
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
Na_2O	0.1	0.1	0.1	0.1	0.1	0.1
MgO	0.1	0.2	0.3	0.3	0.2	0.2
Al_2O_3	1.8	4.3	0.8	0.6	1.3	3.0
SiO_2	1.3	1.6	1.2	1.5	1.3	1.5
P_2O_5	0.0	0.0	0.0	0.1	0.0	0.1
S	0.0	0.0	0.0	0.1	0.0	0.1
K_2O	0.1	0.2	0.0	0.1	0.1	0.1
CaO	0.3	0.4	0.1	0.1	0.2	0.3
TiO_2	0.8	0.6	0.4	0.6	0.6	0.6
V_2O_5	0.1	0.1	0.0	0.1	0.1	0.1
Cr_2O_6	0.1	0.1	0.0	0.1	0.1	0.1
MnO	1.8	1.6	0.1	0.1	0.9	1.4
FeO	91.4	7.7	93.9	5.0	92.7	6.5
CoO	0.3	0.2	0.1	0.2	0.2	0.2
NiO	0.2	0.2	0.1	0.1	0.2	0.2

13.8 Normative Mineral Compositions

13.8.1 Introduction

The theoretical mineral composition of the bulk analyses and the silicate and glass phase analyses was calculated using the method published by Kresten [82]. A worked example is given in Appendix 1. As the work progressed detailed examination of the programme raised several questions concerning some of the assumptions on which the calculation was based. These are

outlined below, although the calculation used in this work
utilised the computer programme devised by Kresten (with minor
programming corrections). The calculation uses a 'cascade'
system by which oxides are ascribed to particular minerals in
fixed relationships until all the oxides have been consumed. It
can be sub-divided into three stages. Firstly, the calculation
of the non-silicate component and the apportionment of the alkali
oxides; secondly, the calculation of the major silicate phases;
and thirdly, the silica balance calculation. The problems lie in
the first stage which determines the amount of silica available
for the major silicate phase determination, and hence the
quantity of free iron oxide calculated.

The first calculation is to apportion phosphorus to apatite,
and Kresten uses the geological formula $Ca_5(PO_4)_3$; in modern
slag work the form $3CaOP_2O_5$ is used and should be used in this
calculation. This change would only have a very small effect on
the overall result due to the small amount of phosphorus
usually present.

The sequence of minerals generated is then based (generally)
on the decreasing melting point of the minerals. The sequence
(with melting points) is as follows:-

Apatite	$[3CaOP_2O_5]$ comes out at	$1760^{\circ}C$
Ulvite	$[2FeOTiO_2]$ " " "	$1305^{\circ}C$
Kalsilite	$[KAlO_2SiO_2]$ " " "	$1750^{\circ}C$
Nepheline	$[NaAlO_2SiO_2]$ " " "	$1526^{\circ}C$
Anorthite	$[CaOAl_2O_32SiO_2]$ " "	$1550^{\circ}C$
Hercynite	$[FeOAl_2O_3]$ " " "	$1440^{\circ}C$
Calcium Silicate	$[2CaOSiO_2]$ " "	$2130^{\circ}C$

There are changes that may be considered for example the replacement of kalsilite by leucite ($2[KAlO_2 2SiO_2]$ m.pt.$=1686^\circ C$) because glasses of this composition have been identified, e.g. by Fells[9]. The most serious difficulty is the use of di-calcium silicate instead of mono-calcium silicate ($CaOSiO_2$, m.pt.$=1436^\circ C$), which is more liable to form in a silica rich melt. Further the question is raised why, if di-calcium silicate is used is it not calculated first (due to its very high melting point)? If it was used all the calcium would be absorbed and hence anorthite could not be calculated and hercynite would be formed, and more silica would have been absorbed leading to an increase in the amount of free iron oxide present. This point must be the subject of further study (see section 13.12). The use of the minerals chosen and di-calcium silicate in particular can be justified for the following reasons. Firstly, a fully liquid 'tap slag' to use the most extreme example is probably at a temperature of $1200^\circ C$ in the furnace, although it may have been subjected to higher temperatures for short periods of time. The slag is in the form of a melted glass, i.e. long silicate chains, and the temperature is well below the melting point of all the minerals quoted above, i.e. if they were present they would be in the solid state. The fact that the oxides which make up these normative minerals are found in the glassy phase in the analysed slags shows that they were the last to solidify, i.e. below the freezing point of fayalite (m.pt.$=1103^\circ C$). Therefore, the temperature cannot be used as the only guide to mineral selection, and mineral stability must be considered. The second reason, specifically for the use of di-calcium silicate, is that lime is commonly present in the fayalite phase and, therefore, it is expected to follow the general rule $2RO.SiO_2$.

13.8.2 Bulk Analyses Normative Mineral Compositions

The bulk normative mineral compositions reflect the variations present in the bulk chemical analyses; for example, the presence of manganese oxide causes tephroite or rhodonite to be calculated. The principal purpose of the calculation of the bulk normative mineral compositions was to determine the ternary groupings. They also demonstrate which slags are silica rich, (orthoclase etc. calculated), which contain excess iron oxide, (wustite calculated), and which are balanced, (neither wustite nor orthoclase etc. calculated), and might, therefore, show some consistent difference between the slag types. Study of the bulk normative mineral compositions shows no such difference; for example, the mean and standard deviations of the normative wustite content for smelting slags are 7.2% and 13.2%, and for smithing slags 17.3% and 19.8% respectively. This, again, demonstrates the heterogeneity of ironworking slags.

13.8.3 Phase Analyses Normative Mineral Compositions

The silicate phases analysed were all fayalitic, tephroite being calculated in the manganese bearing slags. The silicate phases could be either silicate rich, contain excess wustite, or have a balanced composition. The smelting slag silicates were predominantly wustite rich, (mean value=2.7%, S.D.=2.5%), [Levisham 1 was balanced, Baysdale, Ousegill, and Romsey 3, 2.1 and 2.2 were all silica rich]; the smithing slag silicates were predominantly silicate rich (11 out of 21 phases analysed), 3 were balanced, and 7 contained excess wustite, (mean value=1.0%, S.D.=1.9%). The difference was not consistent and could not, therefore, be used to distinguish between the slags.

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The glass phase normative calculations are of only limited use, because of the analytical difficulties outlined above (p212). The smelting and smithing glass phases were silica rich with the exception of the results from Amersham (Sample AM878) and Heybridge (Sample HeyA8). The variation in composition was such that no discrimination between the slag types could be made. for example the means and standard deviations of kalsilite and orthoclase are given in Table 13.11.

TABLE 13.11 MEAN AND STANDARD DEVIATIONS OF GLASS PHASE
KALSILITE AND ORTHOCLASE

	Smelting Slags		Smithing Slags	
	Mean	S.D.	Mean	S.D.
Kalsilite	16.7	15.5	8.3	9.9
Orthoclase	14.1	12.8	26.1	19.7

13.9 Ternary Groupings and r-factors.

The bulk normative mineral composition were sub-totalled into three groups; silicates. glass minerals, and iron oxide (wustite). This enabled an r-factor to be determined for the bulk analyses obtained for each specimen, and hence a qualitative test of chemical homogeneity/heterogeneity. The groupings enabled a direct comparison to be made with the volumetric analysis, using the r-factor anlysis.

The mean and standard deviations of the smelting. smithing and overall ternary phases are shown in Table 13.12 (Vol I p220).

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TABLE 13.12   NORMATIVE TERNARY PHASE GROUPINGS.
                MEANS AND STANDARD DEVIATIONS

| | SILICATE | | GLASS | | IRON OXIDE | |
	MEAN	S.D.	MEAN	S.D.	MEAN	S.D.
Smelting Slag	70.7	13.1	21.5	12.5	7.7	13.5
Smithing Slag	65.9	7.7	16.5	8.7	17.6	19.7
Overall Value	68.2	15.8	18.9	11.0	12.9	17.6

These show that the smelting slags were richer in silicate and
glass phase than the smithing slags, but the standard deviations
again show that the degree of variation is such that no range of
ternary groupings is diagnostic of either smelting or smithing
slags.

The r-mean values and standard deviations are summarised in
Table 13.13.

TABLE 13.13   TERNARY r-MEAN VALUES AND STANDARD DEVIATIONS

	r-mean	S.D.
Tap Slags	6.3	7.7
Rake Slags	9.6	7.2
S.L.B.	4.0	3.8
D.I.S	4.2	2.3
Overall Smelting	6.7	7.1
" Smithing	10.3	10.2

These show the relative homogeneity of the bulk analyses of the
tap slags, slag block, and dense iron silicate slag, compared to
the heterogeneity of the raked and smithing slags. The latter
are more heterogeneous than the other slags, but the standard

deviations clearly show that the degree of heterogeneity is not diagnostic of particular slag types.

13.10   The Comparison of r-factors

Three sets of r-factors were obtained for each sample, the volumetric value, the ternary value, and the volumetric/ternary value. The latter is the method used to compare the volumetric phase percentages, i.e. the observed percentages, and the ternary phase percentages, i.e. the calculated normative phase percentages. The volumetric and the ternary values are indicative of the homogeneity/heterogeneity of the sample. Thus a mineralogically homogeneous specimen would have a low volumetric r-mean value, and a chemically homogeneous specimen would have a low ternary r-mean value. A specimen that cooled under equilibrium conditions would have a low volumetric/ternary r-mean value; the greater the deviation from equilibrium conditions or the greater the mineral or chemical heterogeneity the greater the volumetric/ternary r-factor values (and the greater the r-mean value or standard deviation).

The smelting slags would have been expected to be homogeneous in both mineralogical and chemical composition, since a smelting slag would have been liquid at one time. It may also be expected that there would be a significant difference between the observed and the calculated mineral composition, since great deviation from equilibrium conditions may be expected as the slag is removed from the furnace into ambient temperatures. This deviation from equilibrium was expected to be the greatest for tap slags.

The smithing slags were expected to show considerable

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variation in mineral and chemical composition, since the slag was the result of the accumulation of slag from a number of different operations, in which the components may vary, e.g. a different fluxing sand being used. The slag may have remained in the hearth for long periods, subjected to numerous reheatings and slow cooling. Therefore, equilibrium conditions may have been approached, although homogenisation of the whole slag mass would not have occurred, and chemical and mineral variations would still be present throughout the specimen. Therefore, high volumetric, ternary, and volumetric/ternary mean values may have been expected from smithing slags.

The volumetric and ternary r-mean values have already been given but are re-presented with the volumetric/ternary values, (Table 13.14). The results are also shown graphically (Figures 18-21, Vol II pp226-229).

TABLE 13.14   VOLUMETRIC, TERNARY, AND VOLUMETRIC/TERNARY
r-MEAN VALUES

	Volumetric Values		Ternary Values		Volumetric/Ternary Values	
	Mean	S.D	Mean	S.D.	Mean	S.D
Smelting Slags						
Tap Slags	8	6	6.3	7.7	12.1	8.9
Rake Slags	12	7.5	9.6	7.2	15.8	7.3
S.L.B.	11	5	4.0	3.8	16.5	7.6
D.I.S.	8	5	4.2	2.3	13.7	5.9
Overall Values	10	7	6.7	7.1	13.8	8.3
Smithing Slags						
Overall Values	12	10	10.3	10.2	19.0	13.4

All the results show a general trend of the volumetric/ternary >
volumetric > ternary r-values (and are. therefore, plotted in
this sequence on the graphs). The data supports to some degree
the proposals outlined above. The smelting slags are more
chemically and mineralogically homogeneous than the smithing
slags. They also show significant deviation from equilibrium
conditions, as indicated by the increased volumetric/ternary r-
mean values (Figure 18. Vol II p226). The smithing slags are
chemically and mineralogically heterogeneous and show a large
increase in the volumetric/ternary r-mean value. This probably
results mostly from the heterogeneity of the samples rather than
from deviation from equilibrium cooling.

The graphical plots clearly illustrate that the variation of
the smithing slag values (Figure 19, Vol II p227), as indicated
by the overall means and standard deviations. They are such that
the overall smelting values fall within one standard deviation of
the overall smithing slag mean (Figure 20. Vol II p228). The
raked slags are the most similar, morphologically, to the
smithing slags; Figure 21 (Vol II p229) shows the similarity of
the mean values, and the variation again shows the raked slags to
fall well within one standard deviation of the smithing slags.

The comparison of the r-factors cannot be used to
distinguish the different slag types, in particular
distinguishing raked slags from smithing slags. The r-mean
values and standard deviations, however, do reaffirm the
heterogeneity of all slag types. and thus, clearly show that
simple chemical or optical analysis is not sufficient to identify
a slag type.

13.11 CONCLUSIONS

Early ironworking technologies generated silicate slags as by-products of both the smelting and smithing processes. Their recovery from archaeological excavations poses problems for identification, that are required to be overcome in order that a fuller understanding of the historical-economic basis of a site can be obtained.

In this work the techniques used to attempt to distinguish between smelting and smithing slags have included Morphology, Chemical, Microscopic, and Mineralogy. Statistical analyses of the results obtained have been made.

It has been shown:

1   The majority of slags would have been expected to have been derived from the smithing process, therefore, it was assumed the recovered slag is smithing slag unless proved otherwise.

2   Not all slags can be identified by a single attribute.

3   Slags are heterogeneous in chemical and mineral composition. The degree of heterogeneity must be considered as an attribute of the slags.

4   There are only two attributes that, at present, can be used with certainty to distinguish some smelting slags from smithing slags.

    (a) Morphology

    (b) The presence of a significant percentage of manganese oxide (>0.5% in the bulk analyses) in some smelting slags

5   Other attributes may aid in confirming the slag

identification and provide information as to the efficiency of the process together with hearth or furnace conditions.

6   The ability to distinguish the different slag types enables the archaeologist to obtain a better understanding of the economic basis and economic development of a settlement or community.

13.12   Suggestions for Further Work

The techniques applied to the study of early ironworking slags in this work have not enabled a definitive method of slag identification and/or classification to be produced. Therefore, the application of other analytical techniques may provide better data. For example, the analysis of minor and trace elements using sophisticated electron probe micro-analysers.

The variability in mineral texture should be investigated by cooling experiments. This may also provide valuable data for geological mineralogical studies of silicate melts, which is a field of considerable study at the moment.

The lack of comparative data was very apparent, particularly of smithing slag analyses. Therefore, an expansion of the data base is an essential requirement. This would enable improvements to be made in statistical analyses. Further, mis-identification or classification may have unknowingly occurred in this work. An expansion of the data base would improve the chance of identifying such a mistake.

The method of determining normative mineral compositions is a useful technique in manipulating slag analyses. Further study must be applied to the selection and sequence of minerals used.

The mechanisms of the ancient smith's hearth should be investigated to enable assessments of the quantity of smithing slag generated by particular processes to be made.

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